Healthy air for children

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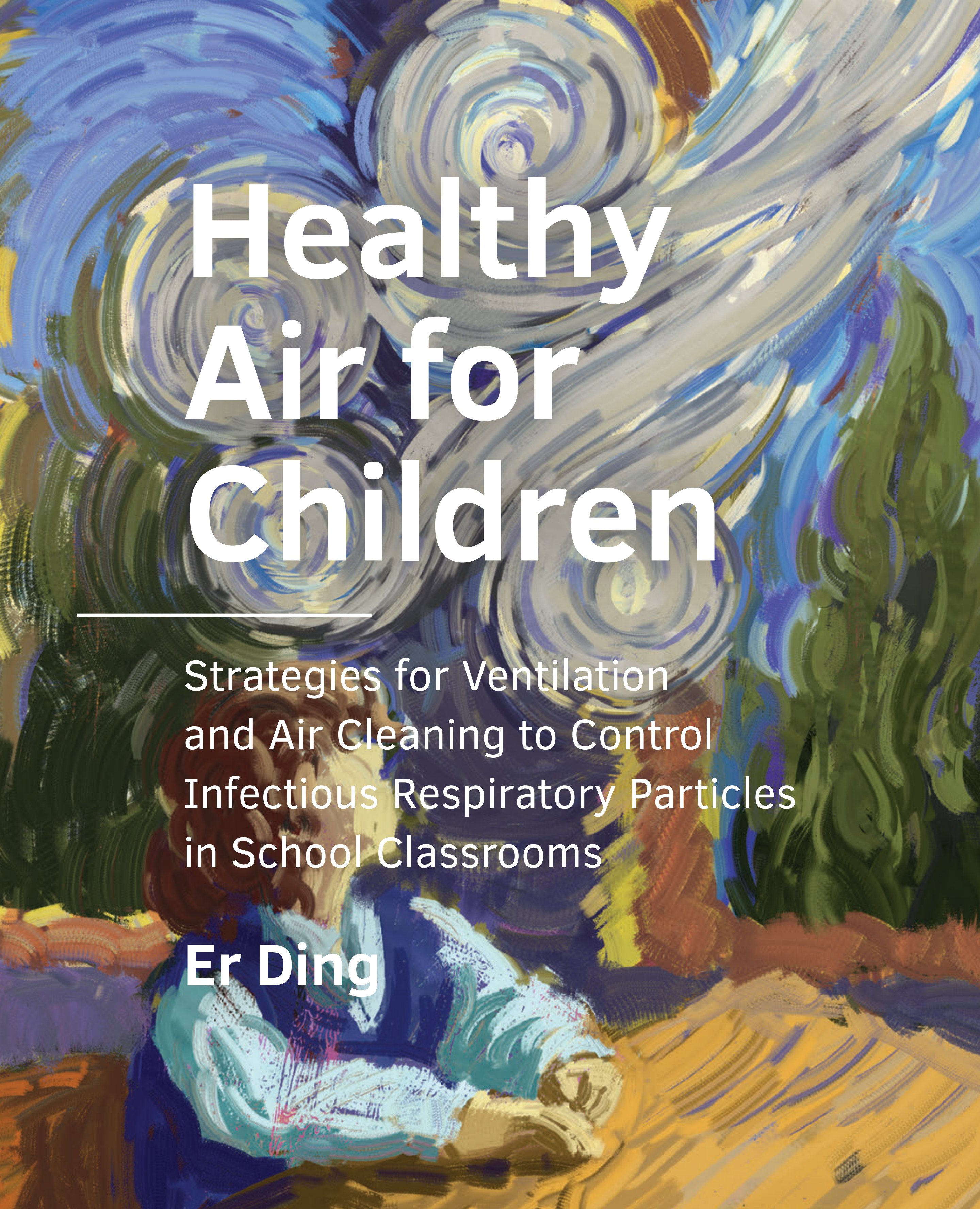

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Healthy Air for Children

Strategies for Ventilation and Air Cleaning to Control Infectious Respiratory Particles in School Classrooms

Dissertation

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chair of the Board for Doctorates
to be defended publicly on
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by

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This dissertation has been approved by the promotors.

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Prof.dr. J.E. Stoter	Delft University of Technology, reserve member

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To those whose love I carry along the way

Acknowledgements

Five years ago, in February 2020, I was at home in Guangzhou, China, anxiously awaiting my visa to the Netherlands. The uncertainty surrounding the start of my PhD journey, compounded by the onset of COVID-19, left me unsure of what the future held. Little did I know how drastically my life would change from that moment. Now, five years later, in February 2025, I find myself sitting at home again – for the first time in years, celebrating the Chinese New Year with my family. With my PhD journey nearing its end, I reflect on the memories I have made along the way, only to realize that words are too limited to capture the most incredible adventure of my life or to express my profound gratitude for the love and support that has continuously illuminated my path.

Thanks to the interdisciplinary nature of my bachelor's study on thermal engineering and HVAC systems, I first developed my interest in the crossing field, the built environment. Later, as I deepened my knowledge and research experience in occupant health and comfort during my master's study on building science and technology, that initial curiosity evolved into a strong desire to explore the interaction between occupants and their surroundings, with the goal of improving people's well-being. This determination, combined with all the good fortune I could have ever asked for, eventually led me to the right people and the right place. I had the privilege of meeting Prof. Philomena Bluyssen, and later Dr. Clara García-Sánchez – my dearest promotors – without whom this work can never be accomplished, and to whom I would like to express my greatest gratitude. They both supported me unconditionally and shared their expertise generously.

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In brief, scientific progress is never the work of a single researcher but the result of collective efforts within the academic community. Therefore, I would like to take this opportunity to thank everyone with whom I have built connections over the years – whether in person or virtually, through manuscripts, presentations, or other forms of exchange. My heartfelt gratitude goes to all the tutors and colleagues, fellow researchers, and collaborators across various sectors who have been part of my journey.

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Er Ding (Erica)
Guangzhou, February 2025

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List of Symbols, Abbreviations, and Units

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List of symbols	
β	regression coefficients of GEE
C_{CO_2}	CO_2 concentration
$C_{CO_2,steady}$	steady-state CO_2 concentration
$C_{CO_2,out}$	outdoor CO_2 concentration
C_{PM}	aerosol concentration
$C_{PM,0}$	initial aerosol concentration of the decay phase at $t = 0$
$C_{PM,\infty}$	aerosol concentration when $t >> k_{PM}^{-1}$
$C_{PM,std}$	standardized aerosol concentration
C_{μ}	empirical constant for turbulent viscosity
$C_{\varepsilon 1}$	constant in the production term for ε
$C_{\varepsilon 2}$	constant in the dissipation term for ε
CO_2	carbon dioxide
d	diameter
ε	turbulence dissipation rate
$\exp(\beta)$	exponentiation of β
F	F-statistic of ANOVA
G_P	average CO_2 generation rate per person
k	turbulence kinetic energy
k_{PM}	decay coefficient of aerosol concentration
$k_{PM,mac}$	aerosol removal rate of mobile air cleaner
$k_{PM,n}$	coefficient of natural decay
$k_{PM,total}$	coefficient of total decay
μ	dynamic viscosity
μ_t	turbulent viscosity

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List of symbols	
n	average number of students in the classroom during the lesson
O_3	ozone
P	probability of statistical tests
$\overline{P}$	time-averaged pressure
P_k	turbulent production term
R^2	coefficient of determination
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε
T	air temperature
T_{in}	indoor air temperature
T_{RMOT}	running mean outdoor air temperature
t	time
u	velocity magnitude
$\overline{U}_i$	time-averaged velocity components in -th direction
$\overline{U}_j$	time-averaged velocity components in -th direction
V	volume of room
y^+	dimensionless wall distance
Y	natural logarithm of VR_p, $\ln(VR_p)$
ρ	density
Φ	diameter

List of abbreviations	
(R)MP	(round) movable panel
AC	activated carbon
ANOVA	one-way analysis of variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATD	air terminal device
CADR	clean air delivery rate
CEN	European Committee for Standardization
CFD	computational fluid dynamics
CI	confidence interval
CMP	computer monitor panel
COVID-19	coronavirus disease 2019
DV	displacement ventilation
ECAi	equivalent clean airflow
EPA	efficient particulate air
ES	electrostatic

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List of abbreviations	
GEE	generalized estimating equations
HDG	horizontal desk grill
HEPA	high-efficiency particulate air (filter)
HPLC	high-performance liquid chromatography
HREC	Human Research Ethics Committee
HV	hybrid ventilation
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
ICND	individually controlled noise-reducing device
IEQ	indoor environmental quality
IF	intake fractions
IRD	infectieuze respiratoire deeltje
IRMM	infection risk management mode
IRP	infectious respiratory particles
ISO	International Organization for Standardization
MAC	mobile air cleaner
ME	only mechanical air exhaust
MLR	verschillende mobiele luchtreiniger
MS	only mechanical air supply
MT	both mechanical air supply and exhaust
MV	mixing mechanical ventilation
ND	natural decay
NV	natural ventilation
PA	persoonlijke afvoer
PASC	post-acute sequelae of SARS-CoV-2
PAC	personalized air cleaner
PCO	photocatalytic oxidation
PE	personalized (air) exhaust
PEM	personal environment module
PL	plasma
PLR	persoonlijke luchtreinigers
PM	particulate matter
$PM_{2.5}$	particulate matters of a diameter of 2.5 μm and smaller
PM_{10}	particulate matters of a diameter of 10 μm and smaller
PS	personalized air supply
PT	persoonlijke luchttoevoer
PV	personalized ventilation/persoonlijke ventilatiesystemen
RANS	Reynolds-Averaged Navier-Stokes
REHVA	Federation of European of Heating, Ventilation, and Air-Conditioning Associations
RH	relative humidity

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List of abbreviations	
RMOT	running mean outdoor air temperature
RVO	Netherlands Enterprise Agency
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2
SBS	sick building syndrome
SD	standard deviation
SPL	sound pressure level
SV	stratum ventilation
TVOC	total volatile organic compound
UV-C	ultraviolet germicidal irradiation of 180-280 nm wavelength
UVGI	ultraviolet germicidal irradiation
VAT	value-added tax
VDG	vertical desk grill
VR	ventilation rate
VR_a	ventilation rate per floor area
VR_p	ventilation rate per person
WHO	World Health Organization
ZonMw	National Organization for Health Research and Care Innovation

List of units	
%	percentage
°	degree
°C	degree Celsius
€	euro
cm	centimeter
dB(A)	A-weighted decibels
h	hour
h^{-1}	per hour
km/h	kilometers per hour
L/h	liters per hour
L/s	liters per second
$L/s/m^2$	liters per second per square meter
L/s/p	liters per second per person
m^2	square meter
m^2/s^2	square meters per square second
m^2/s^3	square meters per cubic second
m^3	cubic meter
m^3/h	cubic meters per hour

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List of units	
m/s	meters per second
min	minute
$\mu g/m^3$	micrograms per cubic meter
μm	micrometer
nm	nanometer
Pa	pascal
ppb	parts per billion
ppm	parts per million
s	second
wt%	weight percent

Summary

Good indoor air quality (IAQ) has long been called for the surrounding environments of children to ensure their health and well-being – a priority that has engaged researchers for decades. The sudden outbreak of the Coronavirus Disease 2019 (COVID-19) pandemic, however, posed substantial challenges to this goal. Infectious respiratory particles (IRPs), transmitted via airborne pathways, can easily cause cross-infection between occupants indoors, presenting serious health threats. School classrooms, characterized by long occupancy hours and high occupant density, are hence particularly vulnerable. When the pandemic hit, the lack of effective mitigation solutions often prevented schools from fully addressing these risks, resulting in disruptions to normal educational activities. Aiming to help improve this situation, this PhD research was conducted to answer the following main research question:

Which ventilation and air cleaning strategies can be used to effectively control the spread of infectious respiratory particles in school classrooms?

This question is addressed through four steps: 1) understanding the state of the art and defining research gaps, 2) examining real-world situations to set directions for improvements, and proposing solutions at 3) room scale and 4) individual level, respectively.

First, a systematic literature review was conducted to establish the research context and background and define the research gaps. A multidisciplinary literature search using a large combination of keywords was performed, which formed three main topics regarding the focus of the research: 1) the current situation of ventilation strategies and IAQ conditions in school classrooms; 2) features and control of airborne transmission of IRPs; and 3) performance and feasibility of advanced ventilation systems. By including 94 research papers, eight standards and guidelines, and five reports, a deep understanding of each topic and the connections among them were obtained. The literature reveals that IRPs, as a primary transmission route for pathogens responsible for infectious respiratory diseases like COVID-19, are small particles produced during respiratory activities. IRPs can be transmitted through both short-range and long-range airborne pathways, each requiring distinct ventilation methods for effective control. While conventional ventilation systems have been shown to effectively mitigate long-range IRP

transmission, the optimal configuration, especially for non-medical environments, is still unclear. Moreover, due to a typical assumption of steady-state and well-mixing conditions, room-scale ventilation methods cannot adequately address the dynamic nature of short-range IRP transmission, for which immediate reaction by the systems is needed. Current ventilation requirements for school classrooms primarily focus on perceived air quality and energy efficiency, often using CO_2 concentrations as an indicator of pollution caused by occupants. The required ventilation levels, therefore, might not be adequate for IRP control. In the real world, on the other hand, many classrooms fail to meet even the existing ventilation requirement. The review hence suggests a necessary shift in ventilation design from a comfort-centric approach to one that prioritizes occupants' health, advocating for more flexible and adaptable strategies. Additionally, personalized ventilation (PV) systems, including personalized air supply (PS) and exhaust (PE), are highlighted as potential solutions to mitigate short-range IRP transmission and enhance IAQ within the proximity of each occupant. However, existing PS and PE systems, developed mainly for high-risk environments such as hospital wards and aircraft cabins, may require further adaptation for effective implementation in classroom settings.

Second, a field study was carried out to investigate the ventilation and thermal conditions in school classrooms during the COVID-19 pandemic. In total, 31 classrooms across 11 Dutch secondary schools were involved, representing a diverse range of locations, types of education, and building ages, covering students aged 12 to 18. To track the evolution of conditions in the classrooms at different stages of the COVID-19 pandemic, as various levels of control and prevention measures were implemented, each school was visited twice: once before and once after a national lockdown. Each school visit consisted of 1) monitoring of the indoor and outdoor CO_2 concentration and air temperature; 2) a short interview with the facility manager; 3) an inspection of the school buildings, HVAC (heating, ventilation, and air conditioning) systems, and classrooms; and 4) monitoring of the occupancy and occupants' behaviors. It was found that most schools opted to keep windows and doors open throughout the day to maximize outdoor air supply as a pandemic control measure. This practice hindered the operation of mechanical ventilation systems as designed, making them no different from using natural ventilation alone. Before the lockdown, classrooms operated at normal occupancy levels but failed to meet recommended ventilation standards, as evidenced by high indoor CO_2 concentrations during occupied hours. After the lockdown, student occupancy was reduced to approximately half, resulting in significantly lower indoor CO_2 levels and improved ventilation rates per person; however, this improvement was primarily linked to decreased occupancy rather than any enhancements in ventilation practices. Additionally, thermal conditions in classrooms were found to be unsatisfactory during both the pre- and post-lockdown periods. Before the lockdown,

many classrooms experienced unacceptably cold temperatures during the heating season; after the lockdown, temperatures varied with changing seasons, leading to instances of classrooms being either too warm or too cold. Overall, despite efforts to maximize outdoor air supply, classrooms struggled with desired ventilation and thermal conditions, highlighting the urgent need for more flexible and effective long-term ventilation strategies.

Third, for controlling long-range airborne transmission of IRPs, mobile air cleaners (MACs) were proposed, considering their flexibility and affordability. Given the large variety of MACs available, first, a set of criteria to guide the selection process, considering both technical and economic factors. Accordingly, eight small- and medium-sized floor-standing MACs were selected, of which seven were assessed via laboratory experiments. The experimental study was conducted in the Experience room of the SenseLab at Delft University of Technology, with an interior of a classroom setting. The assessments included 1) an aerosol decay test to determine the aerosol removal rate and clean air delivery rate (CADR) and 2) a panel perception test to examine occupants' perception of the noise and draft caused by the MACs. The results indicated that MACs with high-efficiency filters (H13) could effectively remove IRPs throughout the room, regardless of their air cleaning technology. A key factor in achieving maximum CADR lies in the induced airflow pattern of the MAC: MACs with an upward airflow supply (vertical or angled) were found to distribute clean air more efficiently compared to horizontal air supply. Device placement also plays a crucial role: the air supply of the MACs should always face the occupied zone within the room. Additional tests conducted in a university classroom confirmed these findings, as well as highlighting the importance of using multiple devices as room size increases. Furthermore, the results revealed that combining MACs with mechanical ventilation can yield a higher CADR than MACs alone. Although higher MAC settings are necessary for achieving desirable CADR, the corresponding noise levels often surpass the prescribed threshold and are unacceptable to the subjects. Air velocities generally met comfort standards, receiving positive feedback. These results highlight the need for user feedback to optimize MAC performance in classrooms, balancing effective air cleaning with occupant comfort.

To investigate the feasibility of the above-mentioned strategies, a follow-up field study was performed in 45 classrooms across five Dutch primary schools. Three MACs of the best performance in the experimental study were selected and were randomly assigned among the classrooms. The evaluation of feasibility included 1) assessing the practicality of implementing the strategies and 2) monitoring IAQ parameters in three classrooms per school for both a control period and an intervention period. Deploying MACs in classrooms presented practical challenges, including limited space, crowded layouts, and insufficient power outlets, which

necessitated adjustments to MAC placements and the use of extension cords. Although positioning differed from the exact experimental setup and operational errors were possible, by ensuring one device at the front and one at the back, with the air supply directed toward the occupied area, the MACs consistently reduced particle concentrations.

Forth, for controlling short-range airborne transmission of IRPs, personalized air cleaners (PACs) were proposed to be used as a localized exhaust, leveraging the advantages of both PE systems and mobile air cleaners. The perceptual assessments of noise and draft of the PAC was first carried out via experimental tests with human subjects, followed by tests on its respiratory aerosol removal efficiency. Then, computational fluid dynamics (CFD) simulations were performed to assess the impact of various positioning on the PAC's suction effect. Experimental results showed that at a higher setting, the PAC caused excessive noise, limiting further tests to the lower level. Nonetheless, it still significantly reduced aerosol concentrations, especially for smaller particles. However, such a promising outcome was attributed to strong air recirculation in a confined setup. CFD simulations revealed that the PAC's suction effect was highly localized and diminished rapidly with distance, hardly reaching the occupant's breathing zone in a larger space. Nevertheless, the central-vertical position demonstrated the best results. In real-life scenarios, this position can also better leverage the rise of exhaled particles caused by the thermal plume of the human body, leading to enhanced capture of IRPs. Compared to other PE systems, the PAC operates at a lower airflow rate, yet increasing airflow may lead to unacceptable noise levels. Other modifications, such as a larger suction surface or closer placement to occupants, warrant consideration but require careful planning and design optimization. Overall, while the PAC shows promise for IRP removal in classrooms, optimized designs are needed for effective, user-friendly operation in real-world applications.

To conclude, this PhD research demonstrated that currently, the ventilation in school classrooms (mostly relying on window-based natural ventilation) often falls short of meeting existing requirements, and thus is likely insufficient to control the spread of IRPs. Therefore, more controllable ventilation approaches, namely mechanical ventilation systems, are needed, alongside complementary interventions like MACs and PACs. The findings reveal that MACs, when appropriately selected and positioned, offer room-scale protection against long-range IRP transmission, while PACs are effective in managing localized, short-range IRP exposure, particularly where seating arrangements or class activities increase close contact. Together, these solutions offer a comprehensive framework for managing IRPs in classroom settings.

Overall, this PhD research provides actionable strategies for various stakeholders, from school administrators, policymakers, and product developers to the occupants themselves, namely students and teachers. The practical implications include 1) systematic plans for using different ventilation and air cleaning methods to improve IAQ conditions in school classrooms; 2) recommendations for future system/product design modifications; 3) advocacy of updates in regulations for ventilation and air cleaning; and 4) knowledge for the occupants to better understand the importance of IAQ and its impact on their health and performance.

For future research, it is recommended to: 1) explore diverse mechanical ventilation configurations, as well as combinations of ventilation and air cleaning methods tailored to varying classroom layouts, climates, and budgetary constraints; 2) optimize PAC design, and develop devices that maximize both comfort and IRP control for school settings; 3) investigate the combined effects of hybrid ventilation and air cleaning solutions, and offer valuable insights into achieving healthier, more resilient indoor environments in schools; 4) to validate the efficacy of the established ventilation and air cleaning strategies, typically via cohort studies, in reducing real-world cross-infection risk during outbreaks of respiratory diseases, or even pandemics.

Samenvatting

Sinds lange tijd is bekend dat een goede binnenluchtkwaliteit van omgevingen waarin kinderen verblijven belangrijk is voor hun gezondheid en welzijn – onderzoekers zien dit daarom al decennia als een prioriteit. De plotseling uitbraak van Corona (COVID-19) zorgde voor extra uitdagingen. De via de lucht overgedragen infectieuze respiratoire deeltjes (IRDs) kunnen binnen gemakkelijk besmetting veroorzaken, wat ernstige gezondheidsrisico's met zich meebrengt. Klaslokalen zijn vanwege de lange en hoge bezetting vooral kwetsbaar. Gebrek aan effectieve maatregelen tijdens de pandemie om deze risico's aan te pakken leidden tot verstoringen van de normale onderwijsactiviteiten. Dit promotieonderzoek is uitgevoerd om bij te dragen aan een verbetering van deze situatie, door de volgende hoofdonderzoeksvraag te beantwoorden:

Welke ventilatie en luchtreinigingsstrategieën kunnen worden ingezet om de verspreiding van infectieuze respiratoire deeltjes in klaslokalen effectief te beheersen?

Deze vraag wordt beantwoord in vier stappen: 1) het begrijpen van de huidige stand van zaken en het vaststellen van kennishiaten, 2) het onderzoeken van realistische situaties om richtingen voor verbeteringen vast te stellen, en het voorstellen van oplossingen op 3) ruimte en 4) individueel niveau.

Om de huidige stand van zaken te begrijpen en kennishiaten vast te stellen werd eerst een literatuurstudie uitgevoerd. De literstuurstudie middels een combinatie van zoektermen over verschillende disciplines resulteerde in drie hoofdonderwerpen: 1) de huidige stand van zaken t.a.v. ventilatiestrategieën en binnenluchtcondities van klaslokalen; 2) kenmerken en beheersing van via de lucht overdraagbare IRDs; en 3) prestaties en haalbaarheid van geavanceerde ventilatiesystemen. Analyse van 94 onderzoeksartikelen, acht normen en richtlijnen, en vijf rapporten, gaf inzicht in elk onderwerp evenals onderlinge relaties. De literatuur gaf aan dat kleine deeltjes die tijdens ademhalingsactiviteiten worden geproduceerd, een primaire transmissieroute voor ziekteverwekkers zijn en verantwoordelijk voor infectieuze luchtwegaandoeningen zoals COVID-19. Deze IRDs kunnen via zowel korte als langeafstandsroutes in de lucht worden overgedragen. Beheersing van overdracht vereist verschillende ventilatiemethoden voor effectieve beheersing nodig. Terwijl conventionele ventilatiesystemen effectief zijn gebleken bij het beperken van

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langeafstandsverspreiding, is de optimale configuratie, vooral in niet-medische omgevingen, nog onduidelijk. Bovendien is ventilatie op ruimteniveau vaak gebaseerd op de aanname van een stationair en goed gemengde luchtverdeling. De dynamische aard van overdracht van IRDs dichtbij, wat een onmiddellijke reactie van ventilatiesystemen vereist, wordt onvoldoende rekening mee gehouden. De huidige ventilatierichtlijnen voor klaslokalen richten zich voornamelijk op de waargenomen luchtkwaliteit en energie efficiëntie, waarbij CO_2 concentraties vaak worden gebruikt als indicator van door mensen veroorzaakte verontreinigingen. De vereiste ventilatie kan daarom mogelijk onvoldoende zijn voor de beheersing van IRDs. In de praktijk voldoen veel klaslokalen niet eens aan de bestaande ventilatierichtlijnen. De literatuur wijst daarom op de noodzaak van een verschuiving in aanpak: van een comfortgerichte aanpak naar een strategie die prioriteit geeft aan de gezondheid van de gebruikers. Dit vraagt om flexibelere en beter aanpasbare ventilatiestrategieën. Daarnaast worden persoonlijke ventilatiesystemen (PV), zoals persoonlijke luchttoevoer (PT) en afvoer (PA), aangedragen als potentiële oplossingen om de overdracht van IRDs op korte afstand te beperken en de luchtkwaliteit in de directe omgeving van elke gebruiker te verbeteren. Bestaande PT- en PA-systemen zijn echter voornamelijk ontwikkeld voor hoog-risico-omgevingen, zoals ziekenhuisafdelingen en vliegtuigcabines, en zullen moeten worden aangepast voor toepassing in klaslokalen.

Vervolgens werd in stap 2 een veldonderzoek uitgevoerd om de ventilatie en thermische condities in klaslokalen tijdens de COVID-19 pandemie te onderzoeken. In totaal werden 31 klaslokalen verspreid over 11 Nederlandse middelbare scholen met leerlingen van 12 tot 18 jaar, op verschillende locaties, met verschillende onderwijstypen en gebouwleeftijden onderzocht. Om het effect van de maatregelen die werden genomen tijdens de verschillende fasen van de COVID-19 pandemie op de condities in de klaslokalen te volgen, werden de scholen twee keer bezocht: voor en na een nationale lockdown. Elk bezoek bestond uit: 1) het meten van de CO_2 concentratie en luchttemperatuur binnen en buiten; 2) een interview met de facilitair manager; 3) een inspectie van de schoolgebouwen, de verwarming, ventilatie en airconditioning systemen, en klaslokalen; en 4) registratie van de bezetting en het gedrag van de gebruikers. Uit de resultaten bleek dat de meeste scholen als pandemiemaatregel ervoor kozen de hele dag ramen en deuren open te houden om zoveel mogelijk te ventileren met buitenlucht. Deze maatregel hinderde echter de werking van mechanische ventilatiesystemen, waardoor de situatie met mechanische ventilatie nauwelijks verschilde van het gebruik van alleen natuurlijke ventilatie. De hoge CO_2 concentraties gemeten voor de lockdown, bij normale bezetting, lieten echter zien dat zelfs bij alle ramen en deuren open, de ventilatie niet voldeed aan de aanbevolen richtlijnen. Na de lockdown resulteerde nagenoeg halvering van de bezetting in aanzienlijk lagere CO_2 niveaus en een hogere ventilatiehoeveelheid per leerling. Deze verbetering was echter vooral toe te schrijven aan de lagere bezetting en niet aan structurele ventilatieverbeteringen. Bovendien bleken de thermische condities in klaslokalen tijdens zowel de pre- als post-lockdownperiode ontoereikend. Voor de lockdown (tijdens het stookseizoen) was het te koud; na de lockdown was het soms te warm en soms te koud, afhankelijk van het seizoen. Ondanks de inspanningen om de toevoer van buitenlucht te maximaliseren bleek het moeilijk om aan de gewenste ventilatie en thermische condities te voldoen. Dit benadrukt de noodzaak van flexibelere en effectievere lange termijn ventilatiestrategieën.

Als derde stap in dit promotieonderzoek zijn verschillende mobiele luchtreinigers (MLRs) om overdracht van IRDs op lange afstand te beheersen op flexibiliteit en betaalbaarheid getest. Gezien de grote verscheidenheid aan beschikbare MLRs werd eerst een lijst met selectiecriteria, van zowel technische als economische aard, opgesteld. Op basis hiervan werden acht MRLs geselecteerd, waarvan er zeven werden beoordeeld via een experimentele studie in de Experience Room van het SenseLab aan de Technische Universiteit Delft, die als een klaslokaal was ingericht. De evaluaties bestonden uit: 1) een aerosolen afname test om de verwijdering van aerosolen in de tijd en daarmee de zogeheten Clean Air Delivery Rate (CADR) te bepalen, en 2) een paneltest om de perceptie van gebruikers van het geluid en de tocht veroorzaakt door de MLRs te onderzoeken. De resultaten toonden aan dat MLRs met zeer efficiënte reiniging IRDs effectief uit de gehele ruimte konden verwijderen, ongeacht de toegepaste reinigings-technologie. De door de MLR veroorzaakte luchtstroming is van cruciaal belang voor het behalen van een zo hoog mogelijke CADR: MLRs met een opwaartse luchtstroming (verticaal of onder een hoek) verspreiden lucht efficiënter dan MLRs met een horizontale luchtstroming. De locatie van het apparaat speelt eveneens een belangrijke rol: de luchtstroming van de MLRs moet altijd gericht zijn op de bezette zone in de ruimte. Aanvullende testen in een klaslokaal op de universiteit bevestigden deze bevindingen en benadrukten bovendien het belang van het gebruik van meerdere MLRs naarmate de ruimte groter wordt. Verder bleek uit de resultaten dat de combinatie van MLRs met mechanische ventilatie een hogere CADR oplevert dan alleen MLRs, en een hoge MLR-stand noodzakelijk is voor het bereiken van de gewenste CADR. Een hoge stand veroorzaakte echter vaak een overschrijding van het voorgeschreven maximale toelaatbare geluidsniveau en werd als onacceptabel ervaren door het testpanel. De luchtsnelheden voldeden over het algemeen aan de richtlijnen en kregen een positieve feedback van het testpanel. Deze bevindingen benadrukten het belang van gebruikersfeedback bij prestatieoptimalisatie (luchtreiniging en gebruikerscomfort) van MLRs in klaslokalen.

Om de haalbaarheid van de hierboven genoemde strategieën te onderzoeken, werd een vervolgstudie uitgevoerd in 45 klaslokalen van vijf Nederlandse basisscholen. Drie MLRs met de beste prestaties uit de experimentele studie werden geselecteerd en willekeurig toegewezen aan de klaslokalen. De studie omvatte 1) het beoordelen van de praktische uitvoerbaarheid van de strategieën en 2) het monitoren van deeltjesconcentraties in drie klaslokalen per school, elk met één van de drie geselecteerde MLRs, tijdens een controle een een interventieperiode. Het inzetten van MLRs in klaslokalen bracht praktische uitdagingen met zich mee, zoals beperkte ruimte, overvolle indelingen en onvoldoende stopcontacten, wat aanpassingen in de plaatsing van de MLRs en het gebruik van verlengsnoeren noodzakelijk maakte. Hoewel de positie niet altijd hetzelfde was als de aanbevolen positie, zo lang als één apparaat aan de voorkant en één aan de achterkant stond, met de luchtstroom gericht op het bezette gebied, verlaagde alle MLRs de deeltjesconcentraties.

Tenslotte, werd voor het beheersen van de overdracht van IRDs op korte afstand, voorgesteld om persoonlijke luchtreinigers (PLRs) te gebruiken als lokale afzuiging, waarbij de voordelen van zowel PA-systemen als MLRs werden gecombineerd. De perceptie van geluid en tocht van de PLR werd eerst getest met proefpersonen, gevolgd door het bepalen van de verwijderingsefficiëntie van uitgeademde aerosolen middels deeltjesmetingen. Vervolgens werden CFD-simulaties uitgevoerd om het effect van verschillende posities op het zuigeffect (afvoer) van de PLR te bestuderen. De experimentele resultaten toonden aan dat bij de hoogste stand, de PLR overmatig geluid veroorzaakte, waardoor verdere tests beperkt bleven tot de laagste stand. Niettemin verminderde die stand de aerosolconcentraties nog steeds aanzienlijk, vooral voor kleinere deeltjes. Dit veelbelovende resultaat werd echter toegeschreven aan de sterke luchtcirculatie in de nagenoeg afgesloten testopstelling. CFD-simulaties lieten zien dat het zuigeffect van de PLR plaatselijk is en snel afneemt met afstand tot de PLR, waardoor de afzuiging nauwelijks de ademzone van de bewoner bereikt in een grotere ruimte. De beste resultaten werden gevonden voor de centrale verticale positie. In bestaande situaties zal deze positie als gevolg van opstijging van uitgeademde deeltjes veroorzaakt door de thermische pluim van het menselijke lichaam tot een zelfs grotere afvangst van IRDs leiden. Vergeleken met andere PA-systemen werkt de PLR bij een lagere luchtstroomsnelheid; het verhogen van de luchtstroom kan echter leiden tot onacceptabele geluidsniveaus. Andere aanpassingen zoals een groter zuigoppervlak of een positie dichterbij, verdienen overweging, maar vereisen zorgvuldige planning en ontwerpoptimalisatie. De PLR is veelbelovend voor het verwijderen van IRDs in klaslokalen, maar voor een effectieve, gebruiksvriendelijke werking in de praktijk is ontwerpoptimalisatie nodig.

Ter conclusie, dit promotieonderzoek heeft aangetoond dat de ventilatie (vooral op raam gebaseerde natuurlijke ventilatie) in klaslokalen momenteel vaak onvoldoende is om te voldoen aan de bestaande richtlijnen, en dus waarschijnlijk onvoldoende om de verspreiding van IRDs te beheersen. Daarom is een beter beheersbare ventilatieaanpak zoals mechanische ventilatiesystemen aangevuld met interventies zoals MLRs en PLRs. De bevindingen tonen aan dat MLRs, wanneer ze op de juiste

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manier worden geselecteerd en gepositioneerd, bescherming op kamerniveau kunnen bieden tegen overdracht van IRDs op lange afstand, terwijl PLRs effectief zijn in het beheersen van gelokaliseerde, korte afstand IRD-blootstelling, vooral daar waar zitopstellingen of klasactiviteiten het contact vergroten. Samen bieden deze oplossingen een uitgebreid kader voor het beheersen van IRDs in klaslokalen.

Al met al biedt dit promotieonderzoek bruikbare strategieën voor verschillende belanghebbenden, van schoolbestuurders, beleidsmakers en productontwikkelaars tot de gebruikers zelf, namelijk leerlingen en leraren. Praktische implicaties zijn 1) systematische plannen voor het gebruik van verschillende ventilatie en luchtreinigingsmethoden om binnenlucht condities in klaslokalen te verbeteren; 2) aanbevelingen voor toekomstige systeem/productontwerpen; 3) pleidooi voor updates in regelgeving voor ventilatie en luchtreiniging; en 4) kennis voor gebruikers om het belang van luchtkwaliteit en de impact ervan op hun gezondheid en prestaties beter te begrijpen.

Voor toekomstig onderzoek wordt aanbevolen om: 1) verschillende configuraties van mechanische ventilatie te onderzoeken, evenals combinaties van ventilatie en luchtreinigingsmethoden die zijn afgestemd op verschillende klaslokaalindelingen, klimaten, en budgettaire beperkingen; 2) het ontwerp van PLRs te optimaliseren en apparaten te ontwikkelen die zowel comfort als IRD beheersing maximaliseren voor scholen; 3) de gecombineerde effecten van hybride ventilatie en luchtreinigingsoplossingen te onderzoeken, en inzichten te bieden voor het bereiken van gezondere, veerkrachtigere binnenmilieus op scholen; 4) de effectiviteit van de vastgestelde ventilatie en luchtreinigingsstrategieën te valideren, doorgaans via cohortstudies, om het risico op kruisbesmetting in de praktijk tijdens uitbraken van ademhalingsziekten of zelfs pandemieën te verminderen.

总结

长期以来，良好的室内空气品质（indoor air quality，简称IAQ）因被公认为是确保儿童健康和成长的关键因素而驱动了研究人员数十年来的关注。然而，新型冠状病毒肺炎（Coronavirus Disease 2019，简称COVID-19）疫情的突然爆发对维持室内环境基本的IAQ形成了重大挑战。通过空气传播的传染性呼吸颗粒（infectious respiratory particles，简称IRPs）容易在室内人员之间引发交叉感染，进而对公众健康构成严重威胁。学校教室由于其人员密度高、停留时间长的特点，其IAQ尤其容易受到这种威胁的影响。当疫情爆发时，由于缺乏有效的防控措施，学校常常无法完全应对这些风险，导致正常的教育活动受到干扰。为了帮助学校改善上述情况，本博士研究旨在回答以下主要研究问题：

在学校教室中，哪些通风和空气净化策略可以有效控制传染性呼吸颗粒的传播？

该问题通过四个步骤来解决：了解现有的研究进展并定义研究空白；考察实际情况以确定改进方向；分别在教室尺度、个体层面提出解决方案。

第一，本研究进行了一项系统的文献综述，以建立研究背景并定义研究空白。通过使用大量关键词组合进行多学科文献检索，该综述聚焦于三个主要研究主题：1）学校教室中通风策略和IAQ状况的现状；2）IRPs的空气传播特性及其控制；3）新型通风系统的性能及可行性。通过对94篇研究论文、8项标准和指南以及5份报告进行分析讨论，该综述获得了对每个主题及其相互关系的深入理解。文献表明，IRPs即人体呼吸活动中产生的微小颗粒，是COVID-19等传染性呼吸道疾病病原体的主要传播途径。IRPs可以通过空气进行近程和远程传播，因此需要使用不同的通风策略来实现对其的有效控制。传统的通风系统能够有效遏制IRPs的远程传播，但此类通风系统的最优配置，特别是针对非医疗环境的适应性策略，目前仍不明确。同时，IRPs近程传播的动态特性要求通风系统能够实现即时反应，然而现有的通风基于对室内空气污染物浓度的稳态和充分混合的假设使得房间尺度的通风形式无法充分满足这一需求。目前，针对学校教室的通风规范主要关注舒适性和能源效率，且通常以二氧化碳（CO_2）浓度作为衡量由人员引起的污染指标，因此往往不足以有效控制IRPs的传播。在实际情况中，许多教室的通风甚至无法满足现行规范的基本要求。因此， 该综述提出，教室的通风设计规范导向应当从单纯舒适性转向人居健康，同时教室内应采用更加灵活和可调节的通风策略。此外，该综述认为，个性化通风（personalized ventilation，简称PV）系统，包括个性化送风（personalized supply，简称PS）和排风（personalized exhaust，简称PE），是减少教室内IRPs近程传播、提升个体微环境IAQ的潜在解决方案。但由于现有的PS和PE系统主要针对高风险环境（如医院病房和飞机客舱等）研发，因而需要改进以便在教室中有效实施。

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第二，本研究进行了一系列有计划的现场调研，旨在调查COVID-19疫情期间学校教室的通风和热环境状况。该调研共包括了荷兰11所中学的31间教室，涉及不同的地理位置、教育类型和建筑年代，室内人员涵盖了12至18岁的中学生。为了跟踪教室内环境在疫情不同阶段及防控措施变化影响下的发展变化，本研究对每所学校进行了两次调研：一次是在全国疫情防控封闭开始之前，另一次是在疫情防控封闭结束之后。每次调研包括：1）监测室内外的CO_2浓度和空气温度；2）与学校设施管理人员进行简短访谈；3）考察学校建筑、暖通空调（heating, ventilation, and air conditioning，简称HVAC）系统和教室内基本情况；4）监测教室的人员数量和开、关窗行为。研究发现，为响应疫情防控，大多数学校的门窗保持全天开启，以最大化新风供应。这种做法时常妨碍机械通风系统按照设定值正常运行，使其与自然通风没有区别。封闭开始前，教室内学生人数基本维持在正常水平，而上课期间室内通风量往往低于规范水平，且CO_2浓度过高。封闭结束后，教室内学生人数减少约一半，导致CO_2浓度显著降低、人均通风量显著增加。然而，数据分析表明，人均通风量提升的主因为室内人员数的减少，而非通风策略的改进。此外，研究还发现，在疫情防控封闭前后，教室的热环境条件都不甚理想。封闭开始前，许多教室在供暖期温度过低；封闭结束后，随着季节变化，室内温度出现波动，导致有些教室温度过高、有些教室温度过低。总体而言，尽管已经尝试将新风供应量最大化，但学校教室在达到理想的通风和热环境条件方面仍然存在欠缺，从而突显了对更灵活有效的长期通风策略的迫切需求。

第三，本研究提出移动式空气净化器（mobile air cleaners，简称MACs）同时具备灵活性和经济性，可用以控制IRPs的远程空气传播。针对MACs种类繁多的特点，研究首先制定了一套同时考量技术性能和经济因素的选择标准，进而根据这套标准，筛选出八款中小型落地式MAC，并对其中七款进行了实验评估。实验在荷兰代尔夫特理工大学SenseLab实验室的Experience Room环境控制室内完成，该室内部模拟了中学教室的室内环境。本研究对MAC的评估包括：1）呼吸颗粒衰减实验，以测定呼吸颗粒去除率和洁净空气输送率（clean air delivery rate，简称CADR）；2）受试者主观感受实验，以评估MACs引起的噪音和气流对使用者的影响。研究结果表明，配备高效过滤器（过滤等级达到H13）的MAC，无论采用何种空气净化技术，都能有效去除房间内的呼吸颗粒物。影响CADR水平的关键因素在于MAC自身的送回风模式。相比水平送风的MAC，采用向上（垂直或倾斜）送风的MAC能够更有效地向整个房间输送洁净空气。此外，设备的安装位置同样至关重要，MAC的送风方向应尽可能涵盖教室内的人员活动区域。在大学教室环境中的附加测试进一步验证了上述发现，并强调了随着房间面积增大，应使用多台设备以确保空气净化效果。此外，研究还表明，将MAC与机械通风结合使用，可提升MAC的CADR水平。另一方面，尽管提高MAC的风速有助于达到理想的CADR，但随之产生的噪音往往超出规定的上限，达到受试者认为不可接受的水平。相反地，受试者们对MAC产生的气流表现出了正向的反馈，且气流的风速普遍符合舒适性标准。上述研究结果凸显了用户反馈对于优化MAC实际使用性的重要性，即在保证空气净化效果的同时，兼顾使用者的舒适性。

为了评估上述策略的可行性，课题组随后在荷兰5所小学的45间教室内开展了现场调研。调研选择了前序实验中表现较佳的三款MAC，并将其随机分配到不同教室内。对

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MAC的可行性评估包括：1）评估该策略的实际可操作性；2）在每所学校选择配备了不同MAC的三间教室，对其在对照期和干预期的IAQ参数进行监测和对比。调研发现，在教室内布置MAC时往往会受到空间有限、布局拥挤以及电源插座不足等条件限制。这些问题导致在实际应用中需要对MAC的安装位置进行调整，并使用延长电缆来供电。尽管设备的实际安装位置与实验室测试时有所不同，且使用者在使用过程中可能存在操作失误，但数据分析结果表明，只要确保一台设备位于教室前部，另一台位于后部，并使送风方向始终涵盖人员活动区域，MAC仍然能够稳定地降低空气中的颗粒物浓度。

第四，本研究提出使用个性化空气净化器（personalized air cleaner，简称PAC）作为教室内的局部排风装置，以控制IRPs的近程空气传播。基于前述研究结果，此策略可以结合PE和MAC的优势。研究首先通过实验评估了受试者对PAC产生的噪音和气流的主观感受，然后测试了PAC的呼吸颗粒物去除效率，随后采用计算流体动力学（computational fluid dynamics，简称CFD）模拟分析不同安装位置对PAC的排风效应的影响。实验结果表明，在风扇以高档位运行时，PAC产生的噪音较大，从而限制了其应用范围，因此后续实验仅在风扇低档位设置下进行。尽管仅在低档位运行，PAC仍显著降低了呼吸颗粒物浓度，尤其是较小颗粒的浓度。这一正向结果主要可归因于实验中设置的局部封闭环境内较强的空气循环效应。CFD模拟显示，PAC的排风效应仅限于局部区域，且随距离增加迅速衰减，在较大空间内较难有效覆盖使用者的呼吸区。尽管覆盖区域有限，通过CFD模拟仍然可以得出，在中央垂直位置安装PAC，其排风效应最佳。在实际应用中，该位置还能更好地利用人体热羽流所引起的呼气颗粒上升效应，从而增强对IRPs的捕获能力。与其他PE系统相比，PAC的运行风量显著更低，但如果单一地提高排风量将会导致过高的噪音水平。其他针对PAC的优化方案，如增大排风口面积或将设备放置得更靠近使用者，均值得进一步探索，但需要谨慎地进行设计和规划。总体而言，使用PAC去除教室内IRPs的策略展现出了良好前景，但仍需优化设计，以确保在实际应用中保障较高的效率和良好的使用感受。

本博士研究表明，学校教室主要依赖窗户进行自然通风，其通风状况通常无法满足现有的IAQ要求，更不足以有效控制IRPs的传播。教室内需要更可控的机械通风系统和相应的通风策略，同时辅以MACs和PACs等干预措施。研究结果显示，经合理选择和布置的MACs可以在房间尺度上有效减少IRP的远程传播。PACs在局部范围内，尤其是在座位安排紧密或因课堂活动而产生近距离接触的情况下，能够有效降低室内人员对近程传播的IRPs的暴露。上述解决方案构成了一个全面的框架，为学校教室中IRPs的控制提供了科学性的策略。

综上所述，本博士研究将为不同的利益相关者提供可操作的策略。涉及到的利益相关者至少包括：学校管理者、政策制定者、产品开发人员以及学生和教师等教室使用者。研究的实际应用价值体现在以下几个方面：1）提出了一套系统性策略，指导如何结合不同的通风和空气净化方法改善学校教室的IAQ；2）探讨了未来通风和空气净化系统及产品的设计优化建议，以提升其性能和适用性；3）建议了相关法规的更新，推动在学校环境中实施更严格的通风和空气净化要求；4）为教室内人员提供了有关IAQ的重要知识，使其更好地理解IAQ对健康和学习表现的影响，从而促进更积极的IAQ管理实践。

本研究展望未来：1）进一步探索多种机械通风配置，以及针对不同的教室布局、气候条件和预算对通风与空气净化的组合应用进行优化；2）对PAC进行深入的设计优化，以开发能够在学校环境中最大限度提升舒适度和IRP控制效果的设备；3）充分探讨通风与空气净化的协同机制，为实现更健康、更具可持续性的学校室内环境提供重要见解；4）采用队列研究等方法，通过分析呼吸道传染病高发期甚至疫情期间感染风险的实际减轻程度，验证本研究所提出的通风和空气净化协同策略的有效性。

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1 Introduction

"Clean air is considered to be a basic requirement for human health and well-being," as declared by the World Health Organization (WHO) in its 2000 publication, *Air Quality Guidelines for Europe, 2nd Edition* [1]. Despite significant advancements in knowledge and technology regarding air quality over the years, a 2018 WHO report revealed that "globally, 93% of all children live in environments with air pollution levels above the WHO guidelines", concluding that "air pollution has a devastating impact on children's health" [2]. This alarming statistic underscores the urgency of ensuring children's right to breathe clean air in their homes, schools, and communities, as emphasized in a 2019 United Nations report on human rights issues [3]. Children represent the future of society, yet they are among its most vulnerable members, with their health particularly susceptible to the harmful effects of polluted air [4]. To date, as the impact of global climate change becomes more evident, society is facing mounting challenges, with one of the most significant being the frequent outbreaks of pandemics. These crises make creating and maintaining healthy environments for children increasingly difficult. Therefore, greater efforts must be devoted to this critical area – this is also the key motivation behind the completion of this work.

1.1 Problem statement

Since December 2019, human society has suffered significant damage to both public health and the economy due to the Coronavirus Disease 2019 (COVID-19) pandemic. Five years later, the global situation of COVID-19 remains dynamic, with new variants of the causative pathogen, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), continuing to emerge and spread [5]. By mid-2024, the total number of COVID-19 infections worldwide has exceeded 700 million, with children accounting for approximately 10-15% of the total infections [6,7]. Moreover, long COVID, or post-acute sequelae of SARS-CoV-2 infection (PASC), affects nearly 100 million individuals worldwide – including children – with a variety of symptoms, for which the diagnosis and treatment remain challenging [8,9].

While combating this fatal challenge, increased attention has been directed toward the sufficiency and efficiency of ventilation in indoor spaces, given that most COVID-19 cross-infections occur indoors [10,11]. This is largely because airborne transmission of infectious aerosols is the primary route through which SARS-CoV-2 spreads between people, which is defined by WHO as infectious respiratory particles (IRPs) [12-15]. In fact, IRPs have also played a significant role in the outbreaks of several other pandemic-prone acute respiratory diseases, including SARS [16], Influenza A [17], and MERS [18]. Despite this, in previous design criteria of ventilation and air cleaning, IRPs were underrecognized as concerning indoor air contaminants in public spaces, apart from nosocomial buildings. It is only in recent years that standards and guidelines have begun to emphasize the control of IRPs in common indoor environments, for example, the ASHRAE Standard 241, *Control of Infectious Aerosols*, released in 2023 [19].

School classrooms, where children spend prolonged periods in close proximity, are high-risk settings for the spread of IRPs. This necessitates the evaluation and implementation of effective ventilation and air cleaning strategies to enhance IRP removal. Prior to the COVID-19 pandemic, existing standards and guidelines for indoor air quality (IAQ) in classrooms were primarily focused on balancing comfort and energy consumption [20], typically recommending minimum ventilation rates of 4-5 L/s per person [21-23]. Correspondingly, a significant proportion of school classrooms worldwide rely solely on natural ventilation through open windows and doors, with others equipped only with basic mechanical systems [24-29]. Studies have reported that many classrooms suffer from insufficient ventilation and poor IAQ conditions [24-29], which can adversely affect children's health, comfort, and productivity [30,31]. However, given current observations, it is unlikely that the existing ventilation systems in most school classrooms will be capable of meeting the requirements for efficient IRP removal in the near term, especially considering the complexity and cost of necessary renovation. For instance, ASHRAE Standard 241-2023 [19] recommends a minimum equivalent clean airflow (ECAi) of 20 L/s per person in classrooms when operating in infection risk management mode (IRMM) – a target far beyond what current systems can achieve. Therefore, alternative solutions to efficiently remove IRPs and ensure healthy indoor environments are urgently needed. In addition, the effectiveness of ventilation strategies in school classrooms is largely influenced by regional factors such as climate and economy, making it beneficial to establish regional databases to better determine tailored solutions to diverse conditions.

The introduction of the term ECAi to infectious aerosol control highlights the growing recognition of the role air cleaning plays in improving IAQ. Air cleaning, within the scope of controlling infectious aerosols, is defined as "reducing the concentration of infectious aerosols in the air through capture and removal or by inactivation" [19].

Numerous studies have demonstrated the effectiveness of air cleaning devices in removing particulate matter (PM) and improving IAQ, thereby benefiting occupants' health [32-34]. Among the various types of air cleaning devices, mobile air cleaners (MACs) stand out for their flexibility and affordability. Although primarily designed for household or office use, recent research has explored the potential of MACs to remove IRPs in school classrooms, offering valuable insights for further investigation [35-37]. However, existing studies are limited due to the vast diversity in MACs – ranging from air cleaning technologies, induced airflow patterns, dimensions, and efficiency – as well as the varying conditions in school classrooms, including layout, occupancy, and ventilation regimes. As a result, systematic strategies for applying MACs in school classrooms, from selection to operation, have yet to be fully developed.

Another crucial factor in aerosol removal lies in the fundamental nature of airborne transmission: IRPs can transmit via long- and short-range routes, each with distinct characteristics [14]. Short-range airborne transmission often occurs during close contact between indoor occupants, involving direct inhalation of particles, while long-range airborne transmission involves the spread of smaller particles over greater distances, often carried by indoor airflows [39-41]. Consequently, room-based ventilation and air cleaning methods can effectively control long-range transmission, yet may not be capable of mitigating short-range transmission [43]. Short-range airborne transmission is a highly dynamic process, influenced primarily by the human microenvironment and the interaction of breathing flows [44,45]. Hence, different manners of ventilation and air cleaning are necessary, particularly in indoor spaces like school classrooms, where close contact is common and short-range airborne transmission may prevail [46-48].

To tackle this, researchers have long been examining the performance of personalized ventilation (PV) and personalized exhaust (PE) systems [49-56]. Although their effectiveness has been well established, such systems are not yet widely implemented in practice. Possible difficulties include the need to integrate with existing ambient ventilation systems, as well as to ensure they do not hinder the functionality of the space [57]. School classrooms, which often rely on natural ventilation and have limited free space, pose additional challenges for implementing PV or PE systems, thus necessitating specific designs. However, relevant studies are rather limited, especially those with a focus on aerosol removal in such settings. Moreover, the proposed designs are often based on background mechanical ventilation systems, making them impractical for many schools in the near term [58-60]. Meanwhile, a new type of personalized device for IAQ control has emerged – the personalized air cleaner (PAC), which shows good potential to be a solution for short-range IRP removal in school classrooms, as promising results were found under scenarios involving natural ventilation [61]. Therefore, further exploration in this area is warranted.

In summary, the COVID-19 pandemic has facilitated the recognition of IRPs as a crucial indoor air contaminant in school classrooms, which poses a threat to children's health. Potential solutions exist for ensuring healthier indoor environments for children, yet their implementation is hindered by the following scientific gaps:

1. A comprehensive understanding of ventilation regimes in school classrooms concerning the airborne transmission of IRPs is missing.
2. A database of ventilation performance in Dutch school classrooms – particularly within the special context of a pandemic – is lacking.
3. Systematic strategies for the effective use of MACs in school classrooms have yet to be established.
4. Research into the feasibility of personalized air cleaning devices in school classrooms remains limited.

1.2 Aim of study

The aim of this PhD research is to better understand the characteristics of ventilation in school classrooms and propose ventilation and air cleaning strategies to effectively control infectious respiratory particles.

1.3 Research questions

1.3.1 Main research question

To achieve the aim of this PhD research, the main research question to be answered is:

Which ventilation and air cleaning strategies can be used to effectively control the spread of infectious respiratory particles in school classrooms?

1.3.2 Sub-research questions

To be able to answer the main research question, the following sub-research questions were explored and addressed in different chapters of this PhD research:

1 **What do we know about the ventilation regimes in school classrooms and the control of infectious respiratory particles?**

The first step is to map the current knowledge on controlling infectious respiratory particles, identify existing paradigms of ventilation regimes in school classrooms, and explore potential solutions to bridge the gaps between them.

2 **What is the ventilation sufficiency of existing ventilation regimes and the current IAQ conditions in school classrooms?**

The second step is to investigate ventilation sufficiency in Dutch school classrooms, considering the possible effects of additional pandemic-related control and prevention measures.

3 **How to use mobile air cleaners to effectively control infectious respiratory particles in school classrooms at a room scale?**

This question is further divided into two questions:

a *Which strategies are recommended for mobile air cleaners in classroom settings to ensure both efficient IRP removal and acceptable perception by occupants?*
b *What is the feasibility of applying these strategies in real school classrooms?*

The third step is to select and evaluate mobile air cleaners suitable for IRP control in school classrooms, considering the IRP removal efficiency and the occupants' subjective perception. This leads to the development of systematic strategies for effective practical implementation. Additionally, the proposed recommendations need to be tested in real-world scenarios to examine their feasibility.

4 **What is the potential of personalized air cleaners to control infectious respiratory particles in school classrooms within individual proximity?**

The last step is to assess the potential of using personalized air cleaning cleaners to locally exhaust IRPs without compromising occupants' comfort and determine the proper configurations for such devices in school classrooms.

Figure 1.1 presents an overview of the main research question, divided into sub-research questions, with their corresponding objectives, and finally leading toward the aim of this PhD research.

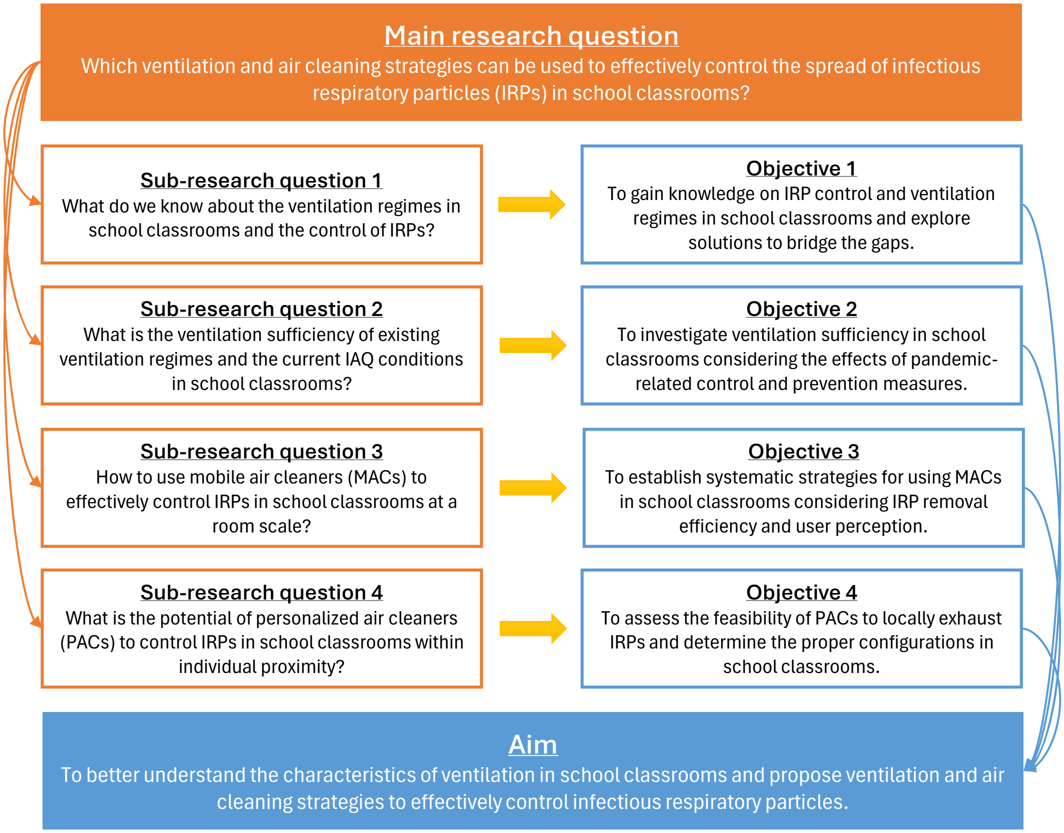

FIG. 1.1 Overview of the main research question, sub-research questions, objectives, and aim of this PhD research.

1.4 Research methodology

The research methodology of this PhD research is shown in **Figure 1.2**. The methodology consists of four parts, each answering one of the sub-research questions correspondingly.

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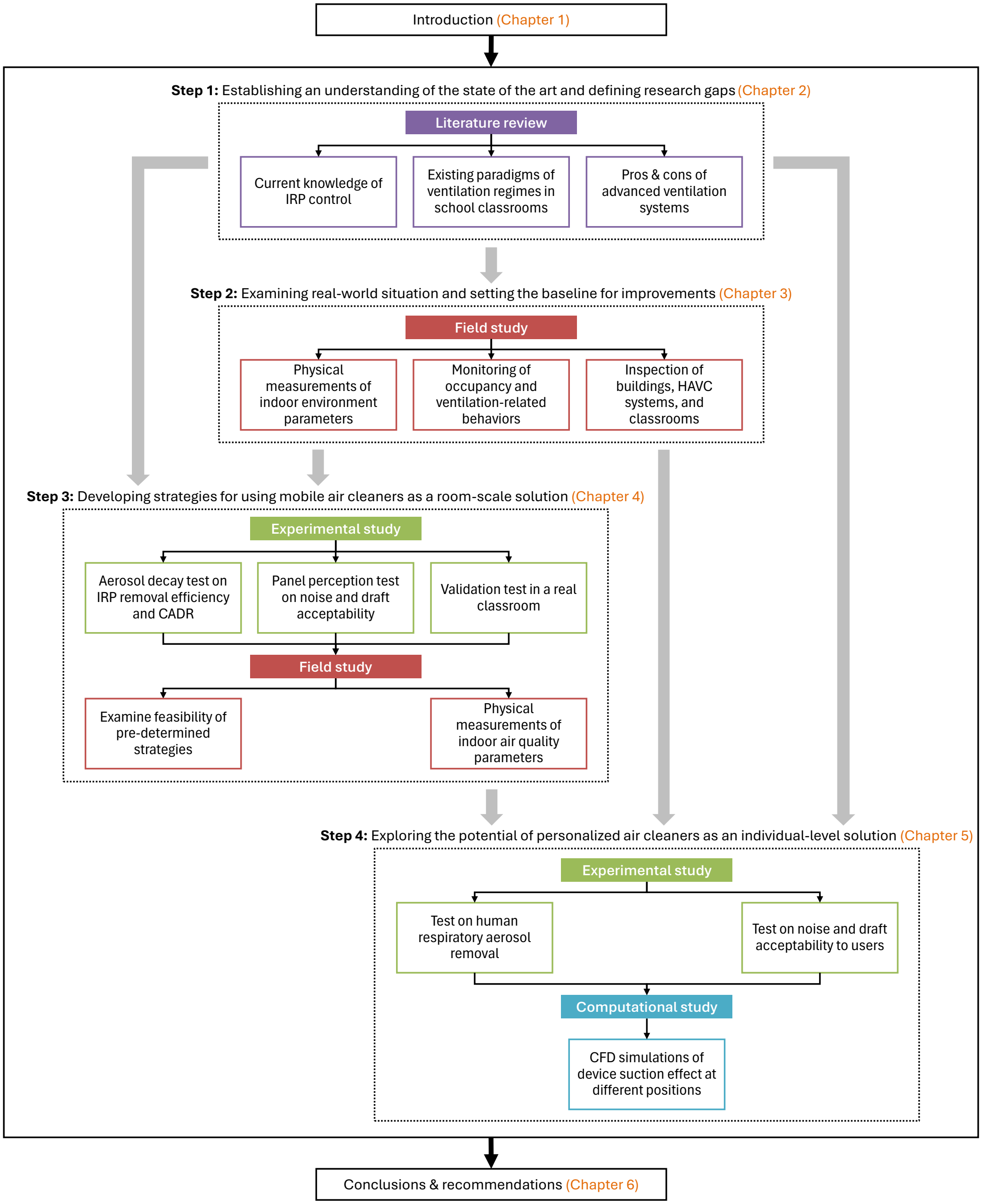

FIG. 1.2 Schema of the research methodology and outline of this PhD research.

All research data supporting the findings described in this PhD research are available in 4TU.ResearchData at: https://doi.org/10.4121/88542bc3-ff1d-4163-b977-9c28d2d88fc4.

1.4.1 Step 1: Establishing an understanding of the state of the art and defining research gaps

The primary research method to establish the context and background for a study is to conduct a literature review. In general, a literature review synthesizes existing knowledge, identifies gaps, and defines key concepts, framing the research questions and objectives. By critically evaluating previous studies, a literature review helps build a solid foundation for the current research, guiding its design and focus.

Hence, to answer sub-research question 1, a systematic literature review was conducted, first through a general literature screening using a large combination of keywords, and then dived deeper into three topics regarding the focus of the research:

1. Current situation of ventilation strategies and IAQ conditions in school classrooms.
2. Features and control of airborne transmission of IRPs.
3. Performance and feasibility of advanced ventilation systems.

Instead of presenting an exhaustive discussion on each topic respectively, this literature review intended to extract and connect the key information among the three topics. Eventually, 94 research papers were included, alongside eight standards and guidelines, and five reports. Accordingly, this part of the PhD research has addressed:

1. The existing design paradigms and actual performance of ventilation regimes and IAQ conditions in school classrooms.
2. The ability of conventional ventilation methods to minimize the airborne transmission of IRPs.
3. The potential of personalized ventilation and personalized exhaust systems as an additional solution.

Publications

Ding, E., Zhang, D., & Bluyssen, P.M. (2022). Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review. *Building and Environment*, *207*, 108484.

Ding, E., Zhang, D., & Bluyssen, P.M. (2021). Ventilation strategies of school classrooms against cross-infection of COVID-19: A review. *Proceedings of Healthy Buildings 2021 Europe Conference*, Paper 262.

1.4.2 Step 2: Examining real-world situations and setting the baseline for improvements

The most suitable research method to gather real-world data is to conduct a field study, as it can provide insights into conditions and behaviors as they occur outside controlled environments. By performing inspections and measurements on-site, a field study often aims to generate findings that are more relevant, realistic, and applicable to everyday situations.

Therefore, to answer sub-research question 2, a field study was carried out in 31 classrooms of 11 Dutch secondary schools, between October 2020 and June 2021. The schools represented a diverse range of locations, types of education, and building ages, covering students aged 12 to 18. To track the evolution of conditions in the classrooms at different stages of the COVID-19 pandemic, as various levels of control and prevention measures were implemented, each school was visited twice: once before and once after a national lockdown. During each visit, the following methods were used for data collection:

1. Measurements of indoor and outdoor CO_2 concentration and air temperature;
2. Completing a technical questionnaire and an interview with school facility managers, as well as inspections on buildings and HVAC systems;
3. Classroom inspection covering indoor environmental settings, humidity problems, indoor climate characteristics, ventilation equipment, and indoor pollution sources;
4. Monitoring of occupancy and ventilation-related behavior.

Accordingly, ventilation rates in each classroom were calculated using the steady-state method. Consequently, this part of the PhD research has addressed:

1. The ventilation sufficiency in Dutch secondary school classrooms;
2. The ventilation-related effects of temporary school or governmental-initiated pandemic control and prevention measures;
3. The thermal conditions because of the implemented measures, in the classrooms under the COVID-19 pandemic.

Publications

Ding, E., Zhang, D., Hamida, A., García-Sánchez, C., Jonker, L., de Boer, A.R., Bruijning, P.C.J.L., Linde, K.J., Wouters, I.M., & Bluyssen, P.M. (2023). Ventilation and thermal conditions in secondary schools in the Netherlands: Effects of COVID-19 pandemic control and prevention measures. *Building and Environment*, 109922.

Ding, E., Zhang, D., García-Sánchez, C., & Bluyssen, P.M. (2023). Effects of COVID-19 measures on ventilation in secondary schools in the Netherlands. *Proceedings of Healthy Buildings 2023 Europe Conference*, Paper 1295.

Ding, E., Zhang, D., & Bluyssen, P.M. (2022). Under Pandemic: Assessment of Ventilation in Secondary Schools in The Netherlands. *Proceedings of Indoor Air 2022 Conference*, Paper 1199.

1.4.3 Step 3: Developing strategies for using mobile air cleaners as a room-scale solution

Since sub-research question 3 is further divided into two questions, two separate studies were performed to answer these questions: an experimental study and a field study.

To develop systematic strategies for using mobile air cleaners (MACs) in school classrooms, first, a set of selection criteria was established based on the specified features of the products and the researchers' knowledge and experience. The criteria considered both technical and economic factors, including air cleaning technology, induced airflow pattern, clean air delivery rate (CADR), noise level, and cost. Establishing a clear set of objective criteria created a structured framework that helped minimize subjective influence. When selection criteria are transparently defined, it becomes easier to evaluate devices consistently and objectively, which reduces the likelihood of personal preferences affecting the results. As a result, eight small- and medium-sized floor-standing MACs were selected after screening over 300 products on the market, of which seven were tested.

Conducting experiments is the primary research method to evaluate a device's performance under controlled conditions. For example, by isolating specific variables, researchers can accurately measure efficiency, reliability, and functionality, providing data on how well the device meets its intended purpose. Meanwhile, it can also help to understand how users perceive or experience a device in a given environment by collecting subjective feedback, focusing on factors like comfort, usability, or acceptability.

Accordingly, the selected MACs were tested for different settings and configurations in the experimental study. The assessments included:

1. An aerosol decay test: the time evolution of aerosol concentration was monitored after filling the room with aerosols generated by a specific spraying technique, to calculate the aerosol removal rate and CADR;
2. A panel perception test: a panel of subjects was recruited to assess noise and air movement induced by the MACs, combined with measurements of sound pressure level and air velocity.

Additionally, a decay test was performed in a real classroom as validation, where background mechanical ventilation was also operating. Based on the results, recommendations have been developed regarding which MACs to use, where they should be placed, and how they should be operated in school classrooms for effective IRP control.

To examine the feasibility of such recommendations in real-world settings, a field study needs to be conducted, as explained in **Section 1.4.2**. In the field study, three MACs were selected based on the outcomes of the experimental study and implemented in real school classrooms. A total of 45 classrooms across five Dutch primary schools participated in the study, with each classroom being assigned one type of MAC. The feasibility of using MACs in school classrooms to control IRPs was evaluated by:

1. Assessing the practicality of implementing the pre-determined strategies for using MACs in school classrooms;
2. Monitoring IAQ, including $PM_{2.5}$ (particulate matters of a diameter of 2.5 μm and smaller), PM_{10} (particulate matters of a diameter of 10 μm and smaller), CO_2 (carbon dioxide), and TVOC (total volatile organic compound) levels, in three classrooms per school – each corresponding to one of the three MAC types – over six weeks, with the devices operating for three weeks (intervention period) and turned off (control period) for three weeks.

Eventually, comparisons between the intervention and control periods were made to assess the effectiveness of MACs in real-world conditions.

Publications

Ding, E., Giri, A., Gaillard, A., Bonn, D., & Bluyssen, P.M. (2024). Using mobile air cleaners in school classrooms for aerosol removal: Which, where and how. *Indoor and Built Environment*, *33*(10), 1964–1987.

Ding, E. & Bluyssen, P.M. (2024). Feasibility of using mobile air cleaners in school classrooms to remove respiratory aerosols. *Proceedings of RoomVent 2024 Conference*, Paper 528.

1.4.4 Step 4: Exploring the potential of personalized air cleaners as an individual-level solution

To answer the sub-research question 4, two studies were performed: an experimental study and a computational study.

Similar to the study on MACs (**Section 1.4.3**), an initial screening of existing products was carried out to identify a suitable personalized air cleaner (PAC) for individual use in school classrooms. Then, in the experimental study, the selected PAC underwent a perception test where a group of subjects evaluated the acceptability of its noise and draft. Based on these results, the optimal conditions were identified and further tested for respiratory aerosol removal, with the same group of subjects acting as the sources of aerosols.

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The purpose of a computational study using CFD simulations is to model and analyze airflow, temperature, or particle dispersion across multiple conditions. By simulating different configurations, CFD enables researchers to compare various scenarios efficiently, providing visual and quantitative insights into how changes in design, placement, or environmental factors affect outcomes. This approach allows for detailed comparisons without the constraints of physical testing, making it a powerful tool for optimizing designs and predicting real-world performance.

Accordingly, a computational study was conducted where the suitable settings determined from the experimental study were modeled under various conditions to identify the optimal positioning of the PAC device. The CFD simulations were performed in ANSYS Fluent 2023R2 software.

This part of the PhD research has achieved the following:

1. Assessing the feasibility of employing a PAC in an educational setting, considering its efficacy as a localized exhaust for respiratory aerosols and occupants' perception regarding noise and draft;
2. Visualizing the PAC's suction effect at different positions and providing possible design modifications to enhance performance for real-world application.

Publications

Ding, E., Giri, A., García-Sánchez, C., & Bluyssen, P.M. (2024). Feasibility of a personalized air cleaner as a localized exhaust for short-range respiratory aerosol removal in classroom settings: A pilot study. (under review)

1.5 Dissertation outline

As shown in **Figure 1.2**, this dissertation consists of six chapters, structured to begin with a general introduction (**Chapter 1**), followed by detailed investigations addressing the four sub-research questions (**Chapters 2-5**), and concluding with general conclusions and recommendations (**Chapter 6**).

Chapter 1. Introduction

This chapter presents the overview of the PhD research, covering the problem statement, research questions and aim, and the methodology of this work.

- **Chapter 2. Understanding theory: Infectious respiratory particles, ventilation in schools, and the possible bridge in between**

  This chapter presents the literature review on ventilation and IAQ-conditions in school classrooms, airborne transmission of infectious respiratory droplets: features and control, and personalized ventilation systems.

- **Chapter 3. Observing reality: Ventilation and thermal conditions in school classrooms during pandemic**

  This chapter presents the field study conducted in Dutch secondary schools during the COVID-19 pandemic, discussing CO_2 concentrations, ventilation rates, and thermal conditions in the classrooms as an outcome of pandemic control and prevention measures.

- **Chapter 4. Developing strategy: Mobile air cleaners for infectious respiratory particle removal**

  This chapter consists of two parts. Part I presents the experimental study on selecting and evaluating mobile air cleaners for reducing respiratory aerosols in a classroom setting, regarding aerosol removal rate and clean air delivery rate, as well as acceptability of sound and air movement. Part II presents the field study on the real-life applicability and effectiveness of mobile air cleaners in Dutch primary school classrooms.

- **Chapter 5. Exploring possibility: Personalized air cleaners as an individual localized exhaust**

  This chapter presents the experimental and computational studies on investigating the feasibility of using a personalized air cleaner to exhaust infectious respiratory particles within individual proximity, as well as exploring the optimal configuration for the device.

- **Chapter 6. Conclusions and recommendations**

  This chapter summarizes the answers to the sub-research questions and the main research question of this PhD research. It also discusses the limitations of the overall research and provides implications and recommendations for future research and practical applications.

1.6 Research relevance and contributions

1.6.1 Scientific relevance

This PhD research addresses significant gaps in the current understanding and implementation of ventilation and air cleaning strategies in school classrooms, particularly in the context of controlling IRPs during pandemic times. The COVID-19 pandemic has highlighted the critical importance of ventilation in healthy IAQ conditions and deepened the understanding of the role airborne transmission plays in the spread of infectious diseases. Despite the increasing recognition of IRPs as a major indoor air contaminant, existing ventilation standards and guidelines have only recently begun to emphasize the control of these particles in non-hospital settings like schools.

This PhD research contributes to the scientific community by:

1. Expanding knowledge framework: This PhD research enhances the theoretical understanding of how existing ventilation regimes in Dutch school classrooms influence the spread of IRPs. By bridging the gap between conventional ventilation methods and the need for enhanced IAQ in the context of infectious disease transmission, this PhD research offers new insights into the limitations and potential improvements in current practices.
2. Providing regional data: This PhD research provides regional data on ventilation performance during the pandemic through field studies conducted in Dutch schools, which is crucial for the development of context-specific solutions. This data is particularly valuable given the regional differences in climate, building design, and economic factors that affect IAQ and ventilation effectiveness.
3. Developing practical strategies: This PhD research proposes and evaluates practical strategies for the application of MACs and PACs in school environments via a systematical approach. These strategies are informed by experimental, field, and computational studies, offering data-informed recommendations that could be adopted in real-world settings.

By addressing these scientific gaps, the research not only contributes to the academic literature but also informs the development of more robust standards and guidelines for IAQ management in educational settings.

1.6.2 Societal relevance

The societal relevance of this research lies in its focus on protecting the health and well-being of children, a highly vulnerable group within society. As emphasized by global organizations such as WHO and the UN, access to clean air is a fundamental human right, yet many children worldwide are exposed to polluted air at levels that pose significant health risks. This research is especially timely and impactful due to the following reasons:

1. Enhancing children's health: By identifying effective strategies to control IRPs in school classrooms, the research directly contributes to creating safer learning environments. This is crucial for reducing the risk of airborne diseases, thereby ensuring good health for students.
2. Supporting public health initiatives: The findings of this study align with broader public health initiatives aimed at reducing occupants' exposure to respiratory infections, particularly in schools. In the context of ongoing and future pandemics, the research provides actionable insights that can help schools implement effective preventive measures.
3. Promoting educational continuity: Maintaining healthy indoor environments in schools is essential to minimizing disruptions to education during crises like pandemics. By improving healthy IAQ conditions, the strategies proposed in this research help ensure that schools can remain open and safe, which is vital for the continuous education and social development of children.

Overall, the research not only advances scientific knowledge but also has a profound impact on public health and education, addressing critical societal needs in the face of global health challenges.

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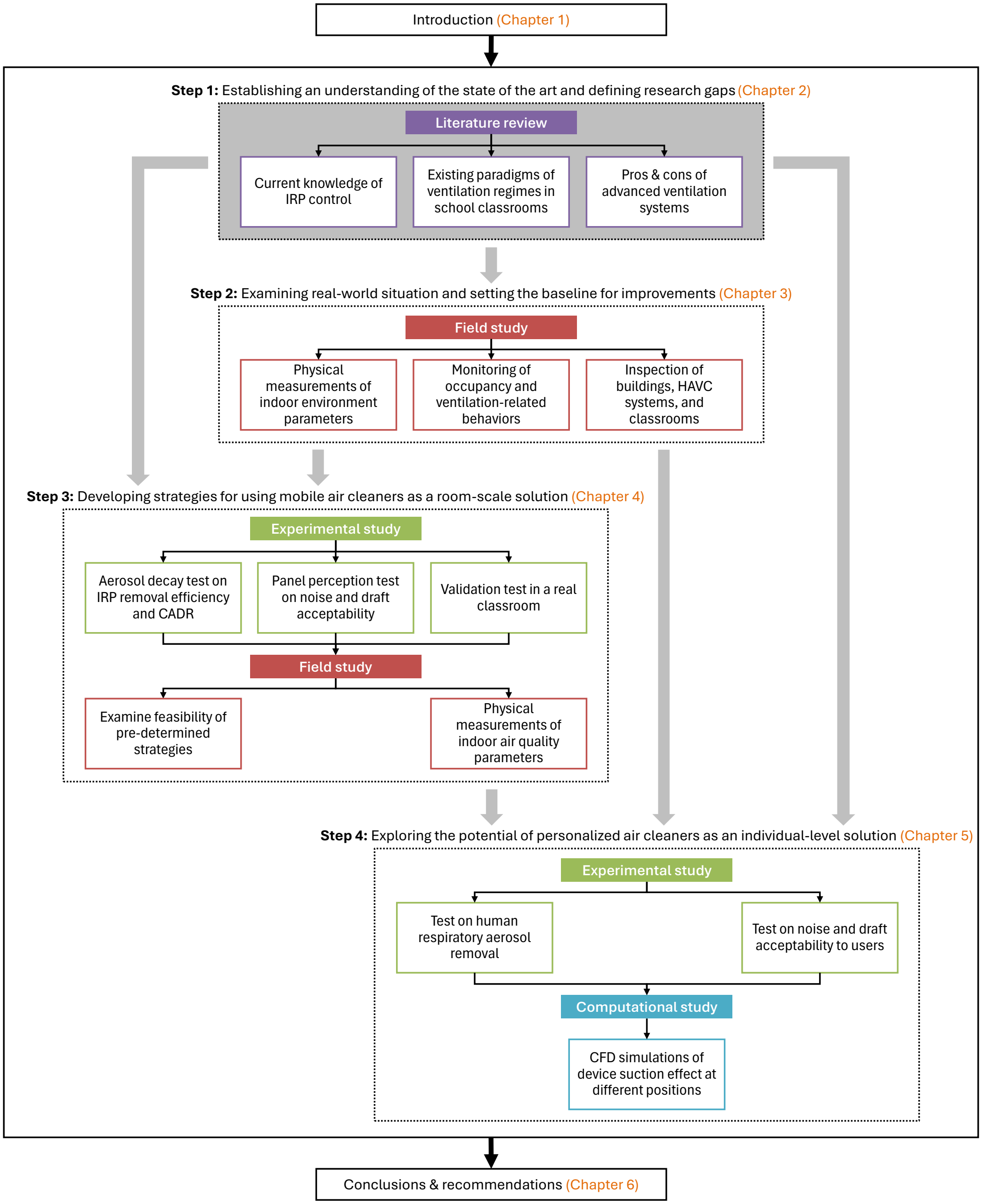
Introduction (Chapter 1)
Step 1: Establishing an understanding of the state of the art and defining research gaps (Chapter 2)
Literature review
Current knowledge of IRP control
Existing paradigms of ventilation regimes in school classrooms
Pros & cons of advanced ventilation systems
Step 2: Examining real-world situation and setting the baseline for improvements (Chapter 3)
Field study
Physical measurements of indoor environment parameters
Monitoring of occupancy and ventilation-related behaviors
Inspection of buildings, HAVC systems, and classrooms
Step 3: Developing strategies for using mobile air cleaners as a room-scale solution (Chapter 4)
Experimental study
Aerosol decay test on IRP removal efficiency and CADR
Panel perception test on noise and draft acceptability
Validation test in a real classroom
Field study
Examine feasibility of pre-determined strategies
Physical measurements of indoor air quality parameters
Step 4: Exploring the potential of personalized air cleaners as an individual-level solution (Chapter 5)
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Conclusions & recommendations (Chapter 6)

TOC

2 Understanding background

Infectious respiratory particles, ventilation in schools, and the possible bridge in between

Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review

First published as: Ding, E., Zhang, D., & Bluyssen, P.M. (2022). Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review. *Building and Environment*, *207*, 108484.

ABSTRACT Airborne transmission of small respiratory droplets (i.e., aerosols) is one of the dominant transmission routes of pathogens of several contagious respiratory diseases, which mainly takes place between occupants when sharing indoor spaces. The important role of ventilation in airborne infection control has been extensively discussed in previous studies, yet little attention was paid to the situation in school classrooms, where children spend long hours every day. A literature study was conducted to identify the existing ventilation strategies of school classrooms, to assess their adequacy of minimizing infectious aerosols, and to seek further improvement. It is concluded that school classrooms are usually equipped with natural ventilation or mixing mechanical ventilation, which are not fully capable to deal with both long-range and short-range airborne transmissions. In general, the required ventilation designs, including both ventilation rates and air distribution patterns, are still unclear. Current standards and guidelines of ventilation in school classrooms mainly focus on perceived air quality, while the available ventilation in many schools already fail to meet those criteria, leading to poor indoor air quality (IAQ). New ways of ventilation are needed in school classrooms, where the design should be shifted from comfort-based to health-based. Personalized ventilation systems have shown the potential in protecting occupants from aerosols generated within short-range contact and improving local IAQ, which can be used to compensate the existing ventilation regimes. However, more studies are still needed before such new ventilation methods can be applied to children in school classrooms.

KEYWORDS ventilation, airborne transmission, respiratory droplets, classrooms, indoor air quality

2.1 Introduction

Since the early stage of the global pandemic of Coronavirus Disease 2019 (COVID-19), researchers have investigated the epidemiological features of pediatric patients, and it is suggested that children in general have milder symptoms than adults [1-3]. However, existing evidence is insufficient to confirm whether children are less frequently infected or infectious with the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is the pathogen of COVID-19. Instead, the large proportion of asymptomatic cases among them may become a hidden threat to susceptible individuals [4,5]. The latest data show that children aged from 0 to 18 years constitute approximately 11-13% of the total number of people tested to be infected [6-8]. According to the report on COVID-19 and children by the European Centre for Disease Prevention and Control [6], the proportion of infected children aged 12-18 to the total confirmed cases has slightly exceeded the population distribution of this age group among 11 EU/EEA countries. Besides, a recent systematic review of over seven thousand cases in China has revealed that all the 318 outbreaks identified with three or more cases took place between people when sharing indoor spaces [9]. Considering the long hours children spend in densely occupied classrooms every day, it is therefore important that schools can provide a safe indoor environment to protect students from cross-infections.

Among all the indoor environmental quality (IEQ) control methods, ventilation has long been recognized as one of the primary measures for indoor air quality (IAQ) control [10]. Airborne transmission of infectious respiratory droplets between indoor occupants has been widely addressed as one of the major transmission routes of SARS-CoV-2 [11-13], as well as the infectious agents of several other pandemic-prone acute respiratory diseases, including SARS [14], Influenza A [15], and MERS [16]. Besides, previous research has presented a large number of pathogens that have the potential to be airborne transmissible [17]. Therefore, for cross-infection control, these pathogen-laden droplets can be treated as indoor air contaminants in occupied zones, which can then be diluted and/or removed through ventilation [18-20]. While researchers have extensively discussed the important role of ventilation in airborne infection control, recent studies have demonstrated that the contact distance between occupants can significantly impact the dispersion of respiratory droplets, and thus influence the efficiency of existing ventilation strategies [21-23]. Nevertheless, in practice, little attention was paid to such contaminants in public spaces other than hospital buildings in terms of ventilation, especially during the previous non-pandemic periods. Consequently, this may lead to an insufficiency of the conventional ventilation strategies to achieve healthy IAQ conditions in non-nosocomial indoor environments such as school classrooms.

Current standards and guidelines for ventilation in school classrooms vary among countries and regions. In most cases, a minimum ventilation rate per person and/or per unit floor area is required based on a balance between indoor air quality control and energy saving [24]. So far, such design criteria have not taken into consideration the airborne transmission of respiratory contaminants, and thus whether they are sufficient for cross-infection control remains unknown. Meanwhile, considering the diversity of schools and the uncertainty of practical operation in real life, whether such requirements can be fulfilled is hard to determine. However, what is clearly demonstrated in previous studies is that IAQ-related health, comfort, and productivity problems have been extensively reported among students across the world [25], [26]. Thus, for the post-pandemic periods, new ways of proper ventilation are needed to solve the IAQ-related problems for children in school classrooms.

In recent years, several advanced air distribution methods, such as personalized ventilation systems (PV), have been developed in order to improve local IAQ. Such systems are suggested to achieve better protection for occupants who are exposed to various contaminant sources [27]. Nevertheless, previous studies mainly focused on specific public spaces such as hospital wards [28], office rooms [29], and aircraft cabins [30]. Considering the differences in indoor settings and activities, as well as the specific psychological and physiological demands of children [31], whether such systems and devices can be applied to school classrooms requires further discussion.

Therefore, a literature review is conducted to address (1) the existing ventilation regimes and IAQ conditions in school classrooms, (2) the ability of conventional ventilation methods to minimize the airborne transmission of respiratory droplets, and (3) the potential of personalized ventilation as an additional solution.

2.2 Methods

Databases including Google Scholar, ScienceDirect, Scopus, Wiley, SpringerLink and PubMed are used to acquire research papers from peer-reviewed journals. Initially, a combination of keywords, including airborne transmission, respiratory droplets, cross-infection, school, classroom, children, student, ventilation, and indoor air quality, was used for the literature search. However, few studies can be found covering all these concepts, especially during the period prior to the pandemic of COVID-19. Therefore, based on the main focuses of this literature review, it was further divided into three topics: (1) the current situation of ventilation strategies and IAQ conditions in school classrooms; (2) features and ventilation control of airborne transmission of respiratory droplets; (3) performance and feasibility of personalized ventilation systems. Instead of presenting an exhaustive discussion on each topic, this literature review intends to extract and connect the key information among the three topics to answer the following questions: *How well do the current ventilation regimes of school classrooms work against airborne transmission of infectious respiratory droplets?* and *What are possible solutions to improve the IAQ in school classrooms for children?*

Since the three topics have relatively specific focuses, an independent literature search was performed for each topic. The keywords used for each literature search are listed in **Table 2.1**. For topic 1, the existing design criteria and requirements of ventilation and IAQ in school classrooms were discussed first, where several examples of the latest standards and guidelines were involved. These documents were obtained from the official websites of international and national agencies including the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Federation of European of Heating, Ventilation, and Air-Conditioning Associations (REHVA) and RVO (Netherlands Enterprise Agency). To identify the current situation of ventilation and IAQ in real school buildings, relevant field studies conducted in primary and secondary school classrooms within the last decade were screened, and some examples from different counties were included. For topic 2, studies addressing the dispersion of human respiratory droplets were involved, with a specific focus on its relationship with droplet size and contact distance between people. Based on the discussion of topic 1, studies performed to investigate the efficiency of airborne infection control of those commonly used ventilation regimes in school classrooms were reviewed. Since fewer studies were conducted under the scenario of school classrooms, studies performed in other indoor environments (e.g., hospital wards) were also included as references. For topic 3, studies conducted to investigate different types of personalized ventilation systems among different indoor spaces with a particular target of reducing airborne transmissible contaminants were discussed.

TABLE 2.1 Keywords for literature search.

	Topic 1		Topic 2		Topic 3	
	AND		AND		AND	
OR	school	ventilation	airborne transmission	ventilation	advanced	ventilation
	classroom	indoor air quality	aerosol	ventilated	localized	exhaust
	educational building	indoor environmental quality	airborne infection	air quality control	personalized	air terminal device
	student		droplet			air diffuser

2.3 Ventilation and IAQ-conditions in school classrooms

2.3.1 Requirements of ventilation and IAQ for school classrooms

Ventilation refers to the process of supplying fresh air to an indoor environment and exhausting polluted air [32]. The ventilation strategy inside an individual room consists of two basic elements: air distribution and ventilation rate [17,33], which can be realized either via a natural or a mechanical way or both (hybrid). Typically, the ventilation rate is expressed in L/s (m^3/h) per person or L/s (m^3/h) per m^2 floor area.

To date, the most widely implemented standards and guidelines of ventilation in school classrooms issued by several authoritative international organizations and agencies include ISO 17772-1 [34], EN 16798-1 [35] and ANSI/ASHRAE Standard 62.1 [36]. Such standards, in general, put forward a minimum ventilation rate (**Table 2.2**). The type of ventilation system or regime to realize this ventilation is, however, not specified.

The minimum ventilation rate is determined by the purpose to dilute and remove the indoor air pollutants generated by the occupants (bio-effluents), their activities and the building materials and components [37]. In both ISO 17772-1 [34] and EN 16798-1 [35], the minimum ventilation rate is approximately 5 L/s per person or 2 L/s per m^2 for a classroom of 50 m^2 with 20 students. It is also stated that CO_2 concentration can be used to present the human emission, while particles (i.e., $PM_{2.5}$ and PM_{10}) are only considered as coming from outdoor emissions.

As for ANSI/ASHRAE Standard 62.1 [36], the minimum required ventilation rate (default occupant density of 25 and 35 persons/100 m^2, for children aged 5 to 8 years and over 9 years, respectively) in the breathing zone is approximately 7 L/s per person or 2 L/s per m^2. It should be noted that the airborne transmission of infectious agents is not addressed. In addition, ISO 17772-1 [34] and EN 16798-1 [35] are not providing relevant information on the design of natural ventilation for non-residential buildings, while it is in fact most commonly used in schools (as demonstrated in **Section 2.3.2**). ANSI/ASHRAE Standard 62.1 [36], on the other hand, involves the general design procedure of natural ventilation, where the specifications of natural ventilation (e.g., ceiling height, location, and size of openings) are included.

TABLE 2.2 Minimum ventilation rates for school classrooms.

Standard/guideline	Minimum ventilation rate for human emissions [L/s/p]	Minimum ventilation rate for building emissions [L/s/m^2]
ISO 17772-1	4	0.4
EN 16798-1	4	0.4
ANSI/ASHRAE 62.1	5	0.6

Besides the minimum ventilation rates, many standards and guidelines have also proposed CO_2 concentration as the indicator of IAQ-condition in school classrooms, for instance EN 16798-1 [35]. Usually, different categories of CO_2 concentration are included, as listed in **Table 2.3**. According to EN 16798-1 [35], if CO_2 is used to represent human occupancy, 550, 800, and 1350 ppm above the outdoor concentration level can be taken as the default design CO_2 concentrations, which are corresponding to the ventilation rates of 10, 7, and 4 L/s per person, respectively. Such CO_2 values, as stated in the standard, can also be used for the demand-controlled ventilation systems. In response to the ongoing pandemic of COVID-19, REHVA has put forward the COVID-19 Guidance for public buildings [38], where the warning and alarm levels for CO_2 concentration monitoring in school classrooms were suggested to be set as 800 and 1000 ppm, respectively. In terms of national standards and guidelines, the Program of Requirements – Fresh Schools [39] is a specific guideline of IEQ control and energy saving for school buildings, issued by the Netherlands Enterprise Agency. In this guideline, three classes of ventilation (i.e., class A, B, C) are defined as excellent, good, and sufficient, with corresponding CO_2 concentrations of 800, 950, and 1200 ppm, respectively.

TABLE 2.3 Limit values of CO_2 concentration in school classrooms.

Standard/guideline	CO_2 concentration [ppm]		
	I/A	II/B	III/C
EN 16798-1*	550	800	1350
REHVA COVID-19 Guidance	-	800	1000
The Netherlands Program of Requirements – Fresh Schools	800	950	1200

* *CO_2 concentration above outdoor level.*

2.3.2 Real situation of ventilation and IAQ in school classrooms

In recent years, researchers have conducted a large number of field studies to observe ventilation and IAQ-related problems in schools of different countries and regions. Several examples published within the past decade are listed in **Table 2.4**. Among these studies, CO_2 concentration has been widely used to assess the ventilation sufficiency and IAQ-condition.

TABLE 2.4 Ventilation strategies in school classrooms.

Reference	Country	Schools (Classrooms)	Ventilation system[a]
[40]	United States	100 (100)	MV: 100%
[41]	United Kingdom	8 (16)	NV: 88% MV: 12%
[42]	Italy	7 (28)	NV: 100%
[43]	China	10 (32)	NV: 100%
[44]	Denmark	389 (820)	NV: 52% HV: 17% MV: 31%
[45]	France	17 (51)	NV: 73% MV: 27%
[46]	The Netherlands	21 (54)	NV: 48% HV: 19% MV: 33%
[47][48]	Finland	2 (4)	HV: 50% MV: 50%

a *NV: natural ventilation; HV: hybrid ventilation; MV: mixing mechanical ventilation.*

Haverinen-Shaughnessy et al. [40] investigated 100 fifth-grade classrooms in 100 American elementary schools (1 classroom per school), which were all equipped with a balanced mechanical ventilation system. The maximum CO_2 concentrations measured in different classrooms ranged from 661 to 6000 ppm, with an average value of 1779 ppm, far exceeding the threshold values. In addition, the ventilation rates were estimated based on the CO_2 concentrations. With the fans continuously in operation, the average ventilation rate among all the classrooms was 4.2 L/s per person, where 87% of them had a ventilation rate below the ASHRAE standard 62.1. Bakó-Biró et al. [41] surveyed 16 classrooms of eight primary schools in the United Kingdom during different seasons, among which only one school had a mechanical ventilation system. The mean CO_2 concentration of each individual classroom varied from 644 to 2833 ppm, while the maximum level in several classrooms reached up to 5000 ppm. Accordingly, the ventilation rates were estimated to be around 1 L/s per person, again failing to meet the standards.

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De Giuli et al. [42] studied 28 naturally ventilated classrooms among seven primary schools in Italy, where children's perception of IEQ-conditions was collected together with IAQ-measurements. The results showed that the CO_2 concentrations in 22 (81%) classrooms were more than 600 ppm above the outdoor level, while 9 (33%) of them were more than 1100 ppm above. Meanwhile, children in four schools (57%) complained about poor IAQ (perceived bad smell). Zhang et al. [43] conducted a longitudinal study among 32 classrooms of 10 junior high schools in China, where the average CO_2 concentration of the two-year measurement was 1290 ppm. This study also indicated that children in these schools commonly suffered from the hazardous impacts of other air pollutants such as PM_{10}, SO_2 and NO_2, which increased the prevalence and incidence of the sick building syndrome (SBS). Toftum et al. [44] investigated 820 classrooms (natural ventilation: 52%, hybrid ventilation: 17%, balanced mechanical ventilation: 31%) in 399 Danish schools during two cross-sectional studies (732 (311) and 88 (88) classrooms (schools), respectively). In these two studies, 56% and 66% of the classrooms presented a median CO_2 concentration greater than 1000 ppm, revealing insufficient ventilation, which was found to have negative effects on children's learning outcomes. Canha et al. [45] assessed the ventilation and indoor air pollutants in 51 classrooms of 17 schools in France with natural ventilation (73%) and mechanical ventilation (27%) systems. In general, the classrooms equipped with mechanical ventilation had a better IAQ, and the air change rate and ventilation rate were significantly higher than those having natural ventilation. The concentrations of CO_2 and VOCs were also observed to be lower in the mechanically ventilated classrooms. However, it is also noticed that the average CO_2 concentration of all classrooms exceeded 1300 ppm, while the average ventilation rate was only 2.9 L/s per person, much lower than the design criteria. Bluyssen et al. [46] conducted an IEQ-survey in 54 classrooms of 21 Dutch primary schools, of which 48% were naturally ventilated only, 19% were mechanical assisted (hybrid ventilation), and the rest (33%) were mechanically ventilated. The average CO_2 concentration in 22 of 37 classrooms measured exceeded 1000 ppm, while 63% of the children self-reported to be bothered by smell, and some also suffered from respiratory symptoms. Besides, the sunshades were found often hampering the use of windows among 29 classrooms. Vornanen-Winqvist et al. [47,48] investigated two comprehensive schools in Finland involving two classrooms equipped with fan-assisted natural ventilation (hybrid ventilation) and two with mechanical ventilation, respectively. Although the CO_2 concentrations were at a moderate level among the classrooms (average 488 ppm, maximum 1431 ppm, minimum 394 ppm), it was found that both the hybrid and mechanical ventilation regimes were initially not properly operated. After adjustments were applied, both of them showed significant improvement in reducing the concentrations of CO_2, TVOC, and $PM_{2.5}$.

2.4 Airborne transmission of infectious respiratory droplets: features and control

2.4.1 Dispersion of respiratory droplets

Normally, the cross-infection of contagious respiratory diseases (e.g., Tuberculosis, SARS, Influenza A, COVID-19) between occupants indoors consists of three stages: first, an infected person generates pathogen-containing droplets by respiratory activities such as breathing, talking, sneezing, and coughing; then the infectious droplets spread with the exhaled jet into the indoor air; and once a susceptible person is exposed to a certain dose of pathogens, infection may take place [17,49]. The movement of a droplet in the air depends largely on its size, yet is also highly subject to other factors such as the initial momentum, airflow patterns (speed and direction), and indoor environmental conditions (temperature and relative humidity) [50,51]. When a droplet is more influenced by gravity, it follows a ballistic trajectory and falls onto the ground or other surfaces (including other occupants' body) [51,52]. Meanwhile, if a droplet is more easily to be airborne and remains suspended in the air, it becomes an aerosol [17,51]. Since the sizes of expelled droplets span a continuum from 0.1 μm to over 1000 μm, the dispersion pathways of droplets also change continuously with their size, and thus cannot be simply classified into one of the two categories [52–54], although a size threshold of droplets and aerosols of 100 μm has been suggested [55,56]. Typically, large droplets with a diameter > 100 μm can settle in proximity (1-2 m) to the source within a few seconds, while small droplets, especially for those < 5-10 μm, have a higher probability to be carried by the airflow for a long time and travelling over long distances [52,56,57]. Besides, due to the difference in temperature and relative humidity between the exhaled jet and the room air, droplets can shrink rapidly through evaporation (while keeping the same amount of infectious material), and thus increase the chance of becoming aerosols [50,53]. Compared to large droplets, aerosols are considered to be more dangerous as they can be inhaled by exposed individuals, penetrate to the deeper area of the respiratory tract, and thus cause severer symptoms [58].

Aerosols have been found to dominate the size spectrum of exhaled respiratory droplets. Yang et al. [59] investigated the size distribution of coughed droplets from human subjects, where the dominant modes were found to be 8.35 μm and 0.74-2.12 μm for the initial and dried droplets, respectively. Morawska et al. [60]

examined human breathing, talking, sneezing, and coughing, and concluded that the droplet sizes of 0.8 μm and 1.8 μm presented the highest concentrations for all expiratory activities. Similarly, Somsen et al. [61,62] measured the exhaled droplets of human cough and speech, and the results showed that fine droplets of 1-10 μm were the most prevalent modes. Large droplets, though, were indicated to be mainly generated by sneezing and coughing, at a relatively low density [11,61]. Considering the real situation of a contagious disease such as COVID-19, where most infected children are found to be asymptomatic, it is very likely that the co-occupants are exposed to the infectious aerosols rather than the droplet spray [1,4]. Hence, minimizing the exposure to pathogen-laden aerosols is one of the key principles to prevent cross-infection.

Based on the dispersion features after generation, the transmission routes of respiratory droplets between indoor occupants are categorized into three types (**Figure 2.1**): (1) direct spray of large droplets onto mucous membranes (droplet-borne transmission); (2) indirect contact via surface touching (fomite transmission); and (3) inhalation of aerosols (airborne transmission). As illustrated in **Figure 2.1**, the airborne transmission of respiratory droplets can be further divided into two sub-routes based on the distance between the infected and exposed person, namely the short-range (at close proximity) and long-range (at room scale) airborne transmission [17,63]. Consequently, when two occupants are having close contact (< 1-2 m), the recipient is exposed to both large droplets and aerosols [22,63]. A recent study by Chen et al. has revealed that during close contact (< 2 m), the short-range airborne transmission of respiratory droplets is the dominant transmission route for both talking and coughing [64]. Similar results were found by Cortellessa et al., where the contribution of large droplet deposition to the infection risk is no more noticeable at a contact distance larger than 0.6 m, comparing to aerosol inhalation [23]. Meanwhile, via the long-range airborne transmission of respiratory droplets, the infectious agents can be spread throughout the indoor space, and may cause threats to a large number of susceptible people [65]. Therefore, both the short-range and long-range airborne transmission need to be taken into consideration when treating aerosol contaminants.

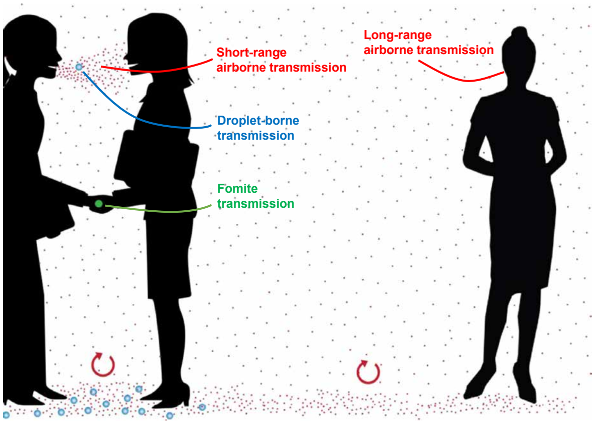

FIG. 2.1 Transmission routes of respiratory droplets between indoor occupants.
Note: reproduced from [51].

2.4.2 Ventilation control of airborne transmission

A large number of studies have shown strong evidence of the association between ventilation and the transmission of infectious diseases in the built environment [18]. According to the observed situation in school classrooms (as discussed in **Section 2.3.2**), most of them are equipped with conventional natural ventilation (opening windows and doors) or mixing mechanical ventilation. Such ventilation regimes are designed to treat the indoor air in a room-based total-volume manner, and previous measurements and discussions are mainly based on the steady-state conditions [19,66].

The exhaled air from an infected person can be divided into two parts. One part flows directly to the exposed person within close contact, and thus can lead to short-range airborne transmission [67,68]. The other part flows into the occupied space and is diluted by the existing ventilation regime, which can then contribute to the long-range airborne transmission. To date, previous studies of aerosol infection mainly focused on the long-range airborne transmission of respiratory droplets, where researchers have extensively discussed whether such contaminant can be effectively tackled with conventional room-based total-volume ventilation methods. Furthermore, most of the investigations were performed under a hospital setting.

For natural ventilation, Escombe et al. [69] tested 70 clinical rooms in Lima, Peru. The results showed that when the outdoor wind speed was higher than 2 km/h (0.6 m/s), the average ventilation rate reached 697 L/s with windows and doors fully open, 458 L/s with windows and doors partly opened, and 37 L/s with

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windows and doors closed. Those results for outdoor wind speed lower than 2 km/h were 454, 128, and 24 L/s, respectively. The predicted infection risk of Tuberculosis was reduced by 66% to 89% when windows and doors were fully open, compared to the condition when everything was closed. Gilkeson et al. [70] carried out an in-situ measurement in two large wards of a hospital in Bradford, United Kingdom, and observed an average ventilation rate in the range of 204 L/s to 390 L/s with outdoor wind speeds of 1-4 m/s. When the windows were closed, the exposure risk was calculated to be four times higher than the fully opened condition. All of these field studies used CO_2 as the tracer gas, so the results are more relevant for fine droplets < 5 μm compared to the larger ones [71]. Zhou et al. [72] conducted a CFD simulation of hospital wards with a central-corridor in Nanjing, China, and the ventilation rates were obtained to be 100 to 700 L/s with outdoor wind speeds between 0.5 and 4.0 m/s. Such a cross-ventilation setting was proven to provide large ventilation rates, yet it can also increase the cross-infection risk between different rooms.

For mixing (mechanical) ventilation, Lai & Cheng [73] simulated the dispersion of two droplet sizes, 0.01 μm and 10 μm, in a chamber occupied with two standing persons. The results showed that under mixing ventilation, droplets from both two size groups were distributed homogeneously into the air within 50 s, due to a high inlet air velocity of 2 m/s (ventilation rate of 320 L/s). The large velocity of supply airflow is one of the primary features for mixing ventilation to achieve highly mixed air distribution and quick dilution of exhaled aerosols (from an infected person), as also recognized by Gao et al. [74], Li et al. [75], and Bolashikov et al. [76]. However, such ability of mixing and diluting does not necessarily lead to a lower exposure risk for the co-occupants. Instead, the exhaled aerosols can be rapidly dispersed to the breathing zone of the exposed persons under mixing ventilation (57 L/s), where the inhaled dose in the first stage (approx. 10 s) were found to be account for almost 50% of the total inhaled dose [75]. Besides, the ventilation rate is often limited due to comfort issues [19]. For instance, under a ventilation rate of 188 L/s, the background air velocity in the occupied zone was found to exceed 0.5 m/s, which may cause draft discomfort to the occupants [76].

The short-range airborne transmission of respiratory droplets, however, cannot be treated with the classical steady-state model, as it is a highly dynamic process [66]. The simulation study conducted by Villafruela et al. [21] indicated that the human microenvironment and the interaction of breathing flows were the key determinants of airborne transmission between occupants within a short distance (< 0.5 m), while the indoor ventilation flow was more important for a longer distance (> 0.5 m). Similar results were observed in the experimental study of Liu et al. [22], and they suggested the threshold distance for short-range and long-range contact to be 1.5 m. Ai et al. [77] adopted a time-related method to evaluate the exposure risk via a full-scale experiment with breathing thermal manikins, and a significant difference was found between the short-term event and the steady-state condition. Based on the extensive evidence, it is concluded by a number of studies that existing ventilation methods are not appropriate for preventing short-range airborne transmission of respiratory droplets between indoor occupants, and new intervention methods, for example personalized ventilation, are recommended [22,63,77].

2.5 Personalized ventilation systems

Conventionally, personalized ventilation (PV) refers in particular to the systems that directly supply clean air to the breathing zone of each occupant. In this paper, PV refers to the general concept of localized (or individually controlled) air distribution system, which includes both the personalized air supply system (PS) and the personalized air exhaust system (PE). Personalized ventilation has been recognized as an efficient tool for compensating the room-based total-volume ventilation systems to improve local IAQ for each occupant, especially when sharing indoor space with others [27,66].

2.5.1 Personalized air supply system (PS)

Personalized air supply (PS) refers to the process of locally supply clean air to the breathing zone of each occupant. Researchers have conducted extensive studies to examine the performance of PS systems in a room with office settings. According to the location of the supply air terminal device (ATD), PS systems can be roughly classified into two types: desk-based and chair-based systems, as illustrated in **Figure 2.2** and **Figure 2.3**.

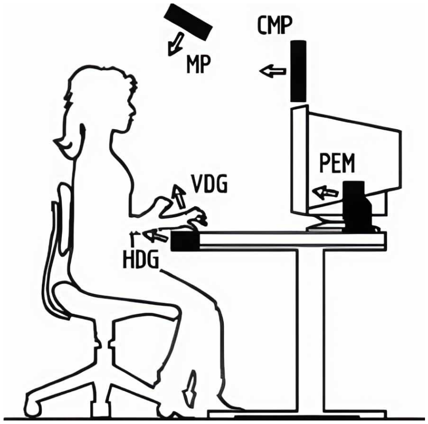

FIG. 2.2 Desk-based ATDs.
Note: (round) movable panel – (R)MP; computer monitor panel – CMP; personal environment module – PEM; vertical desk grill – VDG; horizontal desk grill – HDG [78].

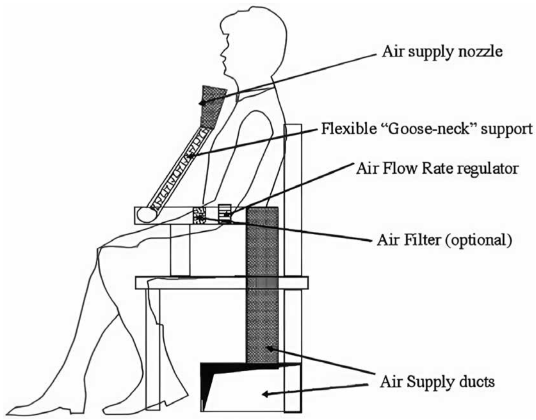

FIG. 2.3 Chair-based personalized air supply system.
Note: adapted from [29].

It is well demonstrated that PS devices can help to efficiently reduce the exposure risk of susceptible co-occupants to airborne contaminants exhaled by a source individual [79,80]. The comparisons of contaminant removal efficiency between the conditions with and without PS in previous studies are presented in **Table 2.5**. Here, only the conditions where all occupants were provided with the same amount of supply airflow rate are included. This is considered to be more relevant to the real situation in school classrooms, where the infected children are sometimes hard to be spotted.

TABLE 2.5 Efficiency of reducing inhaled contaminants with different PS devices.

Reference	AID type	Personalized airflow rate [L/s/p]	Total ventilation rate [L/s]	Contaminant	Efficiency [%][a]
[81]	Round movable panel	15	80	Tracer gas	90
	Vertical desk grill	15			65
[82]	Round movable panel	7	80	Tracer gas, 0.8 μm, 5 μm/16 μm	15/46
		15			87/90
[29]	Chair-based PS	0.8		Tracer gas, 1 μm, 5 μm, 10 μm	70
		1.6	57		90
	Horizontal desk grill	3.5			40
		6.5			60
[83]	Round movable panel	7	26	Tracer gas	64
		15	42		82

a *Percentage reduced in intake fraction (IF) of exhaled contaminants.*

Cermark et al. [81] examined two types of desk-based PS devices in an experimental chamber using manikins, under a background mixing ventilation of a total ventilation rate of 80 L/s. When the personalized supply airflow rate reached 15 L/s per person, the round movable panel and vertical desk grill reduced the inhaled concentration of exhaled air (tracer gas) by 90% and 65%, respectively. He et al. [82] investigated the effects of a round movable panel on the dispersion and concentration of droplets (0.8 μm, 5 μm, and 16 μm) and tracer gas in an office room using CFD simulation. Under a total ventilation rate of 80 L/s, the intake fractions (IF) of the tracer gas, 0.8 μm droplets, and 5 μm droplets were reduced by 15% with a personalized supply airflow rate of 7 L/s per person, and 87% with 15 L/s per person. For the droplets of 16 μm, the IF was reduced by 46% and 90%, respectively. Similarly, Li et al. [29] simulated a chair-based PS and a horizontal desk grill in an office room with a total ventilation rate of 57 L/s. Under mixing ventilation, the chair-based PS reduced the IF of droplets (1 μm, 5 μm and 10 μm) and tracer gas by 70% with a supply airflow rate of 0.8 L/s per person, and 90% with 1.6 L/s per person. Meanwhile, the horizontal desk grill reduced the IF by 40% and 60%, with a supply airflow rate of 3.5 L/s per person and 6.5 L/s per person, respectively. Lipczynska et al. [83] also tested the round movable panel in a manikin experiment with a background mixing ventilation. Under a total ventilation rate of 26 L/s, the personalized supply airflow rate was set as 7 L/s per person, where the IF of tracer gas was reduced by 64%. Under a total ventilation rate of 42 L/s, the personalized supply airflow rate was set at 15 L/s per person, which reduced the IF of tracer gas by 82%. It was also observed that with a moderate increase in airflow rates, PS can be performed as the only ventilation system for the mock office room.

2.5.2 Personalized air exhaust system (PE)

To date, fewer studies have been conducted on PE compared to PS, and most of them focused on aircraft cabin and hospital settings. For aircraft cabins, Dygert & Dang [84,85] designed a localized exhaust system with either built-in seat-back or overhead suction orifices (background mixing ventilation of 45 L/s). The results of CFD-simulation and experimental validation showed an average decrease in co-passengers' exposure to body-emitted contaminants up to 60% with an exhaust airflow rate of 5 L/s per person. For hospital consultation rooms, Yang et al. [86] applied both a top-PE and a shoulder-PE device to the source manikin, respectively. Under a background mixing ventilation of 110 L/s, the IF of exhaled contaminant (tracer gas) was reduced by 87% using both of the PEs with an exhaust airflow of 10 L/s per person, and further reduced by 93% with 20 L/s per person. Moreover, it is also observed that with a higher airflow rate of 20 L/s per person, the IF after a 30 min exposure was lower than that after a 10 min exposure without PE. For hospital wards, Bolashikov et al. [87] developed a wearable PE unit embedded in a headset-microphone to protect the patient from a sick doctor. Different exhaust nozzles (circular, flanged, or flared nozzles), airflow rates (0.24 or 0.5 L/s per person), and distances from mouth (0.02, 0.04, or 0.06 m) were tested with two manikins. The results showed that under a background mixing ventilation of 48 L/s, when the nozzle was placed close enough to the mouth of the source person (0.02 m), the wearable PE system reduced the exposure concentration (tracer gas) of the patients by 67% with an exhaust airflow of 0.24 L/s. Such performance was better than a pure background mixing ventilation of 192 L/s.

2.6 Discussion

2.6.1 Challenges for schools: airborne infection control with current ventilation regimes

Currently, the understanding of airborne transmission of respiratory droplets is being rapidly updated driven by the ongoing pandemic of COVID-19. Human respiratory droplets mainly comprise droplets smaller than 100 μm, which usually follow an airborne transmission route after exhalation. Airborne transmission of respiratory droplets can be divided into a long-range route (at room scale) and a short-range route (at a close proximity < 1-2 m), and can be controlled by IAQ control measures, such as ventilation [17,20,63]. In general, the main ventilation regimes used in primary and secondary school classrooms are natural ventilation and mixing mechanical ventilation (**Table 2.4**). Such conventional ventilation strategies, as indicated by previous studies, can effectively reduce the long-range airborne transmission. However, those analyses are mainly based on steady-state conditions, and the models used for exposure risk evaluation are sometimes restricted by the well-mixing assumption (e.g., the Wells-Riley model [88]), which are usually not the case in real indoor spaces. Meanwhile, other researchers have demonstrated that total-volume ventilation regimes are not sufficient for dealing with short-range airborne transmission, due to the dynamic features of respiratory activities and the significant impacts of microenvironment within the close contact between occupants. In addition, for natural ventilation, although it can achieve in certain situations appropriate ventilation rates and aerosol removal, the performance largely depends on several uncontrollable factors, such as local climate and occupant behavior [70,89]. According to a recent study conducted in schools in New York City, it was found that the exposure risk of airborne transmission of respiratory droplets was always higher during the heating season than during the cooling season, indicating the negative impacts of lower outdoor airflow rates when the windows and doors were closed by the occupants due to cold weather [90]. The performance of natural ventilation can also be strongly influenced by the layout of the building, such as the type of corridor [90,91]. Hybrid ventilation with exhaust fans, as observed in a number of schools as well (**Table 2.4**), is suggested to be helpful when natural forces are not strong enough (e.g., low outdoor wind speed) or opening windows and doors are not preferable (e.g., during cold wintertime) [70,89]. For mixing ventilation, although it can reduce the aerosol concentration in a more controlled manner, a proper ventilation rate remains hard to determine, as the efficiency of aerosol removal is not linearly correlated with ventilation rate [18,92]. Furthermore, since previous studies on ventilation control and airborne infection were mainly conducted in a hospital setting, future research is needed for a better understanding of the situation in school buildings. A recently performed numerical study has proposed the ventilation rates and airing procedures for reducing airborne infection risk in both naturally and mechanically ventilated classrooms [93]. The models have covered several different educational scenarios during school hours, yet they only deal with the airborne transmission at room scale. To summarize, the commonly used ventilation regimes in school classrooms are not fully capable for minimizing both the long-range and short-range airborne transmission of infectious respiratory droplets, while the required ventilation designs (including both ventilation rates and air distribution patterns) are still unclear.

Such information is also missing in relevant standards and guidelines. Current standards of ventilation and IAQ in school classrooms are more focused on the perceived air quality, which mainly target at undesirable odor levels, especially those emitted by occupants. Besides, such standards and guidelines are usually framed under the broader context of energy performance of buildings (e.g., ISO 17772-1 [34] and EN 16798-1 [35]). In many cases, CO_2 in indoor air is used as the tracer of human pollution, and the minimum ventilation rates were calculated based on such emission. However, since CO_2 is a gas, it can behave differently from aerosols of all sizes, especially at a close contact or within a short-term event [71]. Some researchers have also argued that CO_2 concentration cannot be an adequate indicator of airborne infection risk [93]. Therefore, whether the existing design criteria of ventilation in school classrooms are applicable for critical health demands, namely infection control of contagious respiratory diseases, is doubtful. Similar concern has also been addressed by other researchers, where the required ventilation rates of ordinary public spaces determined by the standards and guidelines are considered to be much lower than the suggested level for a good IAQ (8-10 L/s per person) [9]. As in response to the ongoing pandemic of COVID-19, governmental and professional agencies including WHO, CDC, REHVA and ASHRAE have all put forward additional ventilation guidance and recommendations for school managers to facilitate the prevention of cross-infection among children [38,94-96]. To some extent, such action again indicates that existing ventilation strategies in school buildings are not sufficient for tackling potential health-threatening problems. Moreover, these temporary measures cannot be relied on as permanent solutions, since many of them need to be performed at the cost of comfort and energy efficiency. Hence, new criteria of ventilation design in school classrooms are needed, which should be shifted from a comfort-based paradigm towards a health-based one. Human respiratory droplets need to be taken into consideration as one of the major indoor air pollutants in classroom environments, and be handled by proper ventilation.

Apart from the infectious diseases, IAQ-conditions in school classrooms have been proven to be related to children’s health, comfort, and academic performance [24,97]. Yet, according to a number of field studies, ventilation and IAQ-conditions were found to fall short of the existing requirements in a majority of school classrooms across the world prior to the pandemic, which already implies poor ability of health-based control. Therefore, concerning both the potential threats of airborne cross-infection and the unsatisfactory reality of ventilation performance, it is of an urgent need to improve IAQ in school classrooms through rethinking the ventilation strategies.

Moreover, dealing with indoor air contaminants not only influence IAQ-related health and comfort, but can also have impacts on other perceptions such as thermal, visual, and acoustical quality through the interaction of IEQ-factors [98]. One simple example is that an increased ventilation rate may result in undesirable draught [99,100]. Other evidence includes, for instance, increasing ventilation rate may be accompanied with an increase in the background noise level caused by mechanical systems, which leads to annoyance and discomfort, while pollutants’ emission rates may increase with sunlight heating indoor surfaces [37]. Previous studies have also well addressed the cross-modal effects of thermal parameters, sound, and illumination level on perceived air quality and odor perception [101,102]. Therefore, all these possible interactions need to be considered while solving IAQ-problems. Meanwhile, human body mechanisms, together with influences by confounders, modifiers, and individual differences, can produce interaction effects at occupant level [37]. According to an experiment conducted in the SenseLab, children's assessment of smell was significantly affected by the background sound type, especially "children talking", suggesting the possible pre-conditioning in their response by hearing children talk [103,104]. Nevertheless, analysis of such interactions is still short of evidence, and further studies are needed to better tackle the complex IAQ-problems in school classrooms.

2.6.2 Possible solutions to minimize airborne transmission: personalized ventilation

With regard to the ventilation and IAQ-related problems in school classrooms discussed in **Section 2.6.1**, personalized ventilation is proposed as a promising solution, which can be adopted as a complementary system to the total-volume ventilation regimes. PV systems, including PS and PE, have been proven to efficiently decrease the exposure risk (usually indicated as IF) of exhaled contaminants of the source person within a close proximity, and improve local IAQ for the co-occupants. Therefore, while the room-based ventilation can deal with long-range airborne transmission, the PV systems can be used to minimizing short-range airborne transmission.

Among all these studies listed in **Table 2.5**, two occupants (manikins) were involved, namely the source person and exposed person, and they were seated at a close distance with each other (1-2 m). Such results, therefore, evidently demonstrated the ability of PS to reduce the short-range airborne transmission of respiratory droplets between indoor occupants. However, the efficiency of PS varies largely with the AID type and supply airflow rate, with a range of 15-90%, meaning a specific configuration and a higher supply airflow rate are often needed for PS to achieve a desirable aerosol removal efficiency. Previous studies have also indicated that PS-systems can achieve positive effects only when the supply airflow rate for the exposed person is equal to or larger than that for the infected person [29,81,82], while the performance is partly determined by the relative position of the occupants [80]. Consequently, such limitations may hinder the flexibility of individual control.

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According to the literature discussed in **Sections 2.5.1** and **2.5.2**, PE in general showed a more stable performance in terms of decreasing IF or exposure risk of the respiratory contaminants for the exposed occupants compared to PS. Although less evidence can be found about the development and assessment of PE, several studies have already demonstrated that PE can achieve significantly better performance than PS under the same experiment conditions, even with a lower airflow rate [30,105]. Therefore, further investigations are needed to explore the possibilities of PE in future applications.

To date, the research on personalized ventilation with the aim of lowering infection risk is still limited to several specific indoor environmental settings. For PS, besides office rooms, researchers have mainly discussed PS devices in hospital wards [28], aircraft cabins [30], and car cabins [106]. For PE, the scenario is further restricted to aircraft cabin and hospital rooms. Little attention has been paid to school classrooms under this topic. However, when taking into consideration the differences in ventilation strategy, occupant density, and indoor activity, existing results of personalized ventilation systems are difficult to apply to children in school classrooms directly, because such factors can easily affect the efficiency of the system. Particularly, a combination of personalized ventilation systems and natural ventilation has not yet been investigated, yet a majority of schools has not been equipped with mechanical ventilation systems. Hence, further research is needed to determine how to make use of such advanced technologies for improving ventilation and providing healthy IAQ-conditions for children in school classrooms. Moreover, besides the ability of minimizing airborne infection, personalized ventilation systems have also been indicated to have the potential of improving local thermal comfort as well as reducing energy consumption [87,106,107]. Accordingly, personalized ventilation system can be considered as a versatile and sustainable tactic to improve overall IEQ in school classrooms.

2.7 Conclusions

This literature review discussed the current ventilation strategies and IAQ-conditions in school classrooms with a specific concern of airborne infection control, as well as the possible solutions for further improvement.

A major conclusion of this review is that there is a clear lack of knowledge of what ventilation rates and designs are required to provide classroom environments that are reasonably safe from airborne transmissible diseases.

The commonly used ventilation regimes in school classrooms include natural ventilation and mixing mechanical ventilation. Such ventilation regimes are not fully capable to reduce the airborne infection risk of contagious diseases, mainly due to the unique features of respiratory aerosols that differ from other indoor air pollutants, in particular their generation and dispersion. Pathogen-laden aerosols are usually small droplets (< 100 μm) generated from human respiratory system, and thus can directly reach the breathing zone of an exposed person within close contact (< 1-2 m), or remain suspended in the air and travel over long distances, which are named as short-range and long-range airborne transmission, respectively. Conventional ventilation regimes are mainly based on the assumptions of steady-state condition and well-mixing model, which are not applicable to short-range airborne transmission, since it is a highly dynamic process and the concentration of aerosols is not evenly distributed. Besides, although room-based ventilation can efficiently deal with long-range airborne transmission, the proper ventilation rates and air distribution patterns are hard to determine. In other words, the required ventilation for minimizing either the long-range or short-range airborne transmission are still unclear.

Currently, the relevant standards and guidelines of ventilation in school classrooms mainly focus on the perceived air quality, and are subject to the demand of energy saving. Besides, CO_2 concentration is often used to represent human pollution, yet it is not an adequate proxy of respiratory aerosols. Consequently, existing standards and guidelines may not be able to provide sufficient information for establishing environments in school classrooms where the risk of airborne transmission is acceptably low. Moreover, although the required minimum ventilation rates are already considered to be relatively low, in reality a large proportion of school classrooms have failed to meet the requirements, while IAQ-related health, comfort, and performance problems have been widely reported. Hence, developing new criteria of ventilation and IAQ in school classrooms is of an urgent need, where

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respiratory droplets should be considered as a major indoor air pollutant in classroom environments, and tackled by proper ventilation. For future research, ventilation design should shift from a comfort-based design towards a health-based design, and take into account the different contact scenarios between occupants. A more flexible and versatile ventilation strategy is needed, in order to deal with the indoor air contaminants both at the occupant level and room level.

Personalized ventilation, including personalized air supply systems and personalized air exhaust systems, can efficiently decrease the exposure risk of exhaled contaminants of the source person within a close contact, and improve local IAQ for the co-occupants. Therefore, PV systems have a promising potential to be used as a complementary solution to the conventional ventilation regimes, by reducing the short-range airborne transmission of respiratory droplets. However, the efficiency of PV systems varies significantly from one to another, and is largely dependent on the indoor environmental settings. Considering also the types of occupants and their activities, further studies are needed to determine the suitable way to apply PV systems into school classrooms.

Changes in IAQ-conditions can affect other IEQ-factors including thermal comfort, acoustical quality, and visual quality. Such interactions can have significant impacts on occupants' health and comfort, and thus also need to be taken into account when rethinking the ventilation in school classrooms.

Overall, a holistic optimization of ventilation strategies is needed in order to tackle the airborne transmission of infectious respiratory droplets and provide children with healthy IAQ-conditions in school classrooms.

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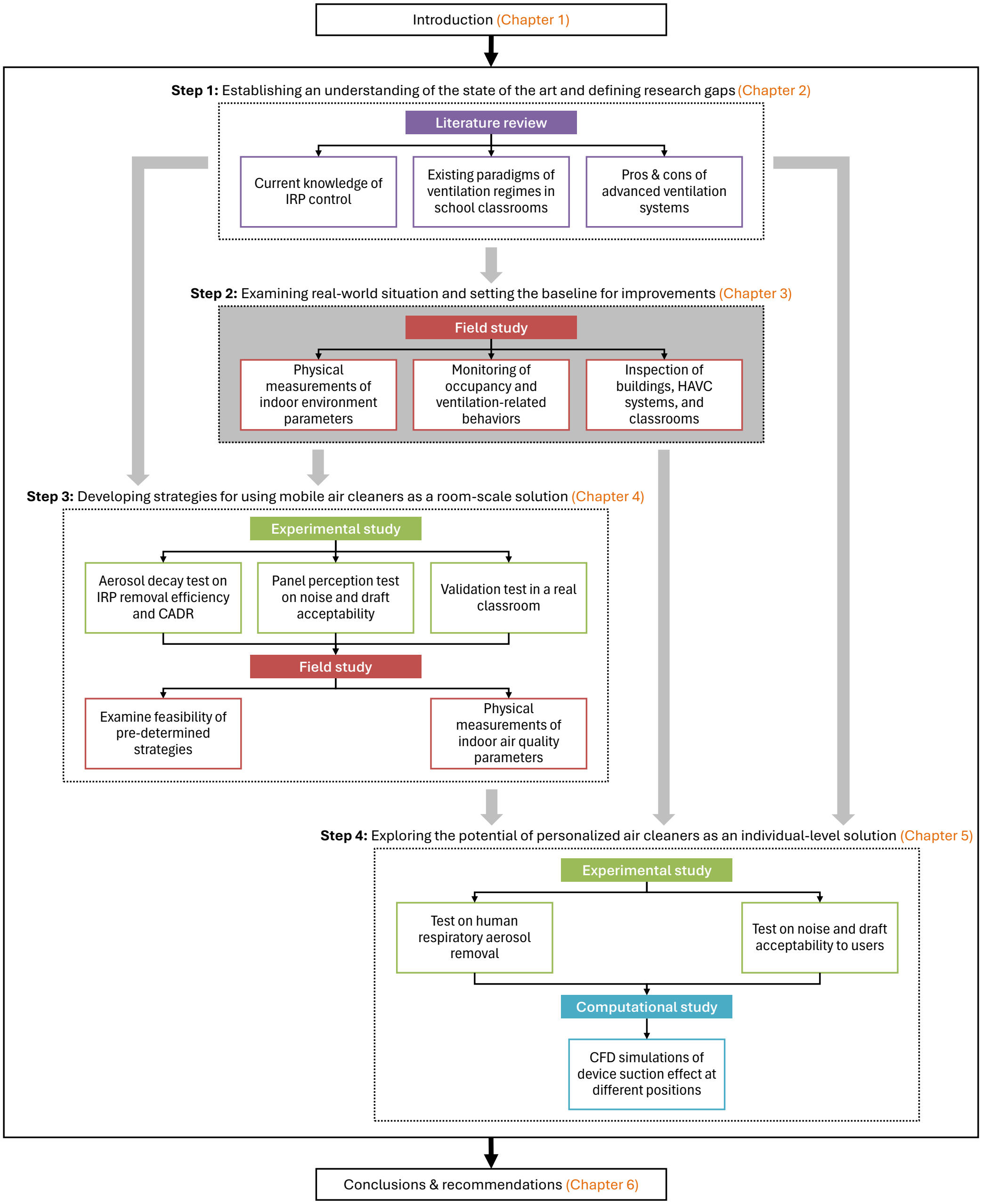
Introduction (Chapter 1)
Step 1: Establishing an understanding of the state of the art and defining research gaps (Chapter 2)
Literature review
Current knowledge of IRP control
Existing paradigms of ventilation regimes in school classrooms
Pros & cons of advanced ventilation systems
Step 2: Examining real-world situation and setting the baseline for improvements (Chapter 3)
Field study
Physical measurements of indoor environment parameters
Monitoring of occupancy and ventilation-related behaviors
Inspection of buildings, HAVC systems, and classrooms
Step 3: Developing strategies for using mobile air cleaners as a room-scale solution (Chapter 4)
Experimental study
Aerosol decay test on IRP removal efficiency and CADR
Panel perception test on noise and draft acceptability
Validation test in a real classroom
Field study
Examine feasibility of pre-determined strategies
Physical measurements of indoor air quality parameters
Step 4: Exploring the potential of personalized air cleaners as an individual-level solution (Chapter 5)
Experimental study
Test on human respiratory aerosol removal
Test on noise and draft acceptability to users
Computational study
CFD simulations of device suction effect at different positions
Conclusions & recommendations (Chapter 6)

TOC

3 Observing reality

Ventilation and thermal conditions in school classrooms during pandemic

Ventilation and thermal conditions in secondary schools in the Netherlands: Effects of COVID-19 pandemic control and prevention measures

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ABSTRACT During the COVID-19 pandemic, the importance of ventilation was widely stressed and new protocols of ventilation were implemented in school buildings worldwide. In the Netherlands, schools were recommended to keep the windows and doors open, and after a national lockdown more stringent measures such as reduction of occupancy were introduced. In this study, the actual effects of such measures on ventilation and thermal conditions were investigated in 31 classrooms of 11 Dutch secondary schools, by monitoring the indoor and outdoor CO_2 concentration and air temperature, both before and after the lockdown. Ventilation rates were calculated using the steady-state method. Pre-lockdown, with an average occupancy of 17 students, in 42% of the classrooms the CO_2 concentration exceeded the upper limit of the Dutch national guidelines (800 ppm above outdoors), while 13% had a ventilation rate per person (VR_p) lower than the minimum requirement (6 L/s/p). Post-lockdown, the indoor CO_2 concentration decreased significantly while for ventilation rates significant increase was only found in VR_p, mainly caused by the decrease in occupancy (average 10 students). The total ventilation rate per classrooms, mainly induced by opening windows and doors, did not change significantly. Meanwhile, according to the Dutch national guidelines, thermal conditions in the classrooms were not satisfying, both pre- and post-lockdown. While opening windows and doors cannot achieve the required indoor environmental quality at all times, reducing occupancy might not be feasible for immediate implementation. Hence, more controllable and flexible ways for improving indoor air quality and thermal comfort in classrooms are needed.

KEYWORDS classrooms, indoor air quality, ventilation, children, COVID-19 pandemic, thermal comfort

3.1 Introduction

In the beginning of 2020, the COVID-19 pandemic aroused worldwide concern about indoor air quality (IAQ) and ventilation, especially in indoor environments with a high occupancy, such as educational buildings. “Proper” ventilation was proposed as a measure to reduce the possible airborne transmission of SARS-CoV-2 [1]. Determining how much ventilation is required and how the indoor space is ventilated are particularly important for school classrooms, because of their dense occupancies of students and a possibly higher risk of airborne transmission [2]. However, in previous studies it has already been observed that school classrooms are often poorly ventilated [3,4], and it became a very urgent problem to be further investigated in light of the ongoing pandemic.

In many countries, schools were closed during the periods of national COVID-19 lockdowns [5,6]. In the Netherlands, the first so-called “intelligent” lockdown started on March 15, 2020, and lasted until June 1, 2020. Then, on October 14, 2020, a “partly” lockdown began, which turned into the first lockdown on December 15, 2020 and lasted until March 1, 2021. During the “partly” lockdown, the pandemic control and prevention measures implemented in schools included opening the windows and doors for a lack of mechanical ventilation systems, and from December 1, 2020, wearing face masks became mandatory inside the school buildings, but not necessary during the lessons. During the first lockdown, schools were mostly closed (only used for exams and students with special needs). After the first lockdown, additional measures were introduced in schools: 1.5 m distance between students, and half occupancy of the classes (e.g., utilizing different school buildings, adjusting classroom floor areas, and alternating online/offline groups). Since June 2021 schools were fully reopened, yet soon later at the end of the summer of 2021 the COVID-19 cases increased, and measures were again introduced. From December 19, 2021 to January 10, 2022, the second lockdown became a fact. Finally, on March 23, 2022 all measures were stopped. Throughout the entire period schools were recommended to open windows and doors in the school classrooms in the absence of a mechanical ventilation system [7].

Indoor environmental quality (IEQ) and ventilation in school classrooms have been a focus of research for many years. Numerous studies all over the world have been performed to document the indoor environment in classrooms and to examine its relations with diseases, disorders and learning ability [8]. Several cross-sectional studies among European countries [9-12] have investigated IEQ and health of school children. In the US, several studies explored the relations between ventilation rates, attendance rates, and student performance (for example in [13-15]). Moreover, in a number of countries (such as Sweden [16], the Netherlands [17,18], the UK [19], Greece [20], Finland [21], Denmark [22], Portugal [23], Australia [24], Japan [25] and China [26]), health effects were assessed using self-administered questionnaires, combined with indoor environmental monitoring of several air pollutant concentrations as well as inspection of buildings with the use of a checklist and/or several physical measurements (e.g., temperature and relative humidity). The studies found several different shortcomings in the environmental conditions in classrooms, such as poor ventilation, noise, inadequate heating or lighting, already during non-pandemic periods.

To determine whether a space is ventilated properly, the indoor CO_2 concentration can be monitored and used as a proxy for ventilation performance [27]. To date, many studies have been conducted around the world to measure the CO_2 concentration in school classrooms and thus examine whether the ventilation performance fulfils the standards and guidelines [28-30]. A CO_2 concentration of 1000 ppm is often taken as the upper limit for a good IAQ according to the previous version of ASHRAE Standard 62.1, and has been also suggested as the upper limit for CO_2 monitoring to ensure sufficient ventilation in the REHVA COVID-19 Guidance, which is approximately equivalent to a ventilation rate of 10 L/s per person [31-33]. In the Netherlands, the Building Decree prescribes minimum ventilation rates expressed in L/s per person for educational buildings that existed before 2012 (3.4 L/s per person) and built after 2012 (8.5 L/s per person) [34]. Meanwhile, the Dutch Fresh Schools guidelines [35] - adapted from several commonly used international standards (e.g., EN 16798-1 [36] and ISO 7730 [37]) with more stringent requirements - has been enacted in particular for primary and secondary schools. In this guideline, the ventilation rate is suggested for three different levels: 12 L/s per person (level A, very good), 8.5 L/s per person (level B, good) and 6 L/s per person (level C, acceptable), for which the corresponding indoor CO_2 concentration is 400, 550, and 800 ppm above the outdoor level, respectively.

With the increased concern about the IEQ driven by the COVID-19 pandemic, researchers once again set off investigations among school classrooms within the past two year. In a study initiated by the Dutch National Ventilation Coordination Team (LCVS) before the second lockdown in which CO_2 monitors were placed in educational buildings, the results showed that only 38% of the tested schools (7340 elementary and secondary schools in the Netherlands) met the ventilation requirements of the Dutch Building Decree [38]. Furthermore, a third of the schools only had natural ventilation, where the fresh air supply in the classrooms was often inadequate. However, when keeping windows and doors opened became a major pandemic control and prevention protocol, especially for the naturally ventilated spaces, lower CO_2 concentrations and better ventilation have been observed among different types of educational buildings [39-41]. Nevertheless, in the meantime studies have also found that such measures for improving ventilation could cause negative impact on other aspects of IEQ for the students, such as thermal comfort and acoustics, according to both physical measurements and subjective assessments [42-44].

Ever since the “partly” lockdown took place, the same ventilation protocol of opening windows and doors has been implemented among the Dutch secondary schools. In addition, other measures such as reducing occupancy were also introduced after the first lockdown. What effects do these measures have on ventilation and the thermal conditions inside the classrooms are still unknown. Therefore, a field study was conducted among the secondary schools in the Netherlands to investigate 1) the ventilation sufficiency, 2) the ventilation-related effects of temporary school or governmental initiated pandemic control and prevention measures, and 3) the thermal conditions as a result of the implemented measures, in the classrooms under the COVID-19 pandemic.

3.2 Methods

3.2.1 Selection of schools and classrooms

Between October and December 2020, 20 secondary schools in different regions and cities of the Netherlands were enrolled on a voluntary basis, as reported in [45]. Among them, 11 schools which were visited both before and after the first lockdown (herein referred to as "the lockdown"), were included in this study (named from S1 to S11). The locations of the selected schools are shown in **Figure 3.1**, where eight of them are located in an urban area, and the other three in a rural area. These 11 schools cover different types of secondary education in the Netherlands, namely pre-university education, general secondary education, and pre-vocational secondary education, with students generally aged between 12 and 18.

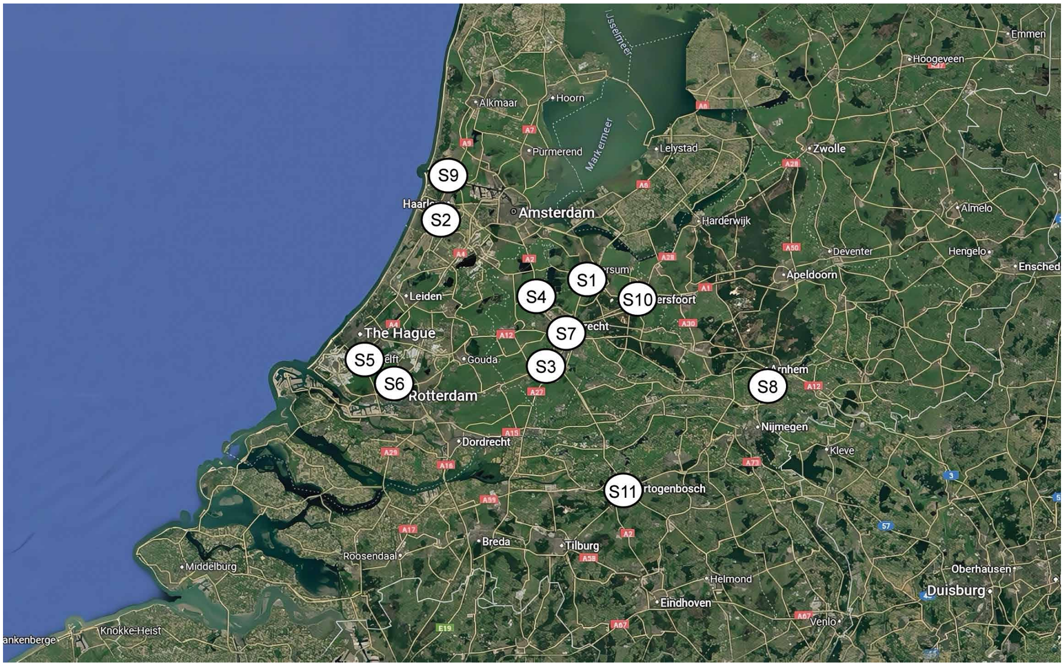


FIG. 3.1 Location of the involved secondary schools in the Netherlands.
Note: adapted from Google Maps, 2022.

The basic information on the 11 schools is listed in **Table 3.1**. The first school visits were all conducted during the heating season (October 20 to December 15, 2020), while for the second school visits, nine (S1-S9) were conducted during the heating season (March 11 to April 23, 2021), and the other two (S10 and S11) during the non-heating season (May 10 and June 3, 2021). Among the 11 schools, nine (82%) of them have classrooms with only natural ventilation (openable windows and doors), three (27%) have classrooms equipped with mechanical air supply, two (18%) have classrooms equipped with mechanical air exhaust, and nine (82%) have classrooms equipped with both mechanical air supply and exhaust. Only two schools (6%), S7 and S11, have a centralized ventilation system, with all the classrooms having the same mechanical air supply and exhaust equipment.

TABLE 3.1 Basic information on the selected schools.

School	Date of 1st visit (pre-lockdown)	Date of 2nd visit (post-lockdown)	Location	Year of construction[a]	Ventilation regime[b]
S1	20/10/2020	08/04/2021	Haarlem (Urban)	1975/1992/2006	NV, ME, MT
S2	21/10/2020	11/03/2021	Hilversum (Urban)	1952/2012	NV, MS, MT
S3	27/10/2020	13/04/2021	IJsselstein (Urban)	1970	NV, MT
S4	28/10/2020	25/03/2021	Breukelen (Rural)	1960/1999	NV, MT
S5	06/11/2020	26/03/2021	Delft (Urban)	1999	NV, MS
S6	12/11/2020	12/03/2021	Delft (Urban)	1965	NV, MT
S7	16/11/2020	23/04/2021	Utrecht (Urban)	1978	NV, MT
S8	26/11/2020	09/04/2021	Arnhem (Rural)	1983	NV, MT
S9	03/12/2020	16/04/2021	IJmuiden (Rural)	1931	NV, MT
S10	10/12/2020	10/05/2021	Amersfoort (Urban)	1960/1990/2013	NV, ME, MS
S11	15/12/2020	03/06/2021	’s-Hertogenbosch (Urban)	1953	NV, MT

a *Some schools have different buildings or different parts of the building complex that were built in different years.*
b *Ventilation regimes available in the school building(s). NV: natural ventilation; MS: only mechanical air supply; ME: only mechanical air exhaust; MT: both mechanical air supply and exhaust.*

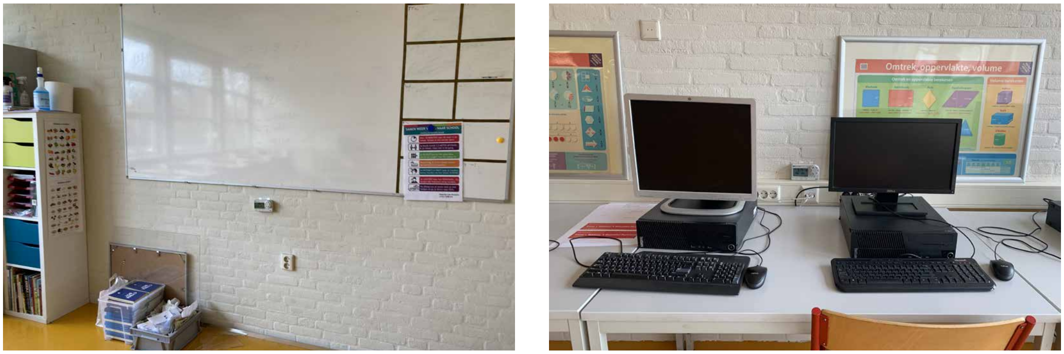
In each school, two to four classrooms were selected, based on the type of ventilation regimes operated. For natural ventilation, one or two classrooms at different orientations or floor levels were selected, while for balanced mechanical ventilation and hybrid ventilation (with only mechanical air supply or mechanical air exhaust), only one classroom was selected. In total, 36 classrooms (named from C1 to C36) were selected to perform the comparison between pre- and post-lockdown periods, of which three (C10, C15, C24) were practical classrooms (with practical settings for preparatory vocational courses of housekeeping and metalworking, etc.), and the rest were theoretical classrooms (with normal classroom settings of desks and chairs). During the post-lockdown period, C12, C23, and C36 were not in use, for which a similar classroom was chosen, as C12', C23', and C36', respectively. Meanwhile, C9 and C20 were used in combination with the adjacent classroom (doubled floor area and volume), and thus are marked as C9' and C20'.

3.2.2 Survey

The survey of the schools consisted of monitoring of the indoor and outdoor CO_2 concentration and air temperature, an interview with the facility manager, an inspection of the school buildings, HVAC (heating, ventilation and air conditioning) systems, and classrooms, and monitoring of the occupancy and occupants' behaviors. Each school visit started in the morning, and lasted for one school day.

3.2.2.1 Monitoring of CO_2 concentration and air temperature

The CO_2 concentration and air temperature were monitored indoors and outdoors, using HOBO® MX1102A loggers (CO_2 sensor: 0-5000 ppm/±50 ppm ±5% of reading; temperature sensor: 0-50 °C/±0.21 °C). In order to obtain a more accurate result of the indoor CO_2 concentration, two sampling points were selected in each classroom, namely on both the front and back walls at the height of the breathing zone of the sitting students (approximately 1.1-1.3 m), where the devices were installed on the walls using adhesive tapes [46]. The CO_2 concentration and air temperature inside the classrooms were continuously monitored and recorded during the school hours, with a time interval of 30 seconds. During the pre-lockdown period, the outdoor CO_2 concentration and air temperature were monitored at the entrance of the school building, both in the morning and in the afternoon, for 15 minutes. During the post-lockdown period, the outdoor CO_2 concentration and air temperature were monitored both at the entrance and in the courtyard (at least 5 m from the building façade in order to reduce the possible influence of indoor CO_2 concentration and human activities) of the school, for the whole school day. In **Figure 3.2** and **Figure 3.3** some examples of the location of the indoor and outdoor sampling points are presented, respectively.



a) b)

FIG. 3.2 Examples of indoor CO_2 concentration and air temperature sampling points in the classrooms: (a) front wall; (b) back wall.

a) b)

FIG. 3.3 Examples of outdoor CO_2 concentration and air temperature sampling points at the schools: (a) entrance; (b) courtyard.

3.2.2.2 Technical questionnaire and interview

Before each school visit, the school facility managers were asked to complete a technical questionnaire based on the characteristics of the school buildings, including the basic information on the building construction, the type of HVAC systems, and the maintenance of the facilities (**Appendix A.1**).

During each school visit, an inspection of the buildings and HVAC systems was made together with the facility manager(s). In addition, a short interview was conducted to ask the facility manager(s) about the COVID-19 measures implemented at the school, ventilation regimes used, occupancy, teaching schedule, and cleaning procedures (**Appendix A.2**).

3.2.2.3 Classroom checklist

The inspection of the selected classrooms was conducted based on a classroom checklist [18], which included items about indoor environmental settings, humidity problems, indoor climate characteristics, ventilation equipment, and indoor pollution sources (**Appendix A.3**). One checklist was completed for each classroom.

3.2.2.4 Monitoring of occupancy and ventilation-related behavior

The teachers giving lessons in the selected classrooms were asked to fill in an observation form for each lesson they taught, which included the time (duration) of the lesson, the number of students present, and their behaviors related to ventilation during the lesson (e.g., opening/closing windows/doors) (**Appendix A.4**). Such observations were also performed by the researchers once per lesson per classroom (**Appendix A.4**).

3.2.3 Ethical aspects

After the recruitment of the schools, the director of the school received a letter with a detailed procedure of the intended monitoring, measurements and observations, as well as the promise that no pictures with children would be made. For ethical approval there was a waiver from the ethics committee of the University of Utrecht, because it did not fall under the Act Research with Human Subjects.

3.2.4 Data analysis

3.2.4.1 Data cleaning

First, the measurement data of CO_2 and air temperature was extracted from the HOBOs and imported to IBM SPSS Statistics 26.0 (SPSS Inc. Chicago, IL, USA). Then the imported data was screened based on Z-scores, where all the data points with a Z-score (absolute value) higher than three were eliminated as outliers [47]. The information collected through the technical questionnaires, inspections, interviews, classroom checklists, and observational forms were manually screened and typed in IBM SPSS Statistics 26.0. All the subsequent statistical analyses were also performed with IBM SPSS Statistics 26.0.

It needs to be noted that for the data analyses, C7, C9 (C9'), C20 (C20'), C30 were excluded because they only had one occupied lesson during at least one of the school visits. C31 was excluded because the indoor CO_2 concentration was most of the time lower than the average outdoor level during the second school visit, which was considered a measurement error. Therefore, the results presented in this paper include 31 classrooms.

3.2.4.2 Time distribution of indoor CO_2 concentration and air temperature

Since the Dutch Fresh Schools guidelines [35] is mostly implemented for school buildings in the Netherlands, it is taken as the major reference for assessing ventilation and thermal conditions of the classrooms in this study. Accordingly, the indoor CO_2 concentration as an indicator of ventilation sufficiency is assessed based on three threshold levels, namely from low to high: level A (Very good), level B (Good), and level C (Acceptable), of which the indoor CO_2 concentration is less than 400 ppm, 550 ppm, and 800 ppm above the outdoor level, respectively. In other words, indoor CO_2 concentration exceeding level C is considered as not acceptable. Therefore, the indoor CO_2 concentration can be sorted into four categories, namely ≤ level A, > level A - ≤ level B, > level B - ≤ level C, and > level C. In this study, the outdoor CO_2 concentration for each school was represented by the average value of the outdoor data collected during each visit. The time distribution of indoor CO_2 concentration among the four categories during the total occupied time (excluding breaks and unoccupied lessons (number of students = 0)) was calculated for each classroom.

Similarly, three ranges of indoor air temperature (min - max) are also prescribed in the Fresh School 2021 guidelines, namely from narrow to wide: range A (Very good), range B (Good), and range C (Acceptable) [35]. The ranges applicable to the heating and non-heating season are different. For heating season the ranges are set as fixed values, where range A = 20-23 °C, range B = 19-24 °C, and range C = 18-25 °C. For non-heating season, the ranges are calculated based on equations (3.1) to (3.3) [35]:

For range A:

$$T_{in} = 0.33T_{RMOT} + 16.4 \pm 2 \quad (3.1)$$

For range B:

$$T_{in} = 0.33T_{RMOT} + 16.4 \pm 3 \quad (3.2)$$

For range C:

$$T_{in} = 0.33T_{RMOT} + 16.4 \pm 4 \quad (3.3)$$

Where:

- T_{in} is the required indoor air temperature [°C].
- T_{RMOT} is the running mean outdoor air temperature (RMOT) [°C]. In this study, due to the limitation of measurements, it is simplified as the average of all outdoor data collected during each school visit.

Although the ranges of required indoor air temperature changes with the outdoor air temperature during the non-heating season, a fixed upper limit is set at 25.5 °C, 26 °C, and 27 °C for range A, B, and C, respectively.

Accordingly, the indoor air temperature can be sorted into seven categories, namely $< C_{min}$, $\geq C_{min}$ - $< B_{min}$, $\geq B_{min}$ - $< A_{min}$, $\geq A_{min}$ - $\leq A_{max}$, $> A_{max}$ - $\leq B_{max}$, $> B_{max}$ - $\leq C_{max}$, and $> C_{max}$, where indoor air temperature lower than C_{min} or higher than C_{max} is considered as not acceptable. The time distribution of indoor air temperature among the seven categories during the total occupied time was then calculated for each classroom.

3.2.4.3 Ventilation rate

The ventilation rate in the classrooms was calculated using the steady-state method, based on the CO_2 concentrations monitored [28]. Based on a prior study [46], for every occupied lesson in the surveyed classrooms, a five-minute period was selected for the calculation, during which time the CO_2 concentration was relatively steady. It was assumed that no factors other than the occupancy and ventilation settings were affecting the CO_2 concentration in the classrooms, and thus the steady-state condition of the selected periods was verified using one-way ANOVA. The average CO_2 concentration among all the sampling points in one classroom during the five-minute period was determined as the steady-state CO_2 concentration. The ventilation rate (VR) per occupied lesson was then calculated according to equation (3.4) [28,48]:

$$VR = \frac{10^6 nG_p}{C_{steady} - C_{out}} \tag{3.4}$$

Where:

- n is the average number of students in the classroom during the lesson.
- G_p is the average CO_2 generation rate per person [L/s per person], which is estimated as 0.0045 L/s per person (16 L/h per person) for both students (12-18 years old) and teachers (30-40 years old) [49].
- $C_{CO_2,steady}$ is the steady-state CO_2 concentration [ppm].
- $C_{CO_2,out}$ is the outdoor CO_2 concentration [ppm], which is calculated as presented in **Section 3.2.4.2** for each school.

The ventilation rate (L/s) of each occupied lesson was then divided by the number of students and the floor area of the classroom, respectively, to calculate the ventilation rate per person (VR_p) (L/s/p) and per m^2 floor area (VR_a) (L/s/m^2).

3.2.4.4 Statistical analysis

The indoor CO_2 concentration and air temperature during the occupied lessons were compared between the pre- and post-lockdown periods using Mann-Whitney *U*-tests for each individual classroom. The percentages of time of 1) CO_2 concentration above the threshold level A, B, and C, 2) air temperature outside range A, B, and C, were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests at classroom level. The ventilation rates were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests also at classroom level. The outdoor CO_2 concentration and air temperature were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests at school level. The significance level was set at 0.05 ($P < 0.05$).

As the ventilation rates should be regarded as clustered by repeated measurements (school visits and occupied lessons) for each classroom, generalized estimating equations (GEE) analysis with linear function was used to study the association between VR_p and 1) student occupancy, 2) number of opened windows, 3) number of opened doors, and 4) pre- and post-lockdown visits [50,51]. Both the univariable analysis of each of the factors and the mutually adjusted multivariable analysis of all the factors were conducted. VR_p was chosen as the main dependent variable of the GEE model because it is the main parameter assessed in relevant standards and guidelines. Accordingly, the subject variable is “classroom ID”, and the within-subject variables are “visit” (pre- and post-lockdown) and “lesson” (occupied lessons). An independent correlation matrix was introduced to the model. The mutually adjusted multivariable regression model can be written as equation (3.5) [50-52]:

$$E(Y) = \beta_0 + \beta_1 occupancy + \beta_2 window + \beta_3 door + \beta_4 visit \tag{3.5}$$

Where:

- Y is the natural logarithm of VR_p per lesson of each classroom, $\ln(VR_p)$. The data of VR_p was transformed because its distribution was right-skewed. In the results, exponentiated beta’s are reported for VR_p.
- β_1 is the main effect of occupancy.
- occupancy is the number of students per lesson of each classroom.
- β_2 is the main effect of opening window(s).
- window is the number of opened windows per lesson of each classroom.
- β_3 is the main effect of opening door(s) compared to door(s) closed.
- door = 1 if the door was opened, 0 if the door was closed, during each lesson of each classroom.
- β_4 is the main effect of visit.
- visit = 1 if before lockdown, 2 if after lockdown.

3.3 Results

3.3.1 Overview of classrooms

The characteristics of the studied classrooms are listed in **Table 3.2**. Among these 31 classrooms, 15 (48%) only use natural ventilation, three (10%) have mechanical air supply, three (10%) have mechanical air exhaust, and 10 (32%) have both mechanical air supply and exhaust. All the classrooms have openable windows, where most of them are top-hung or side-hung windows, and can be opened up to an angle of 30°-45°. During the time when the survey was conducted, windows and doors were often kept opened during the occupied lessons in order to increase outdoor air supply and improve ventilation in the classrooms, as one of the COVID-19 pandemic control and prevention measures. Therefore, natural ventilation should also be considered in use inside many of the classrooms that have mechanical ventilation. The passive grilles available in the classrooms can also contribute to natural ventilation. For the mechanically ventilated classrooms, the air inlets and outlets are all located on the ceiling. With regards to heating, C7, C14, and C20 have floor heating, C35 and C36 have heated air supply, while all the other classrooms have hot water radiators.

TABLE 3.2 Characteristics of the 31 classrooms.

School	Classroom[ab]	Floor area [m^2]	Volume [m^3]	Ventilation regime available[c]	Presence of passive grilles[d]	Location of air inlet[e]	Location of air outlet[f]	Heating[g]
S1	C1	43	151	N	No	-	-	R
	C2	47	122	ME + N	No	-	Ceiling	R
	C3	62	186	MT + N	No	Ceiling	Ceiling	R
S2	C4	55	149	MT + N	No	Ceiling	Ceiling	R
	C5	53	148	N	Yes	-	-	R
	C6	53	148	N	Yes	-	-	R
S3	C8	55	165	N	No	-	-	R
	C10	88	264	N	Yes	-	-	R
S4	C11	59	142	N	No	-	-	R
	C12 (12')	59 (59)	189 (189)	N	No	-	-	R
	C13	64	198	MT + N	No	Ceiling	Ceiling	R
S5	C14	56	280	MS + N	Yes	Ceiling	-	F
	C15	308	893	MS + N	Yes	Ceiling	-	R
	C16	55	187	N	Yes	-	-	R
	C17	84	294	N	Yes	-	-	R
S6	C18	50	150	N	Yes	-	-	R
	C19	46	138	N	Yes	-	-	R
	C21	53	164	N	Yes	-	-	R
S7	C22	67	201	MT + N	No	Ceiling	Ceiling	R
	C23 (23')	56 (61)	168 (183)	MT + N	No	Ceiling	Ceiling	R
	C24	215	645	MT + N	No	Ceiling	Ceiling	R
S8	C25	52	156	N	Yes	-	-	R
	C26	53	159	MT + N	Yes	Ceiling	Ceiling	R
	C27	53	159	N	Yes	-	-	R
S9	C28	58	174	N	No	-	-	R
	C29	74	259	MT+N	No	Ceiling	Ceiling	R
S10	C32	48	163	ME + N	No	-	Ceiling	R
	C33	51	163	MS + N	No	Ceiling	-	R
	C34	100	280	ME + N	Yes	-	Ceiling	R
S11	C35	71	227	MT + N	No	Ceiling	Ceiling	A
	C36 (36')	54 (54)	173 (173)	MT + N	No	Ceiling	Ceiling	A

a *The numbers in the parentheses are the information on the substituting classrooms in the post-pandemic school visit.*
b *C7, C9 (C9'), C20 (C20'), C30, and C31 were excluded from the data analyses due to lack of data or invalid measurements.*
c *Ventilation regime(s) available in the classroom. N: natural ventilation; MS: only mechanical air supply; ME: only mechanical air exhaust; MT: both mechanical air supply and exhaust.*
d *All the passive ventilation grilles are located on the window(s).*
e *Location of the air inlet of the mechanical ventilation system.*
f *Location of the air outlet of the mechanical ventilation system.*
g *R: hot water radiator; F: floor heating; A: heated air supply.*

3.3.2 CO_2 concentrations

3.3.2.1 Indoor and outdoor CO_2 concentrations before and after lockdown

The indoor and outdoor CO_2 concentrations of the classrooms both before and after the lockdown during the occupied lessons are presented in **Figure 3.4**. The indoor CO_2 concentration varied a lot among the classrooms. Before the lockdown, the mean CO_2 concentration in the classrooms ranged from 458 to 1255 ppm, with an average of 825 ppm. The peak CO_2 concentration ranged from 515 to 2604 ppm, with an average of 1254 ppm. Besides, the mean difference of indoor and outdoor CO_2 concentration ranged from 35 to 1084 ppm, with an average of 371 ppm. After the lockdown, the mean CO_2 concentration in the classrooms ranged from 459 to 941 ppm, with an average of 654 ppm. The peak CO_2 concentration ranged from 507 to 1885 ppm, with an average of 903 ppm. The mean difference of indoor and outdoor CO_2 concentration ranged from 4 to 488 ppm, with an average of 216 ppm. For the comparison between pre- and post-lockdown periods, the P values of the Mann-Whitney *U*-tests are marked in **Figure 3.4** for the classrooms. In 24 (77%) of the 31 classrooms the indoor CO_2 concentration during the pre-lockdown period was significantly higher than the post-lockdown period, while in five (16%) classrooms the indoor CO_2 concentration was significantly lower during the pre-lockdown period than the post-lockdown period. In the other two classrooms, the indoor CO_2 concentration showed no significant difference between the pre- and post-lockdown periods.

In addition, the outdoor CO_2 concentration varied considerably, with both time and location. Before the lockdown, the mean outdoor CO_2 concentration ranged from 261 to 450 ppm among the 11 schools, with an average of 371 ppm, while after the lockdown it ranged from 292 to 462 ppm, with an average of 426 ppm. According to the Wilcoxon signed-rank tests, the outdoor CO_2 concentrations were significantly higher during the post-lockdown period than during the pre-lockdown period (P = 0.026) (**Table 3.3**). Interestingly, the schools with a lower outdoor CO_2 concentration are not necessarily located in the rural area, and vice versa. For instance, before the lockdown, S6 and S9 had an average outdoor CO_2 concentration lower than 300 ppm, while after the lockdown it increased above 450 ppm at both locations.

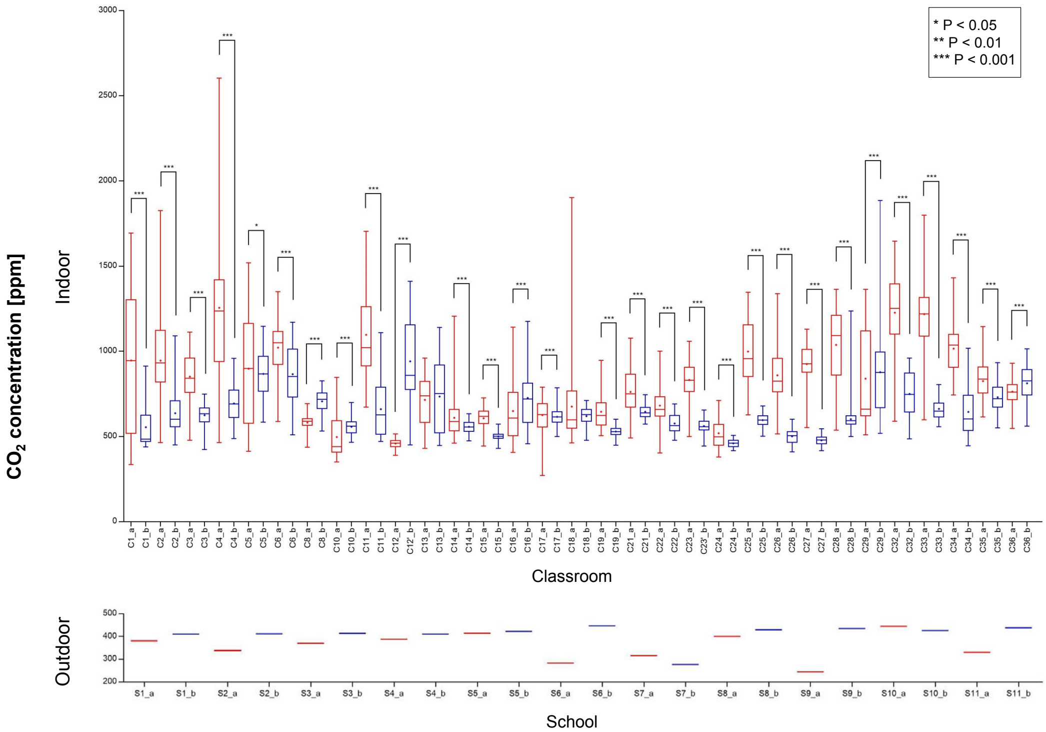


FIG. 3.4 Indoor and outdoor CO_2 concentrations.

Note: a: pre-lockdown period (marked as red); b: post-lockdown period (marked as blue). Above: box and whiskers plot of indoor CO_2 concentration inside the classrooms (P: Mann-Whitney U-tests between pre- and post-lockdown periods); Below: average outdoor CO_2 concentrations at each school.

TABLE 3.3 Comparison of different parameters of CO_2 concertation, occupancy, ventilation rate, and air temperature in 31 classrooms (11 schools) between pre- and post-lockdown period.

Parameter		Pre-lockdown	Post-lockdown	P[a]
CO_2	Outdoor mean (min-max)[b] [ppm]	371 (261-450)	426 (292-462)	**0.026**
	Indoor mean (min-max) [ppm]	825 (458-1255)	654 (459-941)	**< 0.001**
	Indoor - outdoor mean (min-max) [ppm]	470 (35-1084)	216 (4-488)	**< 0.001**
	Mean percentage of time > level A [%]	52	14	**< 0.001**
	Percentage of classrooms all time < level A [%]	16	42	
	Mean percentage of time > level B [%]	32	5	**< 0.001**
	Percentage of classrooms all time < level B [%]	23	68	
	Mean percentage of time > level C [%]	12	1	**0.003**
	Percentage of classrooms all time < level C [%]	58	90	
Occupancy	Number of students in the classroom mean (min-max) [persons]	17 (7-29)	10 (5-21)	**< 0.001**
Ventilation rate	VR mean (min-max) [L/s]	270.2 (66.6-1931.9)	271.3 (71.0-1116.7)	0.302
	VR_a mean (min-max) [L/s/m²]	3.5 (0.9-12.8)	4.6 (1.0-21.1)	0.251
	VR_p mean (min-max) [L/s/p]	21.8 (4.6-241.5)	32.5 (7.4-155.8)	**0.005**
	Percentage of classrooms with mean VR_p < 6 L/s/p (level C) [%]	13	0	
	Percentage of classrooms with mean VR_p < 8.5 L/s/p (level B)[c] [%]	45	6	
	Percentage of classrooms with mean VR_p < 10 L/s/p[d] [%]	45	6	
	Percentage of classrooms with mean VR_p < 12 L/s/p (level A) [%]	65	13	

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TABLE 3.3 Comparison of different parameters of CO_2 concertation, occupancy, ventilation rate, and air temperature in 31 classrooms (11 schools) between pre- and post-lockdown period.

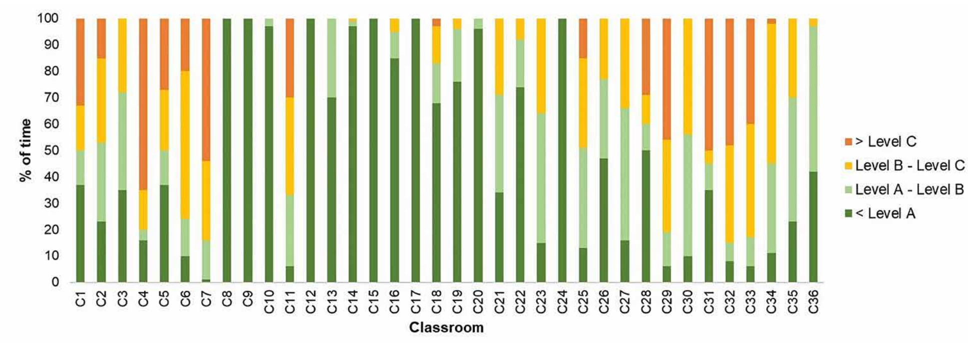
Parameter		Pre-lockdown	Post-lockdown	P[a]
Temperature	Outdoor mean (min-max) [°C]	13.7 (8.6-17.4)	15.5 (8.8-27.5)	**0.021**
	Indoor mean (min-max) [°C]	20.4 (17.3-23.9)	20.9 (17.8-24.4)	0.092
	Indoor - outdoor mean (min-max) [°C]	6.6 (1.6-11.4)	6.2 (-3.5-12.5)	0.784
	Mean percentage of time outside range A [%]	50	34	0.052
	Percentage of classrooms all time inside range A [%]	6	16	
	Mean percentage of time outside range B [%]	22	15	0.140
	Percentage of classrooms all time inside range B [%]	45	45	
	Mean percentage of time outside range C [%]	10	6	0.794
	Percentage of classrooms all time inside range C [%]	68	58	

a Wilcoxon signed-rank test for two groups of 11 schools (outdoor) or 31 classrooms (indoor). Bold values denote $P < 0.05$.
b Mean, Min, and Max value of the means per school (outdoor) or per classroom (indoor).
c 8.5 L/s/p is also the minimum ventilation rate required by the Dutch Building Decree [34].
d 10 L/s/p is suggested by different standards and guidelines [33].

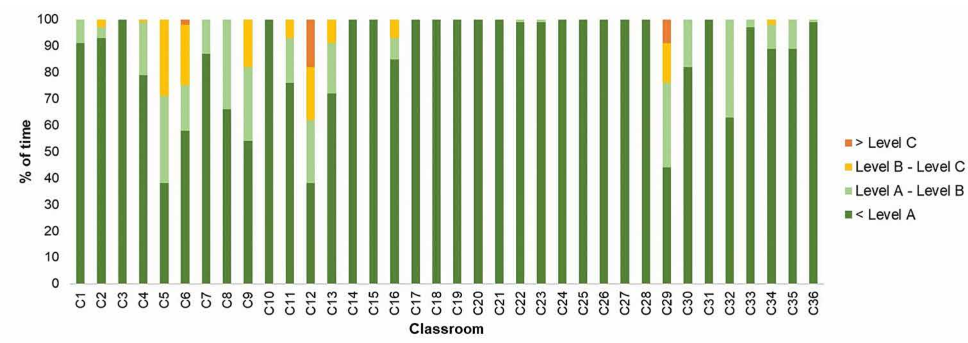
3.3.2.2 Time distribution of indoor CO_2 concentrations

The percentages of time when the CO_2 concentration inside the classrooms fell into the four categories of the Dutch Fresh Schools guidelines are presented in **Figure 3.5**. During the pre-lockdown period, on the one hand 13 (42%) of the 31 classrooms had the CO_2 concentration sometimes above level C, with C4 being the highest (65% of time > level C). On the other hand, 18 (58%) classrooms had the CO_2 concentration always (100% of the time) below level C, and nine (25%) and six (17%) classrooms always below level B and A, respectively. During the post-lockdown period, the number of classrooms having CO_2 concentration sometimes above level C decreased to 3 (8%), with C12 being the highest (18% of time > level C). Moreover, the number of classrooms that had CO_2 concentration always below level C, B, and A had increased to 28 (90%), 21 (68%) and 13 (42%), respectively. On average, before the lockdown in 52%, 32% and 12% of the occupied time the indoor CO_2 concentration was above level A, B, and C, respectively, while after the lockdown the percentages of time decreased to 14%, 5%, and 1%, respectively.

According to the Wilcoxon signed-rank tests (**Table 3.3**), the percentages of time when the indoor CO_2 concentration exceeded level A, B, and C were significantly higher during the pre-lockdown period than that during the post-lockdown period, where for both level A and B, $P < 0.001$, and for level C, $P = 0.003$.



a)



b)

FIG. 3.5 Time distributions of CO_2 concentration during occupied lessons in the classrooms among different categories of Dutch Fresh Schools guidelines: (a) pre-lockdown; (b) post-lockdown.

3.3.3 Ventilation rates

The numbers of opened windows and doors, number of students, and calculated ventilation rates of the classrooms during the occupied lessons before and after the lockdown are presented in **Table 3.4**. During the pre-lockdown period, the mean VR ranged from 66.6 L/s (C28) to 1931.9 L/s (C10) among the classrooms, with an average of 270.2 L/s. The mean VR_p ranged from 4.6 L/s/p (C1) to 241.5 L/s/p (C10), with an average of 21.8 L/s/p. The mean VR_a ranged from 0.9 L/s/m^2 (C28) to 12.8 L/s/m^2 (C12), with an average of 3.5 L/s/m^2.

During the post-lockdown period, the mean VR ranged from 71.0 L/s (C32) to 1116.7 L/s (C27), with an average of 271.3 L/s. The mean VR_p ranged from 7.4 L/s/p (C13) to 155.8 L/s/p (C27), with an average of 32.5 L/s/p. The mean VR_a ranged from 1.0 L/s/m^2 (C24) to 25.3 L/s/m^2 (C20), with an average of 4.9 L/s/m^2. According to the results of the Wilcoxon signed-rank tests (**Table 3.3**), for VR, $P = 0.302$, for VR_p, $P = 0.005$, and for VR_a, $P = 0.251$.

The number of students during the occupied lessons ranged from 7 (C36) to 29 (C19), with an average of 17. The number of students during the occupied lessons ranged from 5 (C32) to 21 (C12' and C13), with an average of 10. Except for a decrease in occupancy in most of the classrooms, it maintained the same in three (10%) classrooms, and increased in one (3%) classroom. Overall, the numbers of students were significantly higher during the pre-lockdown period than those of the post-lockdown period according to the Wilcoxon signed-rank tests (**Table 3.3**), where $P < 0.001$.

Moreover, during the pre-lockdown period, 28 (90%) of the 31 classrooms had at least one window continuously opened during the occupied lessons, and 18 (58%) had the door opened, while during the post-lockdown period 24 (77%) classrooms had at least one window continuously opened during the occupied lessons, and 20 (65%) had the door opened.

TABLE 3.4 Ventilation rates, number of students, and number of opened windows and doors in the classrooms before and after the lockdown.

School	Classroom	Pre-lockdown [Mean (SD)][a]						Post-lockdown [Mean (SD)]					
		Number of opened windows	Number of opened doors	Number of students	VR [L/s]	VR_p [L/s/p]	VR_a [L/s/m²]	Number of opened windows	Number of opened doors	Number of students	VR [L/s]	VR_p [L/s/p]	VR_a [L/s/m²]
S1	C1	1 (0)	0 (1)	21 (4)	95.8 (22.4)	4.6 (0.5)	2.2 (0.5)	1 (1)	1 (1)	10 (1)	418.0 (432.3)	41.3 (43.9)	9.7 (10.1)
	C2	4 (0)	1 (1)	17 (6)	167.8 (20.7)	10.9 (5.7)	3.6 (0.5)	2 (3)	1 (1)	9 (5)	118.6 (39.6)	17.7 (13.5)	2.5 (0.8)
	C3	0 (0)	0 (0)	18 (5)	176.2 (26.4)	10.7 (4.7)	2.8 (0.4)	0 (0)	0 (0)	14 (2)	283.5 (72.0)	19.9 (4.0)	4.6 (1.2)
S2	C4	1 (0)	0 (1)	15 (10)	82.9 (22.2)	7.8 (5.2)	1.5 (0.4)	2 (1)	1 (0)	11 (4)	221.7 (165.2)	18.2 (9.2)	4.0 (3.0)
	C5	2 (0)	1 (1)	24 (1)	211.4 (227.6)	8.4 (8.6)	4.0 (4.3)	1 (1)	1 (0)	14 (2)	146.2 (45.0)	10.4 (2.6)	2.8 (0.8)
	C6	1 (1)	1 (0)	14 (8)	101.6 (47.0)	7.9 (3.8)	1.9 (0.9)	1 (1)	1 (0)	13 (1)	182.7 (101.4)	14.5 (10.0)	3.4 (1.9)
S3	C8	2 (0)	1 (0)	11 (6)	327.9 (349.8)	35.0 (31.8)	6.0 (2.7)	0 (0)	1 (0)	6 (0)	108.1 (48.0)	18.0 (8.0)	1.9 (0.9)
	C10	1 (0)	1 (0)	8 (0)	1931.9 (2798.3)	241.5 (39.2)	22.0 (3.6)	2 (0)	1 (0)	6 (0)	233.5 (11.2)	38.9 (18.7)	2.7 (1.3)
S4	C11	2 (0)	0 (1)	18 (8)	108.7 (39.8)	6.5 (2.0)	1.8 (0.7)	1 (1)	1 (1)	13 (1)	128.9 (26.2)	10.2 (1.8)	2.2 (0.4)
	C12 (12')	6 (0)	1 (0)	13 (4)	752.9 (566.2)	64.1 (38.9)	12.8 (9.6)	3 (0)	0 (0)	21 (1)	166.1 (51.5)	8.1 (2.6)	2.8 (0.9)
	C13	3 (1)	1 (1)	21 (4)	427.9 (452.8)	23.1 (27.8)	6.7 (7.1)	2 (0)	1 (1)	21 (2)	150.0 (9.4)	7.4 (1.2)	2.3 (0.1)
S5	C14	2 (0)	1 (1)	11 (5)	255.8 (114.1)	26.2 (11.7)	4.6 (2.0)	2 (0)	0 (0)	7 (1)	273.3 (69.8)	41.7 (6.2)	4.9 (1.2)
	C15	2 (0)	1 (1)	13 (2)	279.5 (77.8)	21.8 (3.3)	0.9 (0.3)	0 (0)	0 (0)	6 (0)	463.1 (104.2)	77.2 (17.4)	1.5 (0.3)
	C16	5 (2)	0 (0)	19 (9)	414.4 (336.1)	27.9 (21.7)	7.5 (6.6)	5 (1)	0 (0)	9 (3)	135.7 (7.0)	17.1 (6.2)	2.5 (0.1)
	C17	4 (0)	1 (0)	14 (7)	290.1 (82.4)	23.8 (10.8)	3.5 (1.0)	4 (0)	1 (0)	6 (1)	171.5 (31.4)	27.1 (4.6)	2.0 (0.4)
S6	C18	1 (0)	1 (0)	15 (8)	157.4 (120.0)	10.8 (6.7)	3.2 (2.4)	0 (0)	1 (0)	9 (2)	300.6 (34.0)	36.0 (5.0)	6.0 (0.7)
	C19	2 (0)	1 (0)	29 (1)	435.9 (81.6)	15.1 (3.3)	9.5 (1.8)	1 (1)	1 (0)	13 (3)	829.2 (180.3)	70.3 (38.8)	18.0 (3.9)
	C21	3 (0)	1 (0)	23 (5)	271.8 (56.3)	12.5 (4.6)	5.1 (1.1)	2 (1)	1 (0)	11 (2)	256.6 (46.2)	23.1 (2.7)	4.8 (0.9)

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TABLE 3.4 Ventilation rates, number of students, and number of opened windows and doors in the classrooms before and after the lockdown.

School	Class-room	Pre-lockdown [Mean (SD)][a]						Post-lockdown [Mean (SD)]					
		Number of opened windows	Number of opened doors	Number of students	VR [L/s]	VR_p [L/s/p]	VR_a [L/s/m^2]	Number of opened windows	Number of opened doors	Number of students	VR [L/s]	VR_p [L/s/p]	VR_a [L/s/m^2]
S7	C22	4 (1)	0 (0)	20 (2)	215.6 (47.4)	11.3 (3.3)	3.2 (0.7)	2 (1)	0 (0)	8 (1)	123.8 (17.8)	14.8 (1.7)	1.8 (0.3)
	C23 (23')	3 (1)	0 (0)	14 (2)	114.0 (4.5)	8.0 (1.1)	2.0 (0.1)	2 (0)	0 (0)	11 (1)	165.9 (13.6)	15.7 (1.2)	2.8 (0.2)
	C24	1 (0)	0 (0)	17 (5)	367.4 (59.2)	23.3 (5.5)	1.7 (0.3)	0 (0)	1 (1)	8 (1)	211.2 (3.8)	27.6 (1.7)	1.0 (0.0)
S8	C25	3 (1)	1 (1)	17 (6)	115.1 (18.3)	7.6 (2.2)	2.2 (0.4)	3 (1)	1 (1)	6 (2)	150.4 (60.6)	27.6 (7.3)	2.9 (1.2)
	C26	2 (1)	0 (1)	17 (4)	179.1 (24.1)	10.8 (2.7)	3.4 (0.5)	1 (1)	1 (0)	7 (3)	554.3 (309.1)	83.9 (39.1)	10.5 (5.8)
	C27	4 (0)	1 (0)	15 (4)	116.1 (11.3)	8.1 (0.9)	2.2 (0.3)	0 (0)	0 (0)	7 (2)	1116.7 (768.5)	155.8 (80.6)	21.1 (14.5)
S9	C28	1 (0)	1 (0)	10 (2)	66.6 (16.7)	6.9 (0.4)	0.9 (0.2)	0 (1)	1 (0)	10 (1)	381.4 (456.8)	35.7 (41.0)	5.2 (6.2)
	C29	2 (1)	0 (1)	19 (6)	92.7 (16.5)	5.3 (1.2)	1.6 (0.3)	2 (1)	1 (0)	10 (1)	341.7 (66.2)	33.0 (7.0)	5.9 (1.1)
S10	C32	2 (0)	0 (0)	23 (2)	114.2 (6.8)	5.0 (0.5)	2.4 (0.1)	2 (1)	1 (1)	5 (4)	71.0 (3.2)	21.8 (17.8)	1.5 (0.1)
	C33	3 (1)	1 (1)	26 (2)	131.4 (30.0)	5.0 (1.0)	2.6 (0.6)	3 (0)	0 (0)	6 (1)	98.5 (45.5)	17.5 (6.0)	1.9 (0.9)
	C34	2 (0)	0 (0)	27 (5)	199.6 (42.8)	7.5 (0.9)	2.0 (0.4)	3 (0)	1 (0)	11 (4)	280.8 (125.1)	29.1 (19.9)	2.8 (1.3)
S11	C35	0 (0)	0 (0)	13 (6)	104.2 (11.1)	8.3 (1.3)	1.5 (0.2)	1 (1)	0 (0)	7 (2)	111.4 (32.2)	15.7 (2.9)	1.6 (0.5)
	C36 (36')	0 (0)	1 (1)	7 (1)	71.2 (8.8)	11.0 (0.5)	1.3 (0.2)	1 (0)	0 (1)	7 (1)	216.1 (204.8)	32.2 (28.4)	4.0 (3.8)

a *Mean (SD) of the ventilation rates, number of students, and numbers of opened windows and doors during the occupied lessons in the classrooms.*

The results of the GEE analysis are listed in **Table 3.5**. VR_p was significantly associated with the student occupancy in the classrooms ($P < 0.001$) and the visit ($P < 0.001$) according to the univariable analysis. The difference in VR_p between pre- and post-lockdown visits was no longer significant after adjusting for student occupancy and opening of doors and windows, suggesting that the difference between pre- and post-lockdown visits was mainly due to the change in occupancy. Besides, the numbers of opened windows and doors were not significantly associated to VR_p according to both the univariable and multivariable analyses. The association between VR_p and student occupancy remained significant after adjustment, with an estimated exponentiated β of 0.938 (95% CI: 0.915-0.963), meaning on average VR_p is multiplied by 0.938 per one student occupancy increase in the classrooms.

TABLE 3.5 Univariable and multivariable associations between VR_p and occupancy, opening of windows and doors in the classrooms, and visits (pre- versus post-lockdown).

Variable	Univariable			Multivariable		
	Exp(β)	95% Wald CI (lower, upper)	P	Exp(β)	95% Wald CI (lower, upper)	P
Occupancy	0.934	0.919, 0.951	< 0.001	0.938	0.915, 0.963	< 0.001
Window	1.022	0.925, 1.130	0.688	1.081	0.994, 1.176	0.068
Door	1.302	0.909, 1.865	0.149	1.218	0.881, 1.684	0.234
Visit	1.925	1.409, 2.633	< 0.001	1.302	0.928, 1.827	0.126

3.3.4 Temperatures

3.3.4.1 Indoor and outdoor air temperatures before and after lockdown

The indoor and outdoor air temperatures of the classrooms both before and after the lockdown during the occupied lessons are shown in **Figure 3.6**. Similar to the CO_2 concentration, the indoor air temperature in the classrooms varied considerably. Before the lockdown, the mean air temperature in the classrooms ranged from 17.3 °C (C8) to 23.9 °C (C17), with an average of 20.4 °C. The lowest and highest air temperature measured in the classrooms was 16.1 °C (C8) and 24.8 °C (C17), respectively. Besides, the mean indoor-outdoor temperature differences ranged from 1.6 (C24) to 11.4 °C (C34), with an average of 6.6 °C. After the lockdown, the average air temperature in the classrooms ranged from 17.8 °C (C1) to 24.4 °C (C36), with an average of 20.9 °C. The lowest and highest air temperature measured in the classrooms was 15.4 °C (C4) and 27.1 °C (C22), respectively. The mean indoor-outdoor temperature differences ranged from -3.5 (C36) to 12.5 °C (C7), with an average of 6.2 °C. Three classrooms had indoor air temperature lower than the outdoor level, of which two (C8 and C10) were visited in the heating season (April 2021), and one (C36) in the non-heating season (June 2021).

For the comparison between pre- and post-lockdown periods, the P-values of the Mann-Whitney *U*-tests are marked in **Figure 3.6** for the classrooms. In 19 (61%) classrooms, the indoor air temperature during the pre-lockdown period was significantly lower than the post-lockdown period, while in the other 12 (39%) classrooms the indoor air temperature was significantly higher during the pre-lockdown period than the post-lockdown period.

The outdoor air temperature also varied a lot throughout the two school visits. Before the lockdown, the mean outdoor air temperature ranged from 8.6 to 17.4 °C among the 11 schools, with an average of 13.7 °C, while after the lockdown it ranged from 8.8 to 27.5 °C, with an average of 15.5 °C. According to the Wilcoxon signed-rank tests (**Table 3.3**), the outdoor air temperatures were significantly higher during the post-lockdown period than during the pre-lockdown period (P = 0.021).

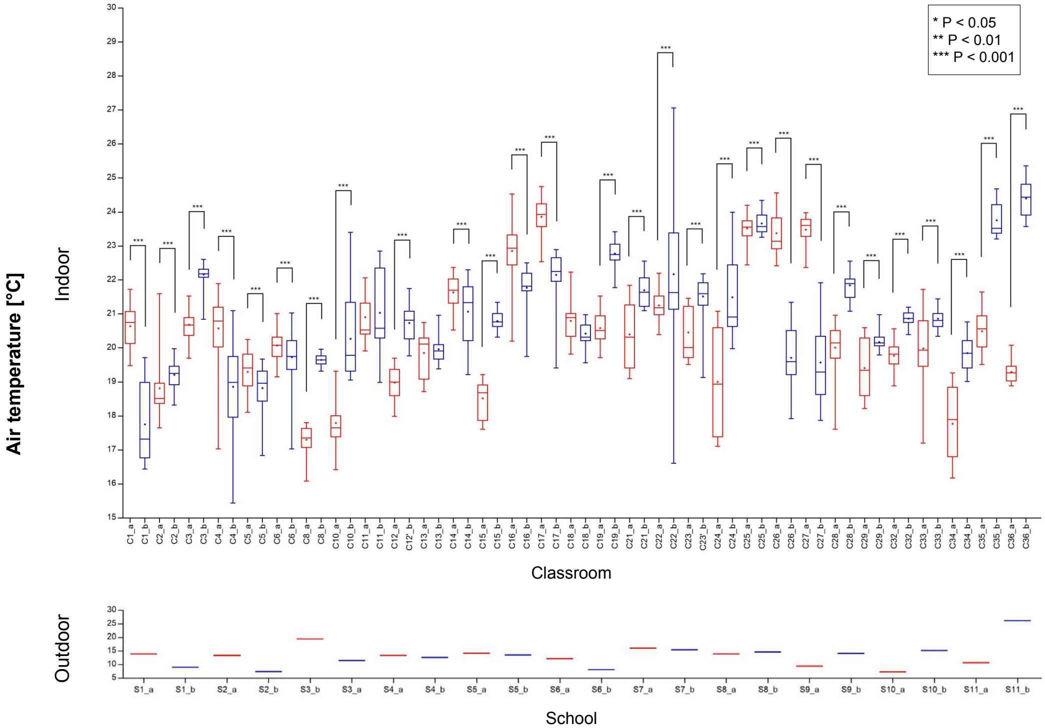


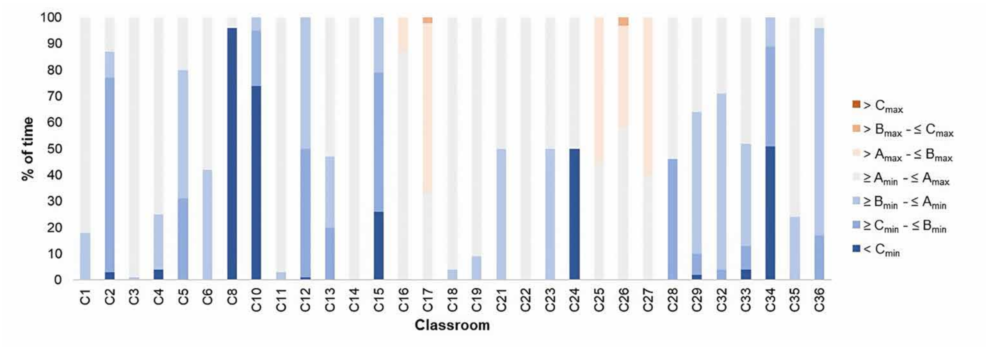
FIG. 3.6 Indoor and outdoor air temperatures.

Note: a: pre-lockdown period; b: post-lockdown period. Above: box and whiskers plot of indoor air temperature inside the classrooms (P: Mann-Whitney U-tests between pre- and post-lockdown periods); Below: average outdoor air temperatures at each school.

3.3.4.2 Time distribution of indoor air temperatures

The percentages of time when the air temperature inside the classrooms fell into the seven ranges of the Dutch Fresh Schools guidelines are presented in **Figure 3.7**. During the pre-lockdown period, the air temperature in 25 (81%) classrooms was sometimes lower than A_{min}, while in 10 (32%) classrooms the air temperature was sometimes even lower than C_{min}, with C8 being the coldest (96% of time < C_{min}). Still, 68%, 45%, and 6% of the classrooms had the air temperature always within range C, B, and A, respectively. During the post-lockdown period, on the one hand, the air temperature was still sometimes lower than A_{min} in 23 (74%) classrooms, and 11 (35%) of them had the air temperature lower than C_{min}. While on the other hand, with the outdoor temperature increased with the seasons, more classrooms had the air temperature exceeded the upper limit of the threshold ranges, particularly in those visited during the non-heating season, where three (10%) of them had the air temperature sometimes higher than C_{max}.

On average, before the lockdown in 50%, 22%, and 10% of the occupied time the indoor air temperature fell outside range A, B, and C, respectively, while after the lockdown the percentages of time decreased to 34%, 15%, and 6%, respectively. However, according to the Wilcoxon signed-rank tests (**Table 3.3**), no significant difference was found in the mean percentages of time between the pre- and post-lockdown periods, with P-values of 0.052, 0.140, and 0.794, for ranges A, B, and C, respectively.



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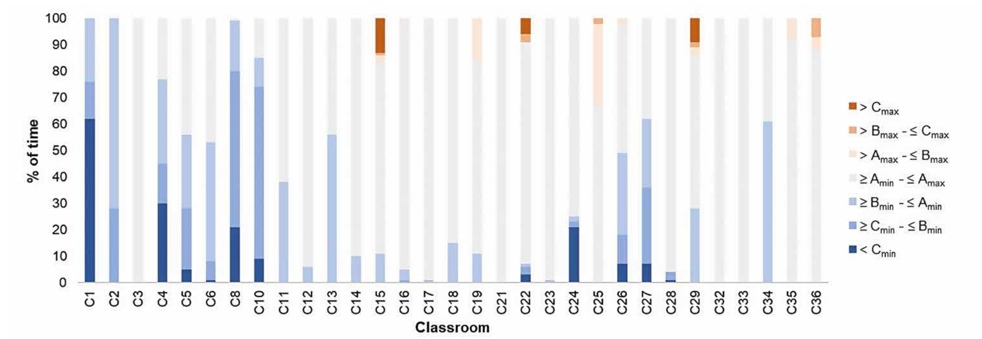

b)

FIG. 3.7 Time distributions of indoor air temperatures during occupied lessons in the classrooms among different categories of Dutch Fresh Schools guidelines: (a) pre-lockdown; (b) post-lockdown.

3.4 Discussion

3.4.1 CO_2 concentrations and ventilation rates in school classrooms

During the pre-lockdown period, the outdoor CO_2 concentration varied considerably among the schools, with an average of 371 ppm and a range of 261-450 ppm. The classrooms were used with normal occupancy (7 to 29 students, mean 17 students) and with windows and doors opened. The average indoor CO_2 concentration spanned a range (458 to 1255 ppm) similar to several recent field studies [39,43,53], but lower than those measured in studies conducted during the previously non-pandemic era (600 to 2500 ppm) [4].

The indoor CO_2 concentration in the classrooms was on average more than 50% of the occupied time higher than level A of the Dutch Fresh Schools guidelines (400 ppm above outdoor level), which is the warning level suggested by the REHVA COVID-19 Guidance [32]. Also, on average over 30% of the time the indoor CO_2 concentration was higher than level B (550 ppm above outdoor level), which is approximately equal to the widely accepted threshold level of 1000 ppm [33]. Moreover, for an average of 12% of the time the indoor CO_2 concentration was higher than level C (800 ppm above outdoor level), which is the upper limit and considered not acceptable. In fact, 58% of the classrooms were able to keep the indoor CO_2 concentration all time below level C, while only one sixth of them had it always below level A, indicating periods of insufficient ventilation occurred in many classrooms even with windows and doors opened.

Before the lockdown, the average VR_p in the classrooms (4.6 to 64.1 L/s/p) was higher than the results reported in a number of recent studies (0.8 to 12.0 L/s/p) [53-55], yet for 13%, 45%, and 65% of the classrooms the average VR_p did not fulfill the level C, B, and A of the Dutch Fresh Schools guidelines, respectively. It should be noted that level B corresponds with the minimum requirement of the Dutch Building Decree (8.5 L/s/p) (**Table 3.3**). Furthermore, according to a number of studies and guidelines [33,56], a minimum ventilation rate of 10 L/s/p is recommended for a good indoor air quality. In the present study, however, 45% of the classrooms had an average VR_p lower than 10 L/s/p (**Table 3.3**).

Compared to the pre-lockdown period, the post-lockdown outdoor CO_2 concentration among the schools was significantly higher, with an average of 426 ppm and a range of 292-462 ppm. The number of occupants in the classrooms was significantly decreased (5 to 21 students, mean 10 students) in order to keep 1.5 m distance between the students. While not much changes were observed in the operation of windows and doors, a significant decrease was found in both the indoor CO_2 concentration (459 to 941 ppm) and the percentage of time the indoor CO_2 concentration was above level A (14%), B (5%), and C (1%), respectively (**Table 3.3**).

While no significant difference was found in both VR and VR_a, VR_p increased significantly after the lockdown (from an average of 15.3 L/s/p to 32.5 L/s/p). After the lockdown, VR_p in all the classrooms fulfilled the minimum requirement of the Dutch Fresh Schools guidelines (level C), 94% fulfilled the requirement of the Dutch Building Decree (level B), and 87% fulfilled level A (**Table 3.3**). Moreover, 94% of the classrooms had a VR_p higher than the recommended 10 L/s/p. Such results, however, were mostly due to the decrease in student occupancy, which was confirmed by the GEE analysis as only the occupancy showed a significant effect on VR_p (T**able 3.5**). In other words, the significant increase in VR_p during the post-lockdown period compared to the pre-lockdown period resulted mainly from the reduction in occupancy, and was not dependent on the operation of windows and doors.

3.4.2 Thermal conditions in school classrooms

Before the lockdown, all the school visits were conducted during the heating season. The outdoor air temperature varied with 8.8 °C and had an average of 13.7 °C. The indoor air temperature in the classrooms ranged from 17.3 to 23.9 °C, which was cooler than those measured in the schools located in the same climate zone during the heating season before the COVID-19 pandemic (19.0 to 26.0 °C) [18,57,58]. As shown in **Figure 3.7(a)**, according to the Dutch Fresh Schools guidelines, more than 80% of the classrooms had an indoor air temperature lower than the “very good” range (range A), while over 30% of them had an indoor air temperature lower than range C. In fact, on average, during 50% of the time the indoor air temperature in the classrooms fell outside range A, and 10% of the time fell outside range C. Only 68% and 6% of the classrooms maintained the indoor air temperature always within range C and range A, respectively (**Table 3.3**). It is hence clear that during the pre-lockdown period the indoor air temperature was on the cold side, and the thermal conditions in the classrooms were not satisfying, possibly causing discomfort to the students and the teachers. Using the adaptive model of thermal comfort prescribed in the ASHRAE 55 standard [59] to assess the average air temperature in the classrooms, it is shown that before the lockdown, five of the 31 (16%) classrooms did not comply with the 80% acceptability limits, and nine (29%) did not comply with the 90% acceptability limits, where all of them were too cool. However, during the school visits it was often observed that students were wearing their jackets inside the classrooms, indicating that their actual thermal sensation may be cooler compared to the model if they wear normal indoor clothes.

Comparing the outdoor air temperature measured during the post-lockdown period with the pre-lockdown period, a significant increase was observed among the schools (**Table 3.3**). However, no significant difference was found in the indoor air temperature before and after the lockdown. Nevertheless, a decrease in the average time of indoor air temperature outside the ranges A, B, and C of the Dutch Fresh Schools guidelines was observed (**Table 3.3**). Although the percentage of classrooms with indoor air temperature all the time fulfilling range A increased by 10%, for range B the number did not change, and for range C it decreased by 10%. Moreover, after the lockdown, not only there were more than 30% of the classrooms with an indoor air temperature colder than the lower limit of range C, but also 10% of them had it warmer than the upper limit of range C, both indicating negative impacts on occupants' thermal comfort. The variations in the indoor air temperature were possibly affected by the outdoor environment. According to the ASHRAE 55 adaptive thermal comfort model [59], three (10%) classrooms did not comply with the 80% acceptability limits, and eight (26%) did not comply the 90% acceptability limits.

In general, keeping the windows and doors opened on the one hand helped increasing outdoor air supply compared to the pre-pandemic era [4], yet on the other hand also harmed the thermal conditions for the students, in particular during the heating season. If the schools had been open in the winter, during which outdoor air temperatures can be much lower than the ones that were measured in this study, the temperature indoors would have been even colder assuming the same measures were taken. Such thermal comfort related problems resulted from improving ventilation by means of increasing opening windows and doors have been extensively reported by recent field studies, both before and during the COVID-19 pandemic [41,60,61].

3.4.3 Limitations

First, the results are limited because in this study almost all the school visits were conducted during a part of the heating season, and thus the situation in both the lockdown period (during the winter time) and the non-heating season were rarely represented. Also, each school visit only lasted for one day, and therefore, not all possible occupancies and behaviors in the classrooms were included in the study. This can have affected the results of the indoor environmental measurements. In particular, the ventilation rates that can be reached with mechanical ventilation (if present) without opening the windows and doors, could not be determined. The monitoring of the outdoor environments was also limited in time, especially during the first school visits, in which not enough data was collected to fully represent the fluctuations of the outdoor environmental parameters, and consequently its effects on the indoor environmental conditions. Nevertheless, by selecting the same classrooms before and after the lockdown, and monitoring the environmental parameters at different locations in the classroom as well as noting the number of occupants per lesson, a comparison could be made of the situations before and after the lockdown.

Second, the intention of the study was to study “normal” conditions before the lockdown, and compare them with “adjusted conditions caused by COVID-19 measures” in schools with different ventilation regimes. Unfortunately, the “normal” situation before the lockdown turned out to be already influenced by COVID-19 measures, namely “opening windows and doors” as much as possible, regardless of the ventilation regimes: natural or mechanical (mechanical supply only, mechanical exhaust only, both mechanical supply and exhaust). This also limited further investigation on the differences among ventilation regimes.

Third, the calculation of ventilation rates in the classrooms was based on a five-minute period of each occupied lesson that fulfilled the steady-state condition, and a fixed number of occupants per lesson, of which the CO_2 generation rate per person was estimated as one fixed value for all occupants, which in fact differs for each person with factors such as sex, age, and activity, etc. [62]. Therefore, such estimation might lack accuracy, since this study has involved students spanning a certain age difference, as well as different types of secondary education with both theoretical and practical settings.

Finally, occupants’ subjective assessments on the IEQ conditions of the classrooms have not been collected in this study. Consequently, the analyses related to comfort issues were purely based on physical measurements, observations, using existing standards and guidelines as the major references, which however, are mostly based on the models of adult occupants. Hence, such results may deviate from the actual perceptions of the students [57,63,64].

3.5 Conclusions and recommendations

In this field study, surveys were conducted among 11 secondary schools in the Netherlands from October 2020 to June 2021, both before and after a national lockdown that lasted from December 15, 2020 to March 1, 2021, to investigate the CO_2 concentration, ventilation rate, and thermal condition in the classrooms. In the end, the results of 31 classrooms were reported, and the conclusions and recommendations are drawn as follows:

3.5.1 Conclusions

Before the lockdown, the classrooms were used under normal occupancy of an average of 17 students, with windows and doors kept open. Only one sixth of the classrooms could maintain the indoor CO_2 concentration below the preferred level A of the Dutch Fresh Schools guidelines, and in 42% of the classrooms it exceeded the upper limit of acceptable indoor CO_2 level during some periods. Meanwhile, the ventilation rate per person (VR_p) in 13% of the classrooms did not meet the minimum requirement (6 L/s/p), while only 55% of the classrooms achieved the level recommended by different standards and guidelines (10 L/s/p).

After the lockdown, the average occupancy decreased to 10 students per classroom, while the operation of windows and doors remained similar. Although the indoor CO_2 concentration decreased significantly, in terms of ventilation rates, only VR_p showed a significant increase. The total ventilation rate per classroom did not change significantly. Over 90% of the classrooms reached a VR_p higher than the recommended level of 10 L/s/p. The GEE analysis showed that the increase in VR_p between pre- and post-lockdown periods was mainly associated with the decrease in occupancy, rather than the operation of windows and doors.

Thermal conditions in the classrooms were, according to the guidelines, not satisfying during both the pre- and post-lockdown periods. Before the lockdown, the air temperature in the classrooms was generally on the cold side, most likely caused by the measure of opening windows and doors constantly, where 32% of them had the indoor air temperature deviating from the required range C. After the lockdown, the percentage increased to 42%, with both unacceptably low and high levels being observed in several classrooms. Such conditions can possibly cause discomfort to the students.

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It is hence concluded that with windows and doors kept open, both the ventilation and thermal conditions in the classrooms did not fulfill the recommended standards and guidelines at all times, and need to be further improved. Reducing occupancy can indeed increase the ventilation rate per student in the classrooms, when the total amount of outdoor air supply achieved does not vary greatly . However, this might not be an immediate solution for the schools to implement, given limited space and staff.

3.5.2 Recommendations

Overall, more controllable and flexible ways for improving indoor air quality and thermal comfort in school classrooms are needed. Well-designed mechanical ventilation systems that can provide sufficient air supply per occupant and can be demand controlled according to occupancy and activities, are needed [65,66]. This is not only essential for maintaining good indoor air quality, but also for ensuring a thermally comfortable indoor environment in the school classrooms.

Previous studies have also indicated the potential of personalized environmental control systems, such as personalized ventilation systems, as a possible solution for improving the local indoor environmental quality of the occupants and ensuring their health and comfort. However, further development is needed concerning the particular scenarios in school classrooms, as well as the preferences and needs of children [67,68].

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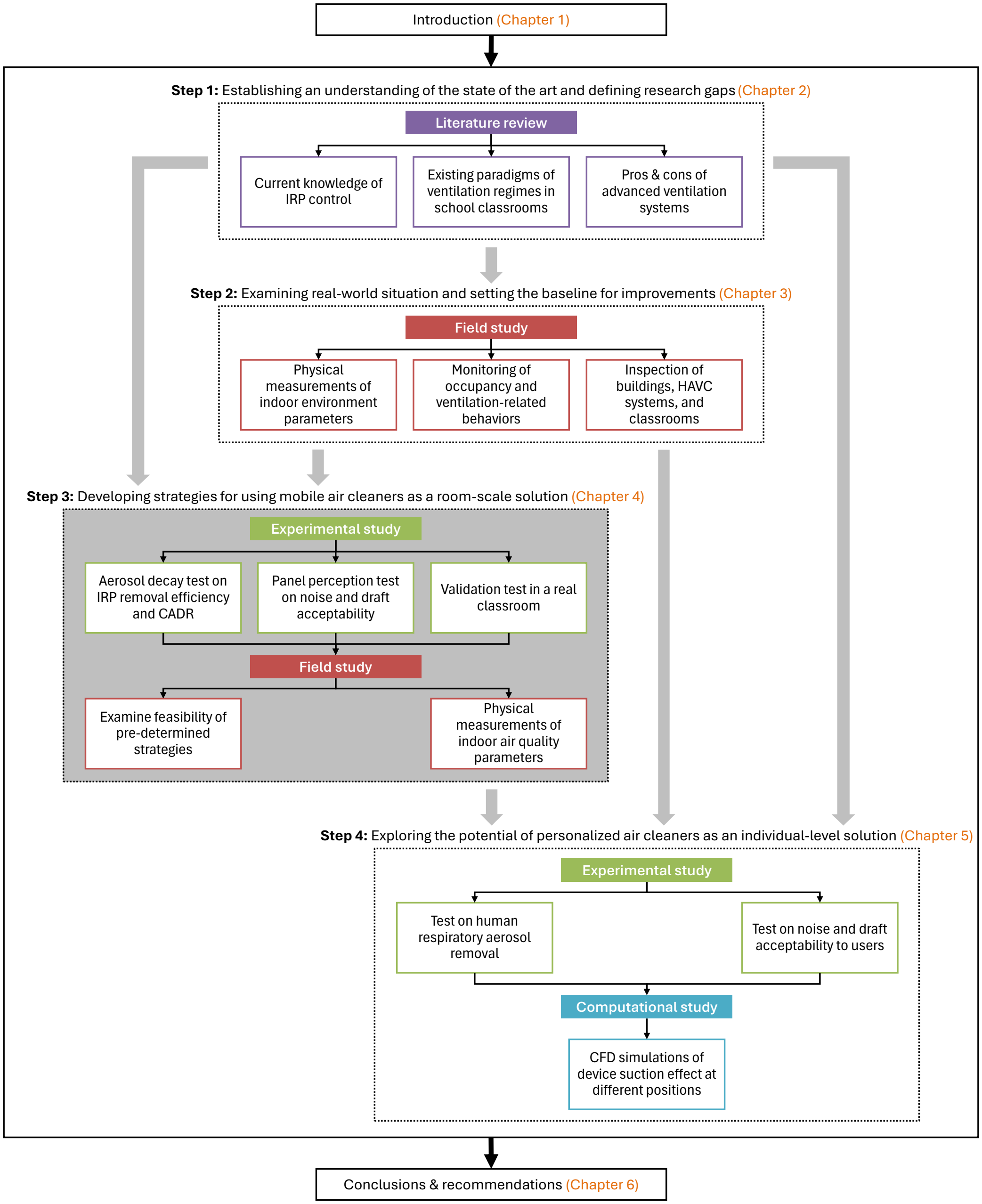
Introduction (Chapter 1)
Step 1: Establishing an understanding of the state of the art and defining research gaps (Chapter 2)
Literature review
Current knowledge of IRP control
Existing paradigms of ventilation regimes in school classrooms
Pros & cons of advanced ventilation systems
Step 2: Examining real-world situation and setting the baseline for improvements (Chapter 3)
Field study
Physical measurements of indoor environment parameters
Monitoring of occupancy and ventilation-related behaviors
Inspection of buildings, HAVC systems, and classrooms
Step 3: Developing strategies for using mobile air cleaners as a room-scale solution (Chapter 4)
Experimental study
Aerosol decay test on IRP removal efficiency and CADR
Panel perception test on noise and draft acceptability
Validation test in a real classroom
Field study
Examine feasibility of pre-determined strategies
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Step 4: Exploring the potential of personalized air cleaners as an individual-level solution (Chapter 5)
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Test on human respiratory aerosol removal
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4 Developing strategy

Mobile air cleaners for infectious respiratory particle removal

Part I: Using mobile air cleaners in school classrooms for aerosol removal: Which, where and how

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ABSTRACT

Mobile air cleaners (MACs) have been proposed as a supplementary solution to combat the spread of respiratory aerosols in school classrooms. To determine which, where and how to use MACs, seven small- and medium-sized MACs were selected and assessed for different settings and configurations by 1) a decay test for determining the clean air delivery rate (CADR), and 2) a perception test with a panel of subjects, together with physical measurements, of noise and air movement. The findings show that to achieve the desired CADR (appr. 1000 m^3/h for 30 students per classroom), the key factors are the induced airflow pattern and the location of the MACs. MACs with an upward air supply toward the occupied zone showed much higher CADR (max. 775-1332 m^3/h) than those with a horizontal air supply (max. 219-333 m^3/h). Moreover, using multiple devices simultaneously was crucial when the room size was increased, and combining mechanical ventilation could improve aerosol removal. Achieving a sufficient CADR would always lead to a noise

level above the limit of 35 dB(A), yet sometimes the rating of the panel was more than 50% acceptable. The air velocities mostly fulfilled the requirement (< 0.2 m/s), which aligned with the positive panel assessment. Hence, the evaluation by a panel of subjects can help to optimize the use of MACs in a classroom.

KEYWORDS mobile air cleaners, clean air delivery rate (CADR), respiratory aerosol, classroom, noise, air movement

4.1 Introduction

For years, the COVID-19 pandemic has significantly raised the public's concern for indoor air quality (IAQ) and the need for effective ventilation and air cleaning. This is due to the airborne transmission of SARS-CoV-2, primarily through pathogen-laden respiratory particles, also called infectious aerosols. Such aerosols are released when individuals breathe, speak, cough or sneeze, serving as a key route for cross-infection amongst indoor occupants [1-4]. Since school classrooms are indoor spaces with a dense occupancy and a long-occupied time per day, there is a high risk of such cross-infection to take place [5]. During the pandemic, schools worldwide were closed to prevent further outbreaks [6]. Such measures, consequently, hindered the teaching and learning activities and affected children's mental and physical health adversely [7,8], which is far from ideal and should not be the only option for combating new crises in the future. Therefore, better strategies for ventilating/air cleaning to minimize the transmission of infectious aerosols in classrooms are needed.

For decades, problems with IAQ and ventilation in classrooms have been widely reported. For instance, in studies conducted in the United States of America [9], the United Kingdom [10], Italy [11], China [12], Denmark [13], France [14] and the Netherlands [15], IAQ-conditions and ventilation performance in classrooms were often found to be unsatisfying or insufficient [16,17]. A study by Ding et al. [18] on Dutch secondary schools during the COVID-19 pandemic showed that with full student occupancy, nearly half of the classrooms had a CO_2 concentration exceeding the upper limit of the national guideline, and one-eighth had a ventilation rate per person lower than the minimum requirement, even with windows and doors open almost all the time. For the post-pandemic era, after gradually returning to normal, the opening of windows and doors is foreseen to be limited due to other aspects of indoor environmental quality (IEQ), such as thermal comfort and acoustics.

Considering that most classrooms only have natural ventilation and renovating the entire building for installing a centralized ventilation system is not always feasible, alternative options should be provided to ensure a good IAQ [19].

Air cleaning, by definition, means “the use of equipment that removes particulate, microbial or gaseous contaminants (including odours) from air [20].” More specifically, according to a recently released ASHRAE standard (ASHRAE 241-2023), within the scope of controlling infectious aerosols, air cleaning refers to “reducing the concentration of infectious aerosols in the air through capture and removal or by inactivation [21].” Previous studies have shown the ability of air cleaning devices to eliminate particulate matters (PMs) (as well as other contaminants) to improve IAQ and its benefits for occupants’ health [22-24]. Air cleaning technologies that are commonly used for removing aerosols include filtration (normally with high-efficiency particulate air (HEPA) filters), electrostatic, plasma/negative ion, ultraviolet germicidal irradiation (UVGI, particularly UV-C with a wavelength of 180-280 nm) and photocatalytic oxidation (PCO) [25]. For the past decade, commercial air cleaning products have become increasingly popular due to the rising awareness of atmospheric air pollution [26]. Nowadays, driven by the pandemic, there are concerns regarding their capability to be used as a supplementary measure for reducing human-generated air pollutants, such as pathogen-carrying respiratory aerosols [27].

Amongst different types of air cleaning devices available in the market, mobile air cleaners (MACs) have the advantage of being more flexible and affordable. Although mainly designed for household or office usage, recent studies have demonstrated that MACs can also serve as a good solution for aerosol removal in school classrooms [28]. For instance, Jhun et al. [29] examined the performance of a small-sized MAC (clean air delivery rate (max. CADR) approx. 200 m^3/h) by week-long monitoring in two groups (control and intervention) of elementary school classrooms for air contamination. The results showed that the indoor PM level was reduced by up to 49% in the intervention classrooms, with four devices placed in the middle of the walls, in comparison to the control classrooms. Burgmann and Janoske [30] tested a large MAC (max. CADR approx. 1200 m^3/h) in a secondary school classroom by monitoring the decay of artificial aerosols, where the MAC was located at the back of the room. The aerosol concentration (size 0.3-10 μm) was decreased by 80% within 30 minutes. Curtius et al. [31] assessed the efficiency of a small-sized MAC (max. CADR approx. 300 m^3/h) by measuring aerosol concentration during actual lessons in a high school classroom. Four devices were placed at different locations in the room: two at the front corners, one at the centre and one at the back. According to the results, when windows and doors were closed, the aerosol concentration was reduced by more than 90% within less than 30 minutes, leading to an experimental CADR comparable to the nominal value.

Previous studies have also indicated that the performance of MACs in school classrooms depends on several important factors. According to Burgmann and Janoske [30] and Narayanan and Yang [32], the location of the contaminant source plays a significant role, and the MAC should be ideally placed close to the source for a higher removal rate of respiratory aerosols. However, in real-world scenarios, it is not always possible to identify the source person, and the space available may be limited due to the activities in the classroom. A more practical approach would be to determine the location of the MAC in combination with the dimension of the device, the fan capacity, as well as the airflow pattern (i.e., the way that the air inlet and outlet are configurated in the MAC), to obtain optimal clean air delivery in the room, as discussed in a number of studies [33-36]. Moreover, the number of devices adopted per classroom should also be considered based on the amount of CADR needed [31,36].

Besides aerosol removal, noise and draughts generated by the MACs are also important. High noise levels of MACs were often reported in previous studies [31,37,38]. However, according to surveys conducted amongst pupils and teachers, the noise generated by MACs was sometimes rated acceptable [31,38]. Compared to noise, however, draught discomfort caused by MACs was less concerning. In the lab experiment conducted by Bluyssen et al. [37], when the airflow rate of the MAC was below 800 m^3/h, the air velocity did not exceed 0.2 m/s, and the panel rating of the draught remained lower than 10% dissatisfied. In the field study by Curtius et al. [31], no evidence of students or teachers being disturbed by draughts from MACs was found.

To summarize, researchers have investigated various aspects of using MACs in classrooms. However, most existing studies mainly investigated a single type of MAC, usually with HEPA filters, under a limited number of conditions. Consequently, systematic strategies for using MACs in school classrooms have not yet been formed. Therefore, the present study aims to determine which, where and how to use MACs in classrooms to reduce respiratory aerosols as efficiently as possible while keeping the occupants comfortable.

4.2 Methods

4.2.1 Selection of mobile air cleaners

4.2.1.1 Collection of information on available mobile air cleaners

To collect information on the available MACs applicable to classrooms, existing products were searched within two ranges: 1) professional organizations or associations and 2) e-commerce platforms. In total more than 300 products were found, and were further screened based on the following criteria, which resulted in a preliminary list of 152 pre-selected products:

1. The brand develops its own mobile air cleaning products.
2. The main air cleaning technology of the product is filtration, i.e., using HEPA (high-efficiency particulate air) or EPA (efficient particulate air) filters, electrostatic (ES) or plasma (PL), can be supplemented by activated carbon (AC) and/or UV-C.
3. Detailed technical specifications of the product are provided.
4. The product is available in or can be bought within the Netherlands.

4.2.1.2 Main specifications of mobile air cleaners

The pre-selected products were categorized and compared using the following eight parameters, based on the specifications provided by the brand:

1. Air cleaning technology: **Figure 4.1** shows the 15 different (combinations of) air cleaning technologies equipped by the pre-selected products.
2. Airflow pattern: **Figure 4.2** presents 26 types of airflow patterns of the pre-selected products. Most commonly, the contaminated air is sucked horizontally from the side of the device, and the clean air is supplied vertically from the top.
3. Efficiency: the pre-selected products all have a specified aerosol removal efficiency of ≥ 99.95%, which is equivalent to the filter class of E12 or higher as prescribed in the European standard EN 1822-1 [39].
4. Fan capacity and CADR: the fan capacity is the maximum airflow rate the MAC can provide, usually in m^3/h. Most of the pre-selected products have multiple settings (of

fan level). For some devices, the CADR (m^3/h) is specified, which equals the aerosol removal efficiency multiplied by the airflow rate or the decay rate of the aerosol concentration multiplied by the room volume, thus indicating both the efficiency and fan capacity of the device [40]. Since all the pre-selected products have an efficiency of ≥ 99.95%, the CADR can be considered approximately equal to the fan capacity. The fan capacity (or CADR) of the selected products varied from 60 to 2500 m^3/h.

5 Noise level: the specified noise level of the pre-selected products varies with the MAC settings, which range from 18 to 60 dB(A).

6 Dimensions: generically the fan capacity of the MAC increases with its size. However, the device should also be able to fit in classrooms causing minimum hindrance to the teaching and learning activities.

7 Maintenance: the maintenance of the MACs includes, most importantly, the filter life and its cost. The supplementary AC filter and UV-C lamp may add to the cost; however, for many products, the AC filter is combined with the main filter.

8 Price: the price of the pre-selected products ranged from 60 to 7000 euros (including VAT).

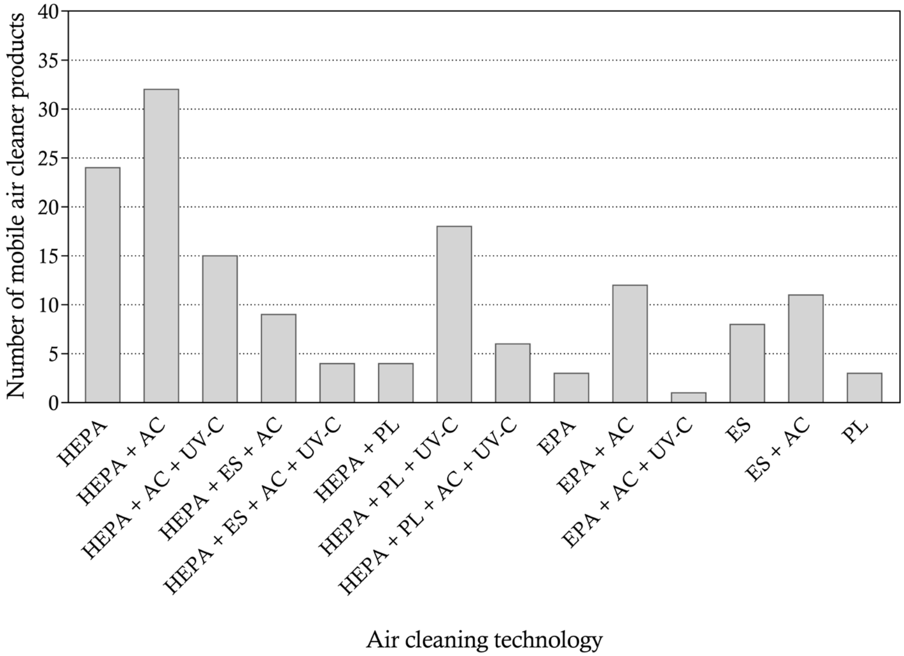

FIG. 4.1 Air cleaning technologies equipped by 152 pre-selected mobile air cleaners.
Note: HEPA: high-efficiency particulate air filter; AC: activated carbon; UV-C: ultraviolet-C; ES: electrostatic; PL: plasma; EPA: efficient particulate air filter.

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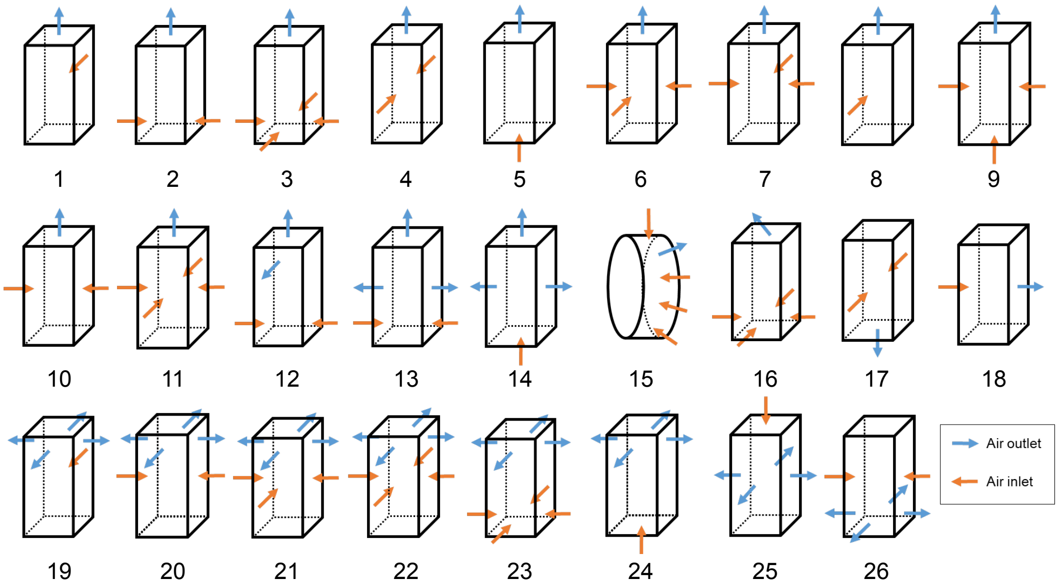

FIG. 4.2 Airflow patterns of 152 pre-selected mobile air cleaners.

4.2.1.3 Selection of mobile air cleaners

To select the proper MACs for the tests, several criteria were considered both for the technical requirements and feasibility of operating such devices in classrooms:

1. Considering the testing methods used in the present study, and recommendations of certain guidelines [41,42], MACs that used UV-C were excluded.
2. To ensure efficient aerosol removal, a filter class of H13 or higher, according to EN 1822-1 [39], is recommended [43]. Hence, the MACs with an efficiency lower than H13 were excluded.
3. According to the Dutch Fresh Schools guideline, the noise level of classroom installations should be ≤ 35 dB(A) [44]. Therefore, the MACs with a minimum noise level above 35 dB(A) were excluded.
4. To ensure a good IAQ, a ventilation rate of 8.5 - 10 L/s per person is recommended [45-47]. Taking the student occupancy in a typical classroom as 30 persons, the total ventilation rate required is thus around 1000 m^3/h. This should also be the requirement of the CADR achieved by the MACs. Considering the product size and fan capacity, for each type of MAC, a maximum of four devices can be used per classroom. Hence, the device should have a CADR ≥ 250 m^3/h, and those that did not were excluded.

5 Considering the affordability of the schools, the total budget of MACs per classroom was set to be 3000 euros. Thus, by multiplying the price and number of devices needed per classroom, those that reached a total cost higher than 3000 euros (including VAT) were excluded.

Based on the aforementioned criteria, 72 products were excluded. The remaining 70 products were then filtered by 1) reducing the number of similar products from the same brand, and 2) eliminating unpractical airflow patterns, such as a vertical air outlet from the bottom, or a stratum airflow. This led to a shortlist of 27 products, from which the most suitable one of each brand was eventually selected, considering the fan capacity (CADR), noise level, dimensions and price. The selection process is illustrated in **Figure 4.3**. In the end, eight types of floor-standing MACs were selected, representing unique combinations of air cleaning technology and airflow pattern that differed in fan capacity (CADR) and dimensions. The brands producers were then approached to purchase the devices. However, until the end of the study, one type of device was not delivered, and thus, only the other seven were tested. Each of these seven types of MACs was given a number for identification in this study, as noted from MAC1 to MAC7. To achieve the required CADR, for MAC5, one device was required; for MAC1, MAC4, MAC6, and MAC7, two devices were required; for MAC2 and MAC3, four devices were required. The detailed information is listed in **Table 4.1**.

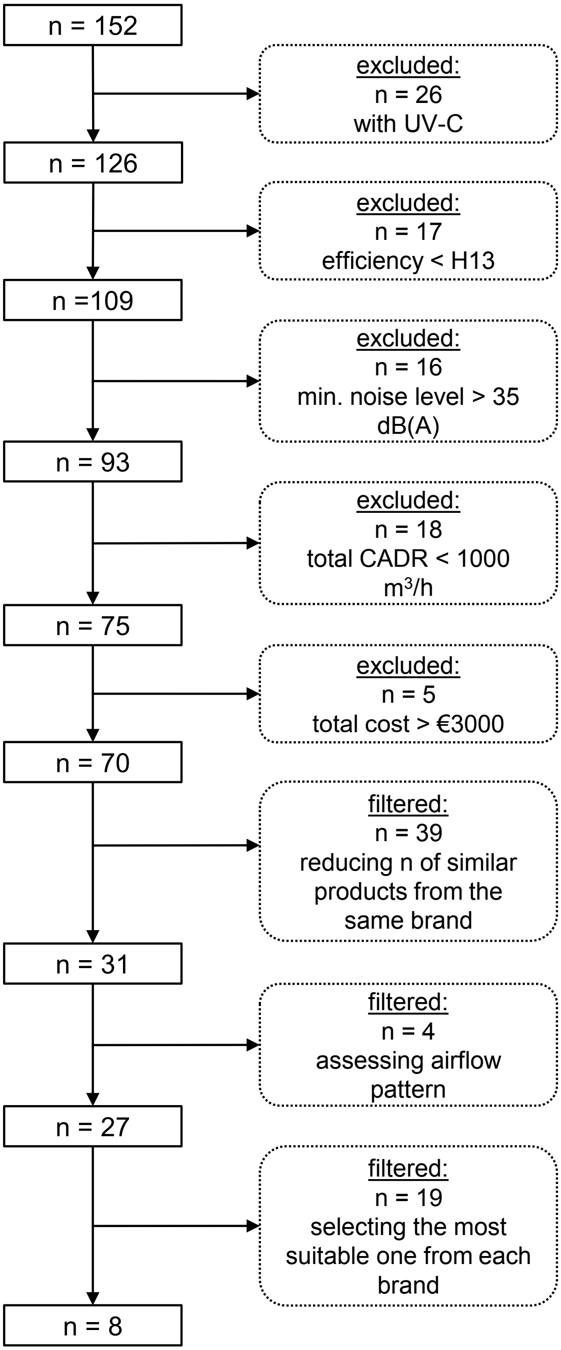

FIG. 4.3 Flowchart of the selection process of the tested mobile air cleaners.

TABLE 4.1 Information on the selected mobile air cleaners.

Devic[e]a	Air cleaning technology[b]	Airflow pattern	Fan capacity (CADR)[b] [m^3/h]	Settings	Efficiency[b]	Noise level[b] [dB(A)]	Dimensions[b] [cm]	Number of devices	Price (including VAT)[b] [€]
MAC1	HEPA + AC	No.23	1000	1-10	H13	30-62	19.0 × 19.6 × 101.8	2	500
MAC2	HEPA + ES + AC	No.3	610	1-3	H13	19-57	30.6 (Φ) × 70.5	4	480
MAC3	ES	No.10	330	1-4	H13	19-53	27.0 × 27.0 × 50.0	4	380
MAC4	ES + AC	No.12	735	1-3	H13	27-55	34.0 × 34.0 × 85.5	2	1100
MAC5	ES + AC	No.7	1386	1-5	H13	33-49	38.0 × 38.0 × 76.0	1	1900
MAC6	HEPA	No.11	565	1-8	H13	18-51	33.2 x 33.6 x 60.6	2	500
MAC7	HEPA	No.15	750	1-8	H13	26-65	68.8 (Φ) x 25.4	2	1500

a *MAC: mobile air cleaner.*
b *As specified by the brand.*
c *The numbers refer to the airflow patterns numbered in* ***Figure 4.2****.*

4.2.2 Assessment of mobile air cleaners

The assessment of the selected MACs consisted of two parts: 1) an aerosol decay test: the time evolution of aerosol concentration was monitored after filling the room with aerosols generated by a specific spraying technique, to calculate the aerosol removal rate and CADR, and 2) a panel perception test: a panel of subjects was recruited to assess the noise and air movement by completing questionnaires. The panel perception test also included physical measurements of sound pressure level and air velocity. All the tests were conducted from May to July 2023, in the Experience room of the SenseLab at the Delft University of Technology [48]. The Experience room has a size of 6.1 (length) × 4.2 (width) × 2.7 (height) = 69.2 m^3, with two windows and one door, and the interior was set up as a classroom, with tables, chairs and a smartboard. The Experience room was equipped with an independent ventilation system, which can switch between mixing and displacement ventilation, with a maximum ventilation rate of 1200 m^3/h and a HEPA filter of a filter class of H14.

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4.2.2.1 Aerosol decay test

Aerosol generator

An aerosol generator was adopted as the source of respiratory aerosols for the decay test, using an artificial saliva liquid made of 98.5 wt% water + 1 wt% glycerin + 0.5 wt% NaCl (salt). The aerosol generator consists of an HPLC pump (model: SHIMADZU LC-10AD), a Pulmospray^{TM} spray nozzle for generating aerosols (provided by Medspray®), and an air compressor. The latter gently blows air around the spray nozzle, dispersing the aerosols and preventing too much coalescence [49]. The Pulmospray^{TM} contains a nozzle (spray chip), a liquid tube and an air tube. When the aerosol generator is operated, the liquid is pumped from a stock bottle to the spray nozzle using the HPLC pump at a flow rate of 0.8 - 0.9 ml/min. The spray nozzle produces multiple parallel liquid jets that break into droplets, which are then mixed with the co-airflow to form a constant spray. After being sprayed into the room air, the water in the droplets evaporates rapidly [50], while the glycerin and salt remain in the form of aerosols. The sizes of the droplets and aerosols produced by the Pulmospray^{TM} were previously determined using the Spraytec laser diffraction system (manufactured by Malvern Panalytical). The average size of the droplets (measured at 10 cm away from the spray outlet) was 7 μm, and the average size of the aerosols (measured at 1 m away from the spray outlet) was 4 μm. The aerosol generator was placed in the middle of the Experience room, with the spray facing the front of the room. The setup is shown in **Figures 4.4-4.5**.

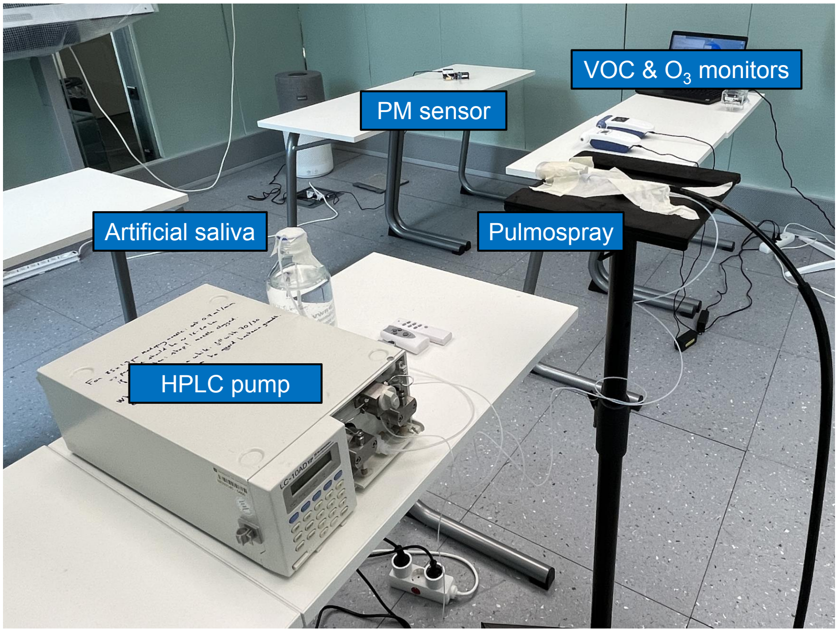

FIG. 4.4 Set-up of the aerosol generator.

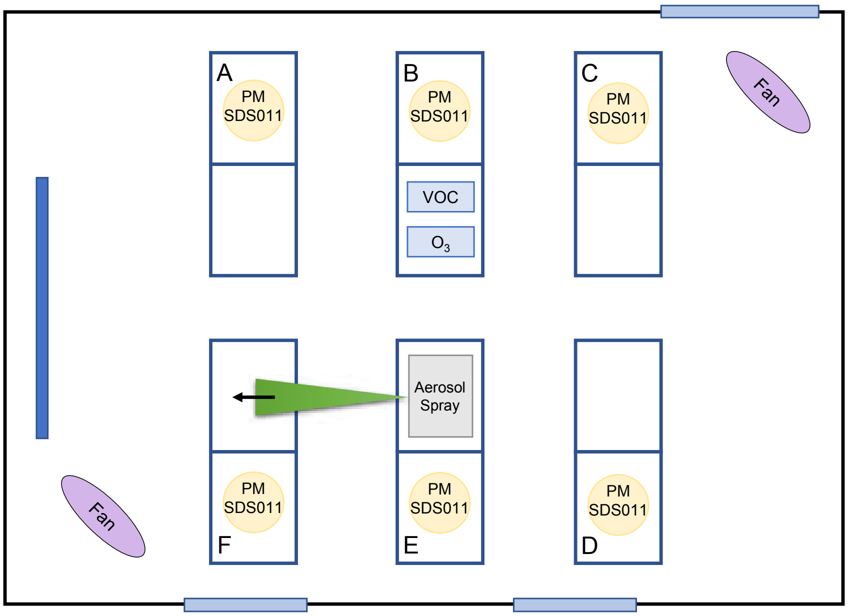

FIG. 4.5 Set-up of the aerosol decay test.
Note: view from the top of the Experience room, where A, B, C, D, E and F represent the tables, the dark blue rectangle represents the smartboard, and the light blue rectangles represent the door (top) and windows (bottom).

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Measurement instruments

Previous studies have shown that the human respiratory aerosol sizes span a wide spectrum from 0.1 μm to over 1000 μm [51-53]. Nonetheless, researchers have also found that aerosols with a size of 1-10 μm are mostly prevalent during a variety of respiratory activities for which $PM_{2.5}$ and PM_{10} can hence be considered good representatives [54,55]. The $PM_{2.5}$ (particulate matters of a diameter of 2.5 μm and smaller) and PM_{10} (particulate matters of a diameter of 10 μm and smaller) concentrations were measured by six NOVA PM sensors (model: SDS011), which were evenly distributed in the Experience room on six tables (**Figure 4.5**). The logging interval was 10 seconds, and the real-time data was read out on a computer outside the room to remotely monitor the PM concentrations. Besides, the concentrations of total volatile organic compound (TVOC) and ozone (O_3) were also continuously monitored by a Kanomax Gasmaster monitor (model: 2750) and an Aeroqual O_3 monitor (model: Series 500), respectively, with a logging interval of 1 minute, to assure the levels are within the acceptable range. These two monitors were placed on a table near the center of the room (**Figure 4.5**).

Test conditions and procedure

The test conditions consisted of two parts: setting and configuration, as presented in **Table 4.2**.

TABLE 4.2 Conditions of the aerosol decay test of the selected mobile air cleaners.

Device[a]	Tested settings[b]	Tested configurations[c]	Number of conditions
MAC1	S1 (L4), S2 (L10)	C1, C2	4
MAC2	S1 (L1), S2 (L2)	C1, C2	3
MAC3	S1 (L2), S2 (L4)	C1	2
MAC4	S1 (L1), S2 (L2)	C1, C2, C3	5
MAC5	S1 (L1), S2 (L5)	C1, C2	4
MAC6	S1 (L4), S2 (L8)	C1, C2, C3	5
MAC7	S1 (L4), S2 (L8)	C1, C2, C3	5

a *MAC: mobile air cleaner.*
b *S: setting; L: fan level. Configuration.*

As shown in **Table 4.1**, the selected MACs all had different settings (i.e., fan levels). For each MAC, to determine the settings for the tests, a pre-test was performed to examine the noise level of each setting. Based on the results, two settings were selected for each MAC, which were:

- Setting 1 (S1): the highest setting with a noise level lower than 35 dB(A).
- Setting 2 (S2): the highest setting with a noise level lower than 55 dB(A), which was normally the maximum setting of the MAC, except for MAC2 and MAC4.

In **Table 4.1**, different numbers of devices are required for each MAC depending on the fan capacity. Hence, the configuration included both the number and location of devices, as shown in **Figure 4.6**:

FIG. 4.6 Configurations of the mobile air cleaners for the aerosol decay test.
Note: view from the top of the Experience room, where A, B, C, D, E and F represent the tables, the dark blue rectangle represents the smartboard, and the light blue rectangles represent the door (top) and windows (bottom).

- For one device, configuration 1 (C1): at the middle of the back wall; configuration 2 (C2): at the front of the room, slightly on the side to avoid blocking the smartboard.
- For two devices, C1: one in the front next to the smartboard, and the other at the middle of the back wall; C2: diagonally at two corners; C3: only one device, at the middle of the back wall, operating at S2.
- For four devices, C1: at four corners; C2 (only for MAC2): two MACs, diagonally at two corners, operating at S2.

Each decay test started with a build-up phase and ended with a decay phase, as shown in **Figure 4.7**. During the build-up phase, the aerosol generator was turned on to fill the room with aerosols. Two floor-standing fans were used to help accelerate the mixing process (**Figure 4.5**). When the real-time aerosol concentrations were read to be well-mixed and reached a steady state, the build-up phase was completed, normally taking 60 minutes. The aerosol generator and the fans were then turned off, and the MAC(s) was(were) turned on to start the decay phase. The decay phase usually lasted for 90 minutes, until the concentrations of both $PM_{2.5}$ and PM_{10} decreased considerably (< 5 µg/m^3). Before and after each test, the mixing ventilation of the Experience room was turned on with an airflow rate of 1200 m^3/h to flush the room for 15 minutes to maintain the aerosol concentrations at a very low level (< 1 µg/m^3).

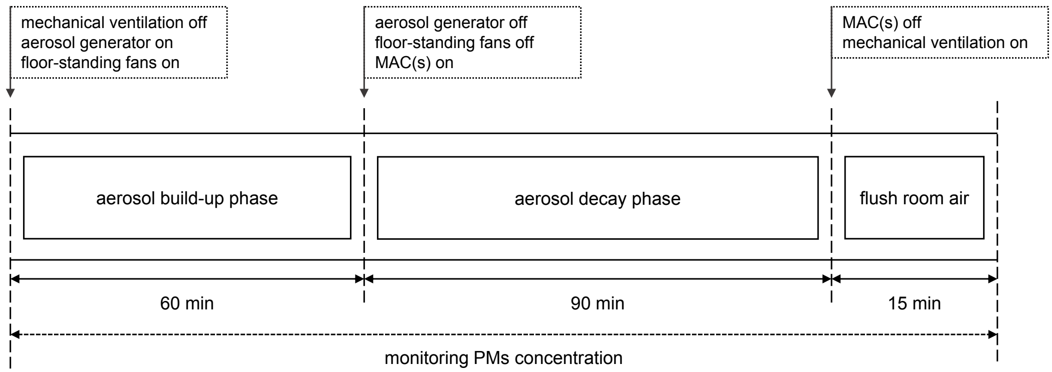

FIG. 4.7 Procedure of the aerosol decay test.

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During the tests, everything was set to be remotely controlled (except for MAC5), and the mechanical ventilation system was turned off with the windows and door closed. In addition, as natural decay (possibly due to gravitational sedimentation in this room) can always take place simultaneously, independent tests of natural decay were performed at different times during two consecutive days in May and one day in July, without any MACs or mechanical ventilation operating in the room. Moreover, air temperature and relative humidity were measured in the meantime by six HOBO® loggers (model: MX1102A) placed next to the PM sensors, with a logging interval of 1 minute.

Aerosol removal rate and clean air delivery rate (CADR)

The total decay (with single or multiple devices, depending on the configuration) and natural decay of aerosol concentration can be described by equation (4.1) [56,57]:

$$C(t) = C_\infty + (C_0 - C_\infty)e^{-k_{PM}t},\ k_{PM} = k_{PM,total}\ or\ k_{PM,n} \tag{4.1}$$

Where:

- C_{PM} is the aerosol concentration [μg/m³].
- t is the time after the decay process starts [h].
- $C_{PM,0}$ is the initial aerosol concentration of the decay phase at t = 0 [μg/m³].
- $C_{PM,\infty}$ is the aerosol concentration when t >> $k_{PM}{}^{-1}$ [μg/m³].
- k_{PM} is the decay coefficient of aerosol concentration [h^{-1}].
- $k_{PM,total}$ is the coefficient of the total decay, here also the total aerosol removal rate [h^{-1}].
- $k_{PM,n}$ is the coefficient of the natural decay [h^{-1}].

Hence, $k_{PM,total}$ and $k_{PM,n}$ can be determined by non-linear regression, here performed by IBM SPSS Statistics 28.0. The aerosol removal rate of the MAC $k_{PM,mac}$ (with single or multiple devices, depending on the configuration) can thus be calculated using equation (4.2) [56,57]:

$$k_{PM,mac} = k_{PM,total} - k_{PM,n} \tag{4.2}$$

As mentioned previously, CADR is a widely adopted indicator of the performance of MACs, as it indicates both the aerosol removal efficiency and the airflow rate the device can achieve. The CADR of the MAC (with single or multiple devices, depending on the configuration) is determined by equation (4.3) [56,57]:

$$CADR = k_{PM,mac} \times V \quad (4.3)$$

Where:

- $k_{PM,mac}$ is the aerosol removal rate of the mobile air cleaner [h^{-1}].
- V is the volume of the room [m^3].

4.2.2.2 Panel perception test

Subjects and questionnaires

Eight PhD students (four males and four females, aged from 28 to 35 years) were recruited as subjects for the perception tests during June and July 2023. For each perception test, a panel of six subjects (three male and three female) was formed to evaluate the sound and air movement generated by MACs. The subjects were first asked to report their perception (feel/not feel) of the sound and air movement. If they did sense any sound and/or air movement, they were further asked to rate the intensity and assessment using a 5-point scale:

- Intensity: for sound: from “quiet” to “loud;” for air movement: from “mild” to “strong.”
- Assessment: for sound and air movement: from “bad” to “good.”

For air movement, an extra question was included, asking the subjects to specify which body part(s) they sensed it. The sample of the questionnaire are presented in **Appendix B.1**.

Test conditions and procedure

Based on the results of the aerosol decay test, the configuration with a higher aerosol removal rate and CADR were selected for each MAC to perform the perception test. For MAC5, MAC6 and MAC7, the difference between the two configurations was insignificant, and thus both configurations were tested. For all the MACs, the same two settings as the decay test were tested with the panel. In addition, for MAC1, MAC3, MAC5, MAC6 and MAC7, a third setting (S3) between the two previous tested settings was included. The total conditions tested for each type of device are listed in **Table 4.3**.

TABLE 4.3 Conditions of the panel perception test of the selected mobile air cleaners.

Device[a]	Tested settings[b]	Tested configurations[c]	Number of conditions
MAC1	S1 (L4), S2 (L10), S3 (L7)	C2	3
MAC2	S1 (L1), S2 (L2)	C1	2
MAC3	S1 (L2), S2 (L4), S3 (L3)	C1	3
MAC4	S1 (L1), S2 (L2)	C2	2
MAC5	S1 (L1), S2 (L5), S3 (L3)	C1, C2	6
MAC6	S1 (L4), S2 (L8), S3 (L6)	C1, C2	6
MAC7	S1 (L4), S2 (L8), S3 (L6)	C1, C2	6

a *MAC: mobile air cleaner.*
b *S: setting; L: fan level.*
c *C: configuration.*

When the subjects arrived, they were asked to rest for 10 minutes in the waiting area while completing a consent form and a general information form to report their mood and the clothing they wore at the time (see **Appendix B.1**), after which they were seated at six tables in the Experience room (same as the aerosol decay test) (**Figure 4.8**). Each type of MAC was tested during an independent session, which started with an acclimatization condition (MAC(s) off), followed by the real test conditions (MAC(s) on). **Figure 4.9** shows the procedure of the panel perception test with a sample session of three test conditions. Each test condition lasted for 6 minutes, during which the MAC(s) was (were) turned on for 5 minutes, and then turned off for the last minute. The subjects were asked to complete the questionnaire 3 minutes after the condition started. For each session, the test conditions were conducted in a randomized order. After each session, there was a 10-minute break for switching the MACs and preparing for the next session, when the subjects were asked to leave the room. The mechanical ventilation system in the Experience room was turned off during the sessions, while during the breaks it was turned on to flush the room air. In addition, air temperature and relative humidity were measured in the meantime by six HOBO® loggers (model: MX1102A), with a logging interval of 1 minute.

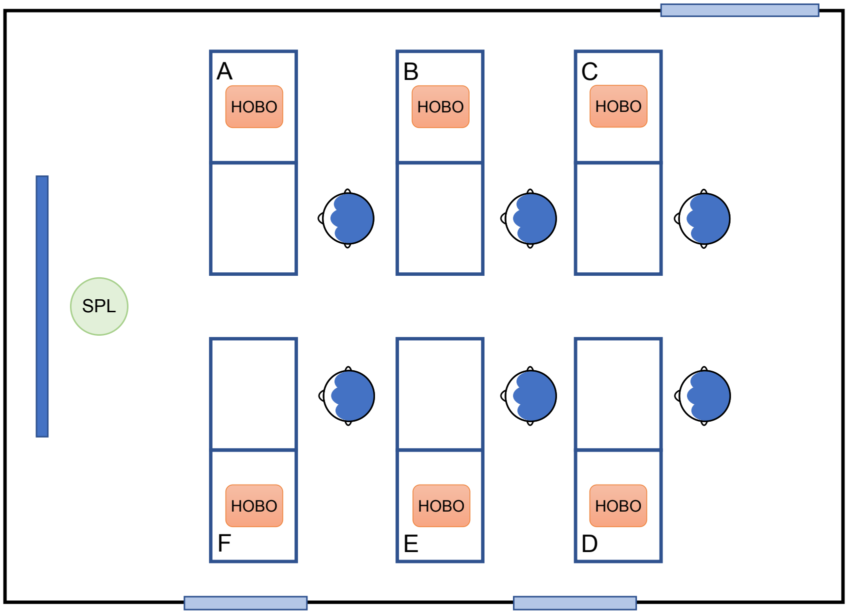

FIG. 4.8 Set-up of the panel perception test.
Note: view from the top of the Experience room, where A, B, C, D, E and F represent the tables, the dark blue rectangle represents the smartboard, and the light blue rectangles represent the door (top) and windows (bottom).

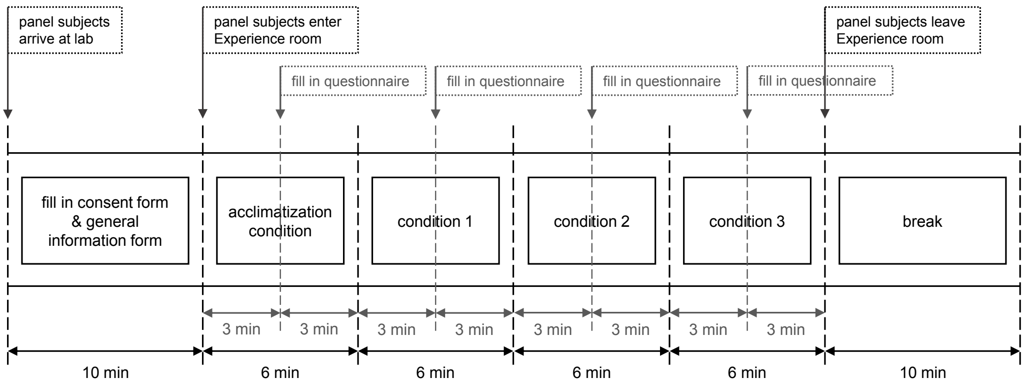

FIG. 4.9 Procedure of the panel perception test.
Note: example with a session of three test conditions.

Measurements of sound pressure level and air velocity

The sound pressure level (SPL) was measured using a Norsonic sound analyzer (model: Nor140), which was placed at the front of the room (**Figure 4.8**), both during the panel perception test and after, when the room was empty. Each measurement lasted for 2 minutes. The air velocity was measured using a Dantec ComfortSense anemometer (model: 54T033), which was placed in front of each table where the subjects were seated, at a height of 1.1 metres (breathing zone). The air velocity measurements were conducted after the panel perception test, and each measurement lasted for 3 minutes.

Ethical aspects

This study was approved by the Human Research Ethics Committee (HREC) of Delft University of Technology on 16th April 2023 (Case ID: 3007).

4.2.3 Application in a real classroom

To examine the performance of the MACs in real-world scenarios and also as a validation of the results of the lab experiment, an aerosol decay test was further conducted in a real classroom at the Faculty of Architecture and the Built Environment of Delft University of Technology during July 2023. The classroom has a size of 6.7 (length) × 6.1 (width) × 3.4 (height) = 139.0 m^3, with six openable windows and one door (**Figure 4.10**). The classroom was equipped with a mechanical ventilation system with air supplies on both sides and an air exhaust in the middle of the ceiling. Based on the results of both the aerosol decay test and the panel perception test conducted in the Experience room, one optimal condition was selected for each MAC to be tested in the classroom, as listed in **Table 4.4**. The procedure of the aerosol decay test was the same as performed in the Experience room, with the same instruments and setup. One natural decay test was performed. During the test the windows and door were closed, yet the mechanical ventilation in the classroom was kept on due to building management. The calculations of aerosol removal rate and CADR were conducted using the same methods as the lab experiment.

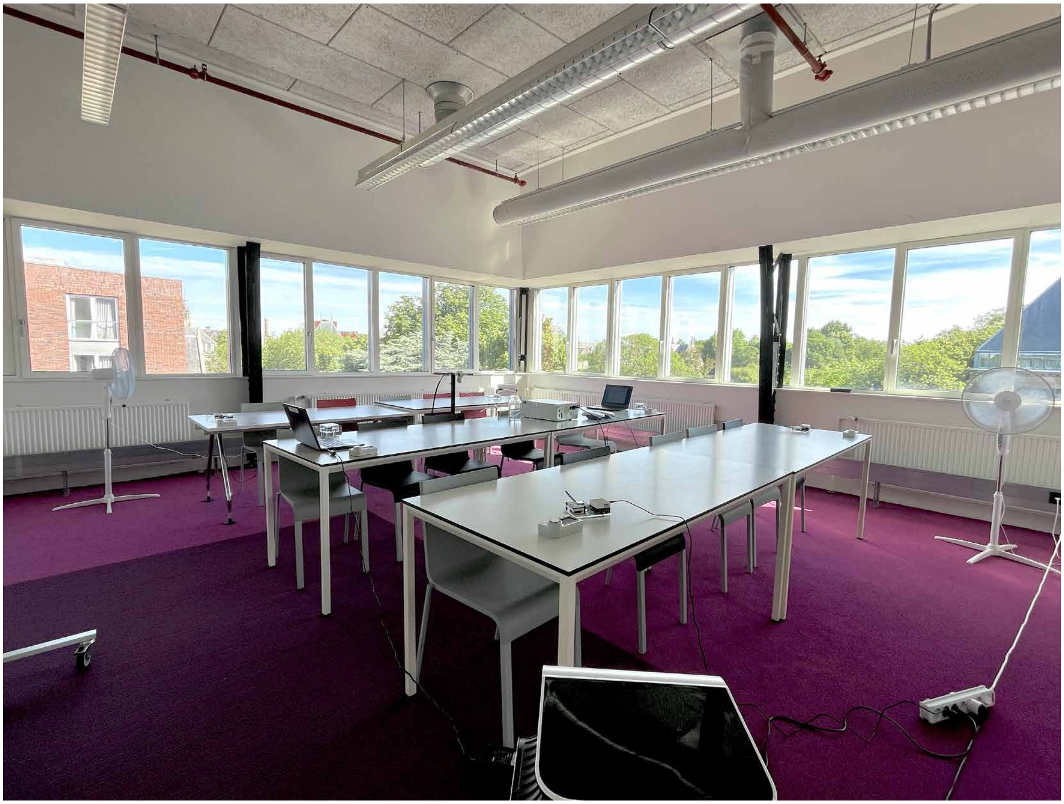

FIG. 4.10 Set-up of the aerosol decay test in the classroom.

TABLE 4.4 Conditions of the aerosol decay test of the selected mobile air cleaners in the real classroom.

Device[a]	Tested settings[b]	Tested configurations[c]
MAC1	S2 (L10)	C2
MAC2	S2 (L2)	C1
MAC3	S2 (L4)	C1
MAC4	S2 (L2)	C2
MAC5	S2 (L5)	C2
MAC6	S2 (L8)	C1
MAC7	S1 (L4)	C2

a *MAC: mobile air cleaner.*
b *S: setting; L: fan level.*
c *C: configuration.*

4.3 Results

4.3.1 Aerosol decay test

4.3.1.1 Aerosol removal rate

For all MACs, the total decay rates of both $PM_{2.5}$ and PM_{10} were similar amongst the six sampling points (see **Appendix B.2** or dataset [58]). Hence, for each condition, the average aerosol concentration was calculated amongst the six locations at each time point, and the average total decay curve was determined using equation (4.1). For natural decay, $k_{PM,n}$ slightly varied among different time periods tested, yet no association was found between such variation and indoor air temperature/relative humidity (see **Appendix B.2** or dataset [58]). Thus, the average natural decay curves were determined by taking the average of all natural decay tests. The original and averaged aerosol concentrations, as well as the fitted average decay curve of MAC1 at S1 under C1, are presented in **Figure 4.11** as an example.

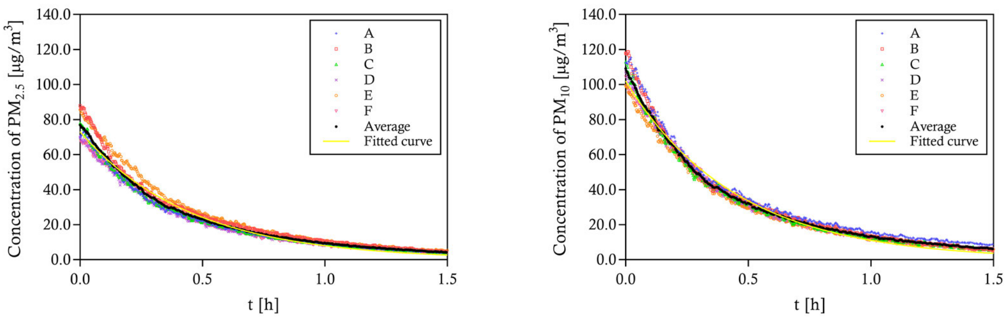

FIG. 4.11 Original and averaged aerosol concentrations and the fitted average decay curve of $PM_{2.5}$ (left) and PM_{10} (right) of MAC1 operating at setting 1 under configuration 1 (S1_C1) in the Experience room.

As the initial concentration $C_{PM,0}$ varied among different conditions, to have a better comparison, the standardized aerosol concentration, $C_{PM,std}$, was determined for both total decay and natural decay from t = 0 to t = 2 h, using equation (4.4):

$$C_{PM,std}(t) = \frac{C_{PM}(t) - C_{PM,\infty}}{C_{PM,0} - C_{PM,\infty}} \quad (4.4)$$

Where:

- $C_{PM,std}$ is the standardized aerosol concentration [-].
- C_{PM} is the aerosol concentration [μg/m³].
- t is the time after the decay process starts [h], here the range of is 0-2 h.
- $C_{PM,0}$ is the initial concentration of the decay phase at = 0 [μg/m³].
- $C_{PM,\infty}$ is the concentration when t >> k_{PM}^{-1} [μg/m³].

The results of the standardized average curves are shown in **Figure 4.12**. For the natural decay, $k_{PM,n}$ = 1.3 h^{-1} (R^2 = 0.996) and 1.4 h^{-1} (R^2 = 1.000) for $PM_{2.5}$ and PM_{10}, respectively. For all MACs, the differences between the total decay curves and the natural decay curves, in other words, the differences between $k_{PM,total}$ and $k_{PM,n}$ (i.e., $k_{PM,mac}$), were clear for all conditions, with MAC1 being the lowest and MAC7 the highest. In fact, except for MAC1, for all the other MACs, the concentrations of $PM_{2.5}$ and PM_{10} were decreased by 90% within 30 minutes under all conditions during the total decay. In addition, $k_{PM,mac}$ was increased with the setting under the same configuration for all MACs. Furthermore, for the MAC with one device (MAC5), $k_{PM,mac}$ was higher under C2 than C1 at all settings. For the MACs with two devices (MAC1, MAC4, MAC6, and MAC7), $k_{PM,mac}$ showed a larger difference between C1 and C2 at S1. For MAC1, MAC4 and MAC7, $k_{PM,mac}$ was higher under C2 than C1, while for MAC6 it was the opposite. However, the difference became negligible at S2. Moreover, for MAC4 and MAC6, $k_{PM,mac}$ of using only one device (C3) at S2 was higher than using two devices at S1, under both C1 and C2. For MAC7, $k_{PM,mac}$ of using only one device (C3) at S2 was almost equal to the one using two devices at S1 under C2. Besides, for MAC2, $k_{PM,mac}$ of using only two units (C2) at S2 showed a similar result as using all four units (C1) at S1.

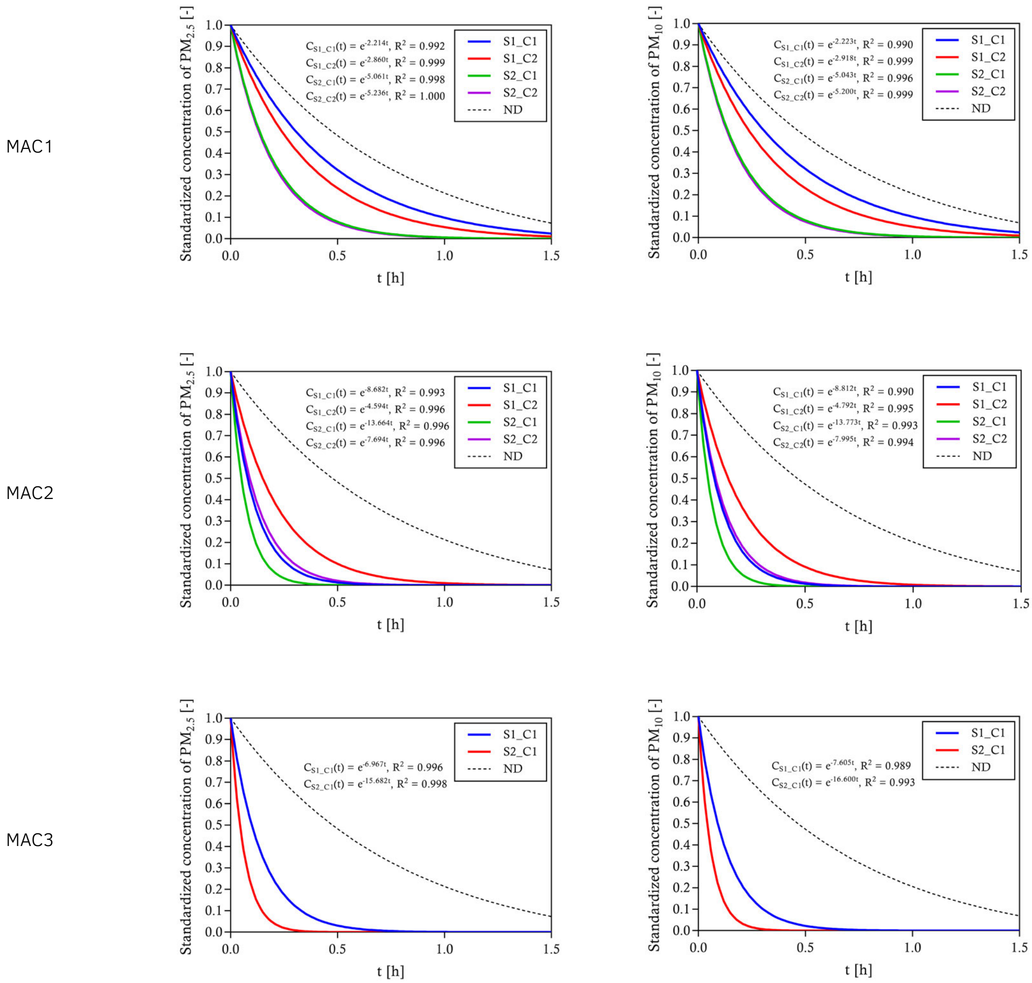

FIG. 4.12 Standardized fitted average total decay curves of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the Experience room.
Note: the regression functions and R^2 are listed in the order of the test conditions (from top to bottom). The standardized average natural decay curves are plotted as the black dashed line (ND). MAC: mobile air cleaner; S: setting; C: configuration.

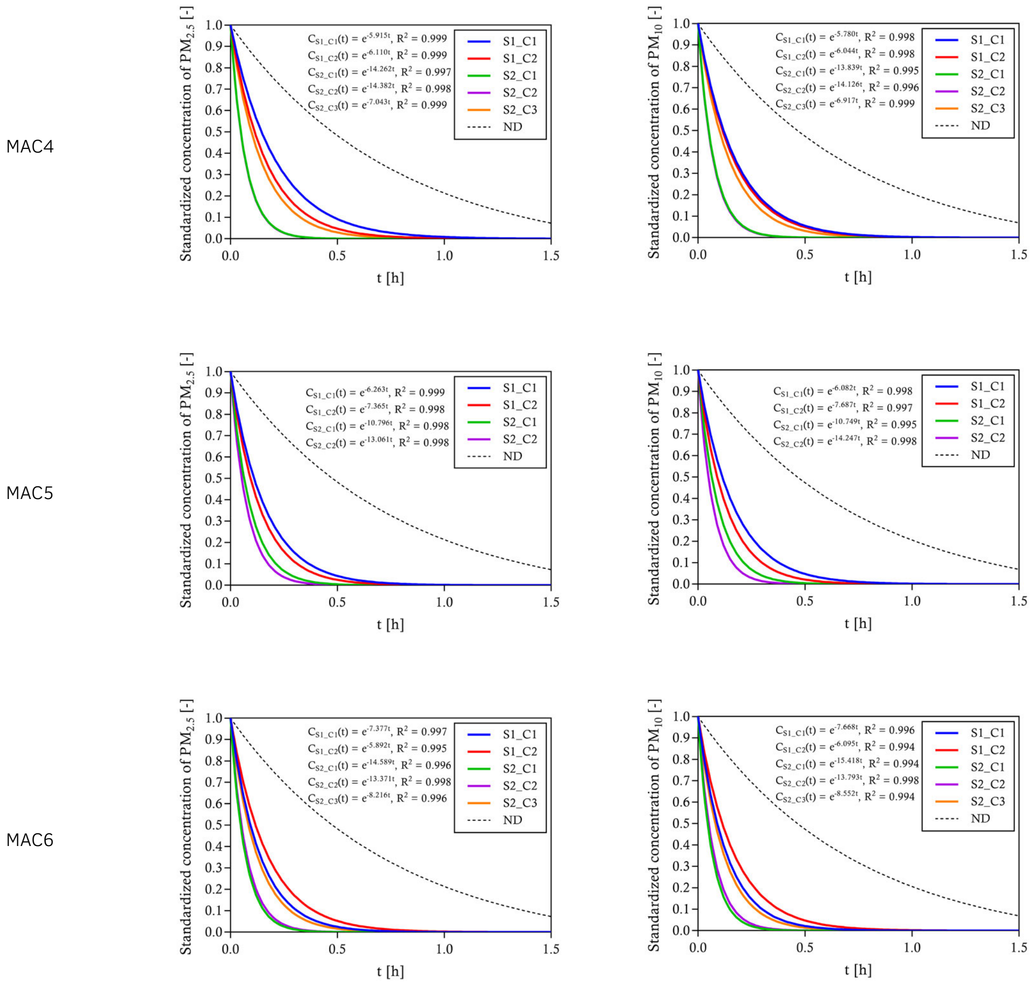

FIG. 4.12 Standardized fitted average total decay curves of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the Experience room.
Note: the regression functions and R^2 are listed in the order of the test conditions (from top to bottom). The standardized average natural decay curves are plotted as the black dashed line (ND). MAC: mobile air cleaner; S: setting; C: configuration.

MAC7

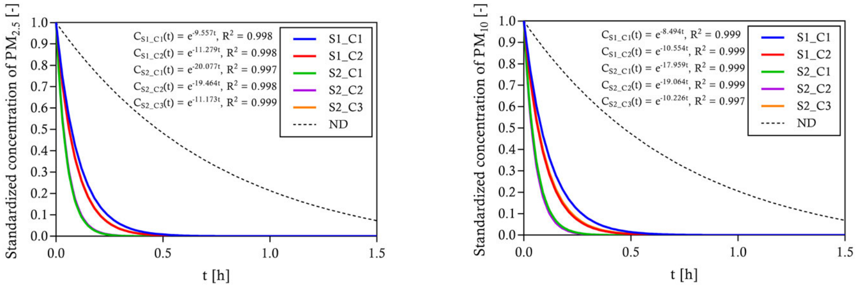

FIG. 4.12 Standardized fitted average total decay curves of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the Experience room.

Note: the regression functions and R^2 are listed in the order of the test conditions (from top to bottom). The standardized average natural decay curves are plotted as the black dashed line (ND). MAC: mobile air cleaner; S: setting; C: configuration.

4.3.1.2 Clean air delivery rate (CADR)

The results of CADR are presented in **Figure 4.13** for both $PM_{2.5}$ and PM_{10}. The same as $k_{PM,mac}$, MAC1 and MAC7 showed the lowest and highest CADR, respectively, while the other MACs showed similar results. As mentioned in the previous sections, the minimum amount of ventilation ("clean" air) required by the Dutch Building Decree [45] in classrooms is 8.5 L/s/person, while the recommended amount of ventilation for a good IAQ is 10 L/s/person [46,47]. Assuming a student occupancy of 30 persons, then the total amount of CADR would be 918 and 1080 m^3/h, respectively, as marked in the figures. For both $PM_{2.5}$ and PM_{10}, only MAC3 (with four devices at S2 under C1) and MAC6 (with two devices at S2 under C1) reached a CADR higher than 918 m^3/h, and only MAC7 (with two devices at S2 under both C1 and C2) reached a CADR higher than 1080 m^3/h.

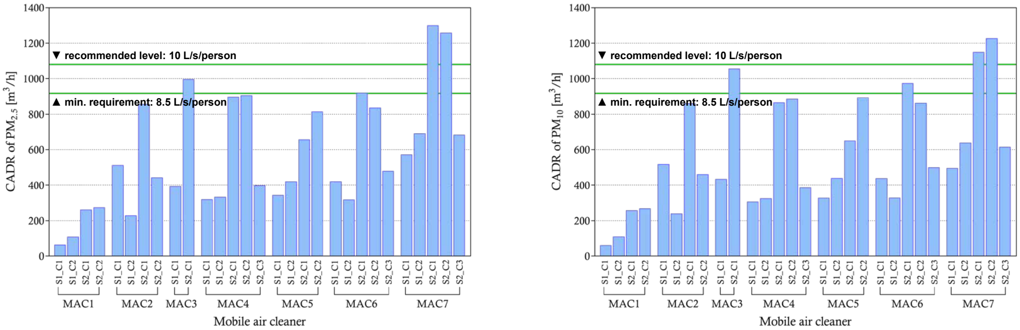

FIG. 4.13 CADR of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the Experience room.
Note: the green lines denote the total amount of CADR based on 1) the minimum ventilation rate per person required by the Dutch Building Decree [45] (8.5 L/s/person and 918 m^3/h in total) and 2) the ventilation rate per person recommended [46,47] (10 L/s/person and 1080 m^3/h in total), with an assumption of 30 student occupancy. MAC: mobile air cleaner; S: setting; C: configuration.

4.3.2 Panel perception test

4.3.2.1 Sound of the mobile air cleaners

The measured SPL of the MACs with and without the panel of subjects is presented in **Figure 4.14**, and the outcome of the panel tests is in **Table 4.5**.

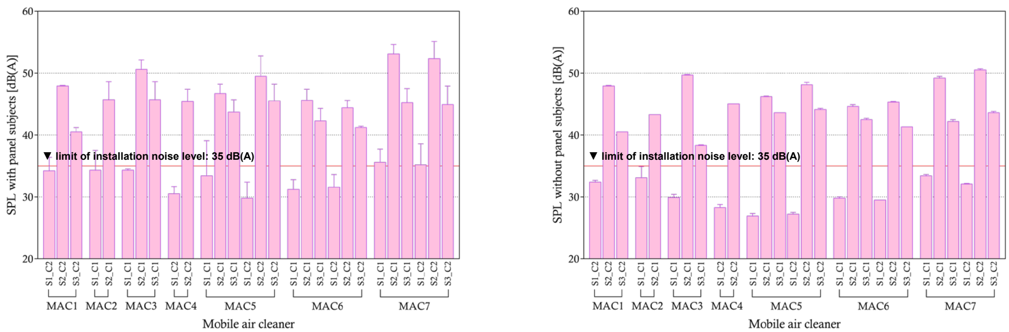

FIG. 4.14 Sound pressure level (SPL) of the tested mobile air cleaners with (left) and without (right) the panel of subjects.
Note: the red line denotes the limit of SPL [35 dB(A)] in classrooms as prescribed by the Dutch Fresh Schools guideline [44]. MAC: mobile air cleaner; S: setting; C: configuration.

TOC

The SPL of the MACs was 1-2 dB(A) lower when the room was empty than when occupied. Under the setting of S1, almost all the MACs could maintain an SPL below 35 dB(A). However, when the setting was increased, the SPL immediately exceeded 35 dB(A) under all conditions, some even reached 50 dB(A). The SPL did not increase linearly with the setting level, as for most of the MACs, the SPL at S3 was very close to S2. Furthermore, for MAC5, MAC6 and MAC7 no significant difference in SPL was found between C1 and C2.

All subjects sensed the sound generated by the MACs under almost all conditions. The average sound intensity was mostly quiet (≤ 2) under S1 while loud (≥ 4) under S2. For MAC5 and MAC7, the sound intensity was much higher with C1 than with C2 configuration, while for MAC6, the results were the opposite. The results of the sound assessment were related to the sound intensity. Taking the score of 3 as neutral, the average assessment was mostly acceptable (< 3) under S1, yet often unacceptable (> 3) under S2 and S3. For MAC5 and MAC7, the sound was less acceptable with C1 than C2, while for MAC6, the results were the opposite. Nonetheless, with regards to the percentage of acceptability, for MAC2 operating under S2, although the average assessment was above 3, 50% of the subjects considered the sound to be acceptable. The same results were found for MAC4, MAC5 and MAC6.

TABLE 4.5 Results of the panel perception test.

Device[a]	Setting[b]	Configuration[c]	Sound				Air movement			
			Perception[d] [%]	Average intensity (1 = quiet; 5 = loud)	Average assessment (1 = good; 5 = bad)	Unacceptability [%][efg]	Perception[d] [%]	Average intensity (1 = mild; 5 = strong)	Average assessment (1 = good; 5 = bad)	Unacceptability [%][efg]
MAC1	S1	C2	100	2.0	2.2	17	33	1.0	1.5	0
	S2	C2	100	4.3	4.5	83	50	2.0	2.3	0
	S3	C2	100	3.5	3.5	67	50	1.7	2.0	0
MAC2	S1	C1	100	2.2	2.5	17	67	1.0	1.8	0
	S2	C1	100	3.7	3.5	50	83	1.4	2.0	0
MAC3	S1	C1	83	1.8	2.2	20	0	-	-	-
	S2	C1	100	4.3	4.0	67	33	1.5	2.0	0
	S3	C1	100	3.3	3.7	50	33	1.0	2.0	0
MAC4	S1	C2	100	1.3	1.5	0	0	-	-	-
	S2	C2	100	3.7	3.5	50	67	1.8	2.3	0
MAC5	S1	C1	100	1.7	2.0	17	17	1.0	2.0	0
	S2	C1	100	4.5	4.3	100	50	2.3	2.0	0
	S3	C1	100	4.0	4.0	67	50	1.3	1.7	0
	S1	C2	100	1.3	2.0	17	17	1.0	3.0	0
	S2	C2	100	3.2	3.3	33	17	2.0	4.0	100
	S3	C2	100	2.8	2.8	33	17	2.0	2.0	0
MAC6	S1	C1	100	1.5	2.0	17	50	1.3	2.0	0
	S2	C1	100	2.7	2.8	17	67	1.5	1.8	0
	S3	C1	100	2.7	2.5	17	83	1.4	1.6	0
	S1	C2	100	1.8	2.0	0	0	-	-	-
	S2	C2	100	4.0	3.8	67	83	1.6	1.6	0
	S3	C2	100	3.5	3.5	50	67	1.5	1.5	0
MAC7	S1	C1	100	2.7	2.7	17	83	1.4	2.0	0
	S2	C1	100	4.7	4.8	100	83	2.6	1.8	0
	S3	C1	100	3.5	3.5	33	83	2.0	1.6	0
	S1	C2	100	1.7	2.2	17	83	1.2	1.6	0
	S2	C2	100	4.2	4.2	67	83	2.6	1.8	0
	S3	C2	100	2.7	2.8	17	83	2.0	1.6	0

a *MAC: mobile air cleaner.*
b *S: setting.*
c *C: configuration.*
d *Percentage of subjects that sensed sound or air movement generated by the MAC.*
e *Unacceptability vote: assessment of sound or air movement > 3.*
f *Unacceptability percentage amongst subjects who sensed sound or air movement caused by mobile air cleaners.*
g *-: none of the subjects sensed sound or air movement generated by the mobile air cleaners.*

4.3.2.2 Air movement of the mobile air cleaners

The measured air velocity of the MACs is presented in **Figure 4.15**, and the outcome of the panel tests is in **Table 4.5**.

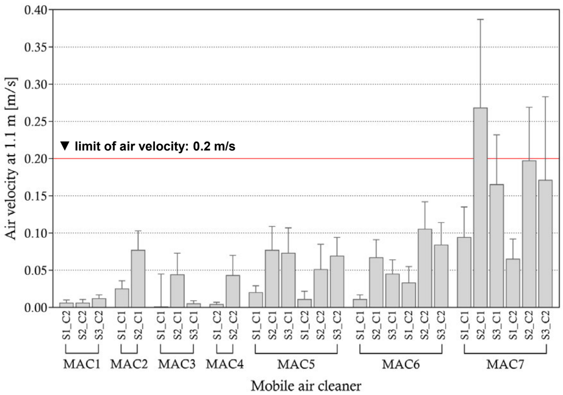

FIG. 4.15 Air velocity of tested mobile air cleaners that were placed at 1.1 m in the Experience room.
Note: the red line denotes the limit of air velocity for avoiding draught discomfort (0.2 m/s) in classrooms prescribed by the ASHRAE 55 standard [59]. MAC: mobile air cleaner; S: setting; C: configuration.

The average air velocity caused by the MACs did not exceed 0.2 m/s, which is specified in several standards and guidelines (e.g., ASHRAE 55 [59]) as the upper limit for avoiding draught discomfort (when the operative temperature is lower than 23 °C), except for MAC7 under S2 with C1 configuration. The air velocity, like the sound pressure level, did not show a linear relationship with the setting, as for some MACs the air velocities under S3 were even higher than under S2. Significant differences between the two configurations were found for MAC6 and MAC7: for MAC6, the air velocity was higher with C2 than C1 configuration, while for MAC7, it was the opposite.

The number of subjects that sensed air movement generated by the MACs was much lower than that of sound. Under S1, for most MACs less than 50% of the subjects perceived air movement, except MAC7. The average air movement intensity was mild (≤ 2) for all conditions, except for MAC5 under S2 with C1 configuration, MAC7 under S2 with both C1 and C2 configurations. Additionally, no difference was observed between the two configurations for MAC5, MAC6 and MAC7. The air movement was assessed to be acceptable under all conditions, except for MAC5 under S2 with C2 configuration. With regards to the body parts where the subjects sensed air movement, face, arms and hands were most frequently recorded (see **Appendix B.3** or dataset [58]).

4.3.3 Real classroom test

For MAC1, MAC2, MAC3 and MAC4, the optimal condition selected to be tested in the real classroom was mainly based on the results of the aerosol removal test. The optimal conditions were, for 1) MAC1 and MAC4: under S2 with C2; 2) MAC2 and MAC3: under S2 with C1 configuration. For MAC5, MAC6 and MAC7, the selection of conditions also involved the results of the panel perception test. The optimal conditions are, for 1) MAC5: under S2 with C1 configuration; 2) MAC6: under S2 with C1 configuration; 3) MAC7: under S1 with C2 configuration.

Similar to the lab experiment, the total decay rates of both $PM_{2.5}$ and PM_{10} in the real classroom amongst six sampling points were similar (see **Appendix B.4** or dataset [58]). Hence, the average total decay curves were calculated accordingly. The natural decay in the real classroom also included the aerosol removal caused by the mechanical ventilation present, resulting in a higher $k_{PM,n}$ than in the Experience room. For $PM_{2.5}$, $k_{PM,n}$ = 3.073 h^{-1}, R^2 = 0.999, and for PM_{10}, $k_{PM,n}$ = 3.190 h^{-1}, R^2 = 0.999. Same as in the lab experiment, the standardized average curves were determined using equation (4.4) for both the total decay and natural decay (see **Figure 4.16**).

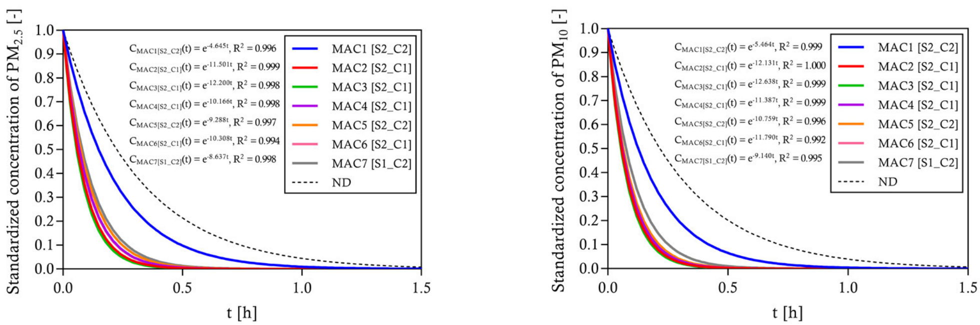

FIG. 4.16 Standardized fitted average total decay curves of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the classroom.

Note: the regression functions and R^2 are listed in the order of the test conditions (from top to bottom). The standardized average natural decay curves are plotted as the black dashed line (ND). MAC: mobile air cleaner; S: setting; C: configuration.

According to **Figure 4.16**, for $k_{PM,mac}$, MAC1 always showed the lowest results and MAC7 was tested at the lower setting, for the other MACs, the ones tested with four devices (MAC2 and MAC3) showed the highest $k_{PM,mac}$, followed by the ones with two devices (MAC4 and MAC6). The one with a single device (MAC5) produced the lowest

$k_{PM,mac}$. Furthermore, compared to the Experience room, was decreased by 47% for $PM_{2.5}$ and 41% PM_{10} for the MAC tested with one device (MAC5) in the classroom. For the MACs tested with two devices, MAC4, MAC6 and MAC7 showed similar results: $k_{PM,mac}$ was decreased by approximately 46% for $PM_{2.5}$ and 37% for PM_{10}. For MAC1, $k_{PM,mac}$ showed a much larger decrease compared to the others: 59% for $PM_{2.5}$ and 42% for PM_{10}. For the MACs tested with four devices, $k_{PM,mac}$ was decreased by 30% for both $PM_{2.5}$ and PM_{10} for MAC2, while for MAC3 $k_{PM,mac}$ was decreased by 38% for both $PM_{2.5}$ and PM_{10}.

The results of CADR are presented in **Figure 4.17** for both $PM_{2.5}$ and PM_{10}. The same as $k_{PM,mac}$, MAC1 and MAC3 showed the lowest and highest CADR. For $PM_{2.5}$, MAC4 and MAC6 reached a CADR above 918 m^3/h, while MAC2 and MAC3 reached a CADR above 1080 m^3/h. For PM_{10}, MAC5 reached a CADR above 918 m^3/h, while MAC2, MAC3, MAC4 and MAC6 reached a CADR above 1080 m^3/h. Moreover, compared to the Experience room, in the classroom, for the MAC tested with one device (MAC5), CADR was increased by 6% for $PM_{2.5}$ and 20% for PM_{10}. For the MACs tested with two devices, MAC4, MAC6, and MAC7 showed similar results, with an increase of CADR by approximately 10% for $PM_{2.5}$ and 30% for PM_{10}. For MAC1, CADR showed a decrease of 20% for $PM_{2.5}$ and an increase of 25% for PM_{10}. For the MACs tested with four devices, MAC2 showed an increase in CADR of 37% for $PM_{2.5}$ and 47% for PM_{10}, while for MAC3 CADR increased by 27% for both $PM_{2.5}$ and PM_{10}.

FIG. 4.17 CADR of $PM_{2.5}$ (left) and PM_{10} (right) for the tested mobile air cleaners in the classroom.
Note: the green lines denote the total amount of CADR based on 1) the minimum ventilation rate per person required by the Dutch Building Decree [44] (8.5 L/s/person and 918 m^3/h in total) and 2) the ventilation rate per person recommended [45,46] (10 L/s/person and 1080 m^3/h in total), with an assumption of 30 student occupancy. MAC: mobile air cleaner; S: setting; C: configuration.

4.4 Discussion

4.4.1 Assessment of aerosol removal rate and CADR

The results of the aerosol decay test clearly showed that the selected MACs were able to remove respiratory aerosols evenly at different locations in the room. However, since great differences were observed amongst the MACs, certain factors were indicated to be more important than others regarding the aerosol removal rate and CADR.

For aerosol removal, MAC1, MAC6 and MAC7 used HEPA filters, MAC3, MAC4 and MAC5 used ES filters, while MAC2 had both HEPA and ES filters (**Table 4.1**). As presented in **Figures 4.9-4.10**, MAC2 to MAC6 showed similar results, while MAC1 and MAC7 were the lowest and highest, respectively, which indicates that the air cleaning technologies used by the MACs had little influence on the differences in aerosol removal and CADR.

On the other hand, such results indicate that the aerosol removal rate and CADR of the MACs were related to the airflow patterns induced by the MACs, especially the air outlet. As shown in **Table 4.1**, MAC2 to MAC6 all supplied the clean air vertically from the top (MAC4 also horizontally from the front), while for MAC1 the airflow was supplied horizontally from the top, and for MAC7 radially at an angle of 45° above the horizontal plane. Therefore, for small- and medium-sized floor-standing MACs (standing at a height of 0.5-1 m), an air supply at a higher angle or vertically up can promote clean air to travel further and reach a wider area in the room. MAC7 was the only one equipped with a centrifugal fan while the other six all used axial fans, which might be the reason that MAC7 has a higher CADR than the others.

The aerosol removal rate and CADR of some MACs were also found to be associated with their in-room location. For instance, MAC5 showed a higher CADR of 100-150 m^3/h under C2 than C1, which might be because, with only one device used, the location closer to the center could better distribute the clean air throughout the room, giving the type of air supply it had. For MAC6, the CADR was higher by 100 m^3/h with C1 than C2 configurations, which could be due to that the middle position in the room allowed better distribution of clean air delivered horizontally from the front. For MAC7, the CADR was 130 m^3/h higher with C2 than C1 configuration under S1, yet the difference became negligible under S2. A possible explanation could be that with C2 configuration, the airflow of MAC7 was more towards the occupied zone (where the sensors were located), yet such difference was compensated by the high airflow rate under S2.

Since the tested MACs did not achieve the nominal CADR mentioned in the specifications even in the mock-up classroom, the number of devices adopted in this study (or more) should be considered necessary for practical use in real classrooms. In addition, for MAC4, MAC6 and MAC7, although the CADR of only using one device at S2 was found to be comparable with that of two devices operating under S1, such levels of CADR did not fulfil the requirements. For MAC2, the CADR of only using two devices under S2 was not better than using four devices under S1.

In summary, when adopting high efficiency (≥ H13) MACs in classrooms, it is more important to consider the induced airflow pattern generated by the devices and the air distribution in the room, which are mostly dependent on the configuration of the clean air supply and the location of the MACs. To achieve a better understanding of this, a more detailed investigation, such as computational fluid dynamics (CFD) modelling, is needed. Moreover, the aerosol removal rates can readily be used to do a risk analysis in case the aerosols contain airborne virus particles such as SARS-CoV-2 [60].

4.4.2 Assessment of sound and air movement

4.4.2.1 Assessment of sound

Overall, the SPL and perceived sound intensity of the MACs mainly increased with the settings, and higher SPLs and sound intensities often resulted in a worse sound assessment and a higher percentage of unacceptability (**Figure 4.14** and **Table 4.5**). The fact that most of the MACs need to operate at the maximum fan capacity to achieve a desired CADR inevitably led to SPLs always exceeding the prescribed limit. Still, in some cases, with maximum setting more than half of the panel subjects considered the sound to be acceptable. Similar results were found in studies conducted by Curtuis et al. [31] and Granzin et al. [38] Another factor that showed moderate influence on the sound was the air cleaning technology used. The MACs using only ES filters showed a lower SPL compared to the ones using HEPA filters at S1. This could be because of the lower resistance of ES filters for air to pass through than HEPA filters. However, such a difference became negligible when the MACs were operated under S2. Similar results were observed in the panel tests (**Table 4.5**).

Under S1, the MACs using ES filters, the panel sensed a lower sound intensity and a better sound assessment, while under S2, the votes of the panel varied a lot, and no difference was found amongst the air cleaning technologies, which might be related to the distribution of SPL amongst different frequencies. On the other hand, the airflow pattern induced by the MACs did not show any clear relationship with the sound they generated. For MAC5, MAC6 and MAC7, the SPL was similar between the two configurations, while the votes from the subjects were significantly different, which could be due to the differences in individual sensitivity and preference of the subjects who were seated closer to the devices. Furthermore, the MACs tested with multiple devices did not show a higher SPL or a worse panel assessment than the MAC tested with one device.

4.4.2.2 Assessment of air movement

Similar to SPL, the air velocity measured for the MACs mainly varied with the settings (**Figure 4.15**). It was also partially related to the induced airflow pattern. As discussed in the previous section, for MAC1, the supplied air might be hindered by the furniture in the room, and thus resulted in a low air velocity at the sampling points. For MAC7, on the other hand, because of the centrifugal fan and the narrow design of the outlet, the air was leaving the device as a concentrated jet at a high speed, which then led to a high air velocity near the occupants. The air cleaning technology and configuration of the MACs did not have any significant effect on the measured air velocities. Nonetheless, the panel's perception of the air movement caused by the MACs was not always in accordance with the air velocity measurements (**Table 4.5**). There were fewer subjects who sensed air movement from the MACs only using ES filters, yet it did not differ amongst the induced airflow patterns or configurations. The air movement intensity and assessment, however, were more dependent on these two factors. In general, the air movement caused by the MACs was mild and was assessed as acceptable by the panel, except when MAC5 was operating in front of the room, which might be due to individual sensitivity and preferences. It is thus concluded that the air movement created by the MACs had no negative effect on occupants' comfort, which agrees with the findings of Curtuis et al. [31] and Bluyssen et al. [37]. Yet, the panel tests were conducted in the summer season, and during the tests, the mean (standard deviation) air temperature and relative humidity were 24.1°C (1.1°C) and 52.2% (8.2%), respectively. Tests should be repeated in the heating season to investigate whether such air movement is still acceptable.

4.4.3 Applicability in a real classroom

The results in the real classroom (**Figures 4.16-4.17**) demonstrated the applicability of using MACs with the selected settings and configurations in classrooms for aerosol removal. In the classroom twice the volume of the Experience room, $k_{PM,mac}$ of the MACs was decreased by 30% to 60%. However, a higher CADR was observed for all MACs, except for MAC1. This leads to an important finding of this study, which is that the mechanical ventilation in the classroom helped to mix the room air during the decay phase, and most likely accelerated the aerosol removal, where $k_{PM,n}$ was increased by 1.36 times compared to $k_{PM,n}$ of the Experience room. Such a finding indicates the potential of combining mechanical ventilation and MACs in classrooms for a better IAQ, for which, nonetheless, the air distribution in the room needs to be well organized, which requires further investigation (e.g., CFD modelling). Another important observation is that, as the room size was increased, the number of devices used in the room became more crucial for aerosol removal. The MACs tested with four devices (MAC2 and MAC3) showed the lowest decrease in $k_{PM,mac}$ and the highest CADR, followed by the ones tested with two devices (MAC4, MAC6), and then the one with a single device (MAC5). This outcome shows that multiple devices (≥ 2) are necessary for applications to real classrooms to achieve a better clean air delivery.

4.4.4 Limitations

Firstly, in this study, only the removal rate of particles (aerosols) was tested for the MACs. However, to determine whether MACs can be used as a sufficient substitute for ventilation, their removal of other indoor air contaminants (e.g., microbial and gaseous contaminants) should also be investigated [20]. Furthermore, the method used in this study for assessing aerosol removal performance, i.e., the aerosols decay tests, is only suitable for MACs using air cleaning technologies that physically reduce the number of aerosols. Hence, MACs using other air cleaning technologies, such as UV-C to inactivate microbes, were not investigated. Future study is needed to obtain a more comprehensive comparison.

Secondly, the lab tests were conducted without any background ventilation, while the tests in the university classroom showed that mechanical ventilation can have certain influences on the performance of the MACs. Considering that in real classrooms there can be various ventilation conditions (natural and/or mechanical ventilation), further investigation should be performed to better understand the interactive effects between ventilation and MACs.

Thirdly, the tests were performed during summer time, while in real life, the MACs are most likely more often needed during the heating season, when natural ventilation in classrooms is limited, and the incidence of respiratory infectious diseases is, in general, higher [61-63]. Since the change in outdoor air temperature and relative humidity can affect indoor air conditions, whether the MACs can maintain steady performance during different seasons remains unclear. Moreover, the change in indoor and outdoor air temperature and relative humidity can also affect occupants' perception of the MACs.

Fourthly, the panel recruited for the perception test only contained eight adults, which was a rather small sample, and the subjects' psychological and physiological responses to the indoor environment may differ from pupils. Thus, the results may not be sufficiently representative. Moreover, for the test in the real classroom, the perception test was not included. To comprehensively evaluate the performance of MACs in practical use, further research on their sound together with other background sound sources (e.g., HVAC installation), the sound perception and acceptability during actual teaching and learning activities, as well as the air movement and draught discomfort (possibly with background ventilation and/or infiltration), is needed.

Finally, investigations on the cost and difficulty of maintenance and a possible efficiency degradation over time of the MACs were not included, which are also important factors to be considered for real-life usage.

4.5 Conclusions and recommendations

For reducing respiratory aerosols in school classrooms, a large number of MACs were found available on the market. Several criteria, including the air cleaning technology used, the filter efficiency level, the fan capacity and the noise level, etc., can be set for preliminary selection. In this study, seven small- and medium-sized commercial floor-standing MACs were selected and tested to investigate proper strategies for practical use. The following conclusions and recommendations can be drawn:

Overall, the MACs with high-efficiency filters (filter class ≥ H13) all have the ability to remove aerosols in the room besides the natural decay. However, the primary criterion for using MACs in classrooms is to provide an adequate amount of clean air, which not all the tested MACs could achieve. A key factor to this is the airflow pattern induced by the device, especially the air outlet. In general, the MACs with an upward (either vertical or angled) air supply can better distribute the clean air throughout the room compared to the ones with a horizontal air supply. Meanwhile, the location of the devices is also crucial, as it can greatly influence the air distribution in the room, which thus needs to be well configured. Briefly, the supply airflow should be towards the occupied zone as much as possible. On the other hand, the main air cleaning technology for aerosol filtration used by the MACs, namely HEPA or ES, did not play an important role. Furthermore, with the room size increasing, higher CADRs were observed with multiple devices compared to a single device, which suggests that two or more devices should be adopted for real-life usage. The test in the real classroom also indicated the advantage of using both mechanical ventilation and MAC for better aerosol removal, which, nonetheless, requires careful configuring.

Two other critical factors of the applicability of MACs in classrooms are noise and draft, which could vary mainly with the setting of the MACs. For sound, although at the maximum setting, the SPL always exceeded the prescribed limit, the assessment of the panel varied amongst different conditions. For the draught, the air velocities in general fulfilled the requirements, and the panel also provided positive feedback for the air movement. It is thus important to involve the evaluation by a panel of subjects to optimize the use of MACs in classrooms with minimum compromise of both the devices' performance and occupants' comfort.

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Part II: Feasibility and efficiency of using mobile air cleaners in school classrooms to remove respiratory aerosols

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ABSTRACT

To investigate the feasibility of using mobile air cleaners (MACs) in real-world classrooms for reducing respiratory aerosols, a follow-up field study was conducted based on previous tests at Delft University of Technology. Three MACs were selected and tested across 45 classrooms in five Dutch primary schools. The classrooms were divided into three groups, each assigned one of the MAC types with two devices. The placement of the MACs was adjusted based on the available space and power supply locations, yet still ensuring that one device was placed at the front and one at the back, with the air supply facing the occupied area. User instructions were provided for each device. In each school, one classroom from each group was monitored for indoor air quality (IAQ) parameters – $PM_{2.5}$, PM_{10}, CO_2, and VOC – over six weeks, alternating between three weeks with the MACs on and three weeks off. The results showed that the MACs proved to work well at the pre-determined settings and (adjusted) locations. All MACs significantly reduced the concentrations of $PM_{2.5}$ and PM_{10} in the classrooms when turned on compared to the off state. Recommendations are provided for conducting more comprehensive studies in the future.

KEYWORDS mobile air cleaners, respiratory aerosol, indoor air quality, classroom, children

4.6 Introduction

Airborne pathogen-laden respiratory particles, also known as respiratory aerosols, are the primary transmission route for respiratory infectious diseases such as COVID-19 [1]. These aerosols are expelled when individuals breathe, speak, cough, or sneeze. School classrooms, with their high occupancy and long hours of use, present a heightened risk for cross-infection [2]. To address this issue, mobile air cleaners (MACs) have been proposed as a supplementary solution for classrooms with limited ventilation [3].

In our prior study [4] (**Part I** of **Chapter 4**), a comprehensive assessment was conducted on different types of mobile air cleaners (MACs) to provide a reference for practical use in classrooms. Initially, 152 products were pre-selected from over 300 market options, followed by categorization and comparison based on technical specifications, feasibility, and affordability. Seven MAC models (MAC1 to MAC7) were then selected for further assessment, representing a variety of air cleaning technologies, airflow patterns, fan capacities, and dimensions. These MACs were tested under different fan settings and configurations (location and number of devices) in the Experience Room of the SenseLab at Delft University of Technology, which is half the size of a typical classroom (70 m^3) and mimics a classroom interior.

The assessments included two key tests: 1) an aerosol decay test, which monitored aerosol concentration over time after filling the room with aerosols generated by a specific spraying technique, to calculate the aerosol removal rate and clean air delivery rate (CADR); and 2) a panel perception test: a panel of subjects was recruited to assess noise and air movement generated by the MACs, combined with measurements of sound pressure level and air velocity. Based on the results, the optimal condition of each type of MAC was determined, balancing adequate air cleaning with acceptable noise levels.

The outcome of the experimental study was further validated by repeating the aerosol decay test in a real classroom (139 m^3) within the Faculty of Architecture and the Built Environment at Delft University of Technology. The MACs were operated under the pre-determined optimal conditions from the initial study. The results showed that MACs with multiple devices achieved better CADR in the larger room compared to the Experience room. Moreover, the background mechanical ventilation further enhanced aerosol removal. Therefore, as a continuation of the previous study [4], this research aims to investigate the feasibility of using the selected mobile air cleaners (MACs) in real classroom settings.

4.7 Methods

4.7.1 Selection of schools and classrooms

Following the studies conducted in the lab and the university classroom, a field study was carried out in November and December 2023. Five Dutch primary schools (designated as School 1 to School 5) voluntarily participated in the research. School 1 has eight classrooms, and School 3 has ten classrooms, while the other schools each have more than ten. Thus, all classrooms from Schools 1 and 3 were included in the study, whereas nine classrooms were selected from each of the remaining schools, resulting in a total of 45 classrooms. The selected classrooms spanned all age groups (5-12 years old) and were coded numerically based on their school. These classrooms were similar in size, with floor areas ranging from 40 to 50 m^2, typically accommodating 20 to 25 individuals. All classrooms had multiple openable windows and doors for natural ventilation, except for those in School 1, which were additionally equipped with a balanced mechanical ventilation system.

4.7.2 Installation and operation of the mobile air cleaners

Based on the results of prior tests [4], three MACs – MAC4, MAC6, and MAC7 – were selected for use in the classrooms and are referred to as MAC-A, MAC-B, and MAC-C, respectively. Detailed information on these MACs is provided in **Table 4.6**. In School 1, two classrooms were assigned MAC-C, three classrooms received MAC-A, and another three were assigned MAC-B. In School 3, four classrooms were equipped with MAC-C, three with MAC-A, and three with MAC-B. For the remaining schools, the three MAC types were evenly distributed across the nine selected classrooms. The allocation of the MACs was determined randomly, with each classroom having two devices, as recommended by the prior tests [4].

TABLE 4.6 Information on the selected mobile air cleaners.

Device[a]	Air cleaning technology[b]	Airflow pattern	Fan capacity (CADR)[b] [m^3/h]	Settings	Efficiency[b]	Noise level[b] [dB(A)]	Dimensions[b] [cm]	Number of devices	Price (including VAT)[b] [€]
MAC-A	ES + AC	No.12	735	1-3	H13	27-55	34.0 × 34.0 × 85.5	2	1100
MAC-B	HEPA	No.11	565	1-8	H13	18-51	33.2 x 33.6 x 60.6	2	500
MAC-C	HEPA	No.15	750	1-8	H13	26-65	68.8 (Φ) x 25.4	2	1500

a MAC: mobile air cleaner.
b As specified by the brand.
c The numbers refer to the airflow patterns numbered in ***Figure 4.2****.*

The schools were visited during the first week of November 2023, and the MACs were delivered to the classrooms. Although the ideal placement of the MACs was outlined in **Table 4.4**, it was found that many classrooms were crowded and cluttered, limiting available space for the devices. As a result, the MACs' placement had to be adjusted for each classroom. Despite these challenges, it was ensured that in every classroom, one MAC was positioned at the front and one at the back, with the air supply directed toward the occupied area. Additionally, many classrooms lacked sufficient power outlets, requiring the use of extension cords and splitters to plug in all necessary devices.

For MAC-A and MAC-B, it was recommended to operate them at their maximum settings, while MAC-C was advised to be used on its low setting, as specified in **Table 4.4**. Clear instructions were provided on each device, guiding users on how to switch the devices on and off and adjust them to the suggested settings. These instructions were placed by the researchers to ensure ease of use and proper operation throughout the study.

Starting from the second week of November 2023, the field study spanned six weeks, divided into two three-week periods where the MACs were alternately turned ON and OFF(referred to as "ON period" and "OFF period", respectively). In Schools 1, 4, and 5, the study began with the ON period. During this period, school directors and teachers were instructed to switch the MACs on at the start of each school day and off at the end. After the first three weeks, the MACs were turned OFF for the subsequent three weeks. Conversely, in Schools 2 and 3, the first three weeks were OFF, followed by three weeks with the MACs turned ON.

4.7.3 Monitoring indoor air quality in the classrooms

The main indoor air quality (IAQ) parameters investigated in this study were aerosols, CO_2, and volatile organic compounds (VOCs). Aerosols, either liquid droplets or solid particles, can originate from various indoor and outdoor sources. Indoor sources include: 1) respiratory droplets generated by humans when breathing, speaking, coughing, or sneezing, which are responsible for the transmission of respiratory diseases; 2) dust, such as human dander and textile fibers, which become aerosolized through activities like sweeping or rubbing clothes; and 3) mould. Outdoor sources include pollution particles from car traffic and nearby industries, which can enter the room via natural (window opening) or mechanical ventilation.

CO_2 is often used as a proxy for the presence of humans since human breath is the only source of CO_2 which, when doors and windows are closed, accumulates in the air without escaping. VOCs are chemical gases that may or may not be smelled such as benzene, ethylene glycol, formaldehyde, methylene chloride, tetrachloroethylene, toluene, xylene, and 1,3-butadiene. Indoor sources include perfume, flatulence as well as cleaning products. They may also be released from building materials such as paint, varnishes, caulks, adhesives, carpets and vinyl flooring.

In each school, IAQ was monitored in three classrooms, each equipped with a different type of MAC (one with MAC-A, one with MAC-B, and one with MAC-C). The following parameters were monitored:

- CO_2 (carbon dioxide) concentration [ppm].
- $PM_{2.5}$ (airborne particles of diameter < 2.5 μm) concentration [μg/m^3]
- PM_{10} (airborne particles of diameter < 10 μm) concentration [μg/m^3]
- TVOC (total volatile organic compounds) concentration [ppb].

CO_2 concentration was measured using the MH-Z19B sensor, with a range of 0-2000 ppm and an accuracy of ±50 ppm. For measuring $PM_{2.5}$ and PM_{10} concentrations, different sensors were used in the schools: Schools 1, 2, and 4 employed the SDS011 sensor (range: 0-999.9 μg/m^3, accuracy: ±10%) [5], while Schools 3 and 5 used the PMS5003 sensor (range: 0-5000 μg/m^3, accuracy: ±10% for concentrations < 100 μg/m^3) [6]. Total VOC (TVOC) concentration was measured using the SGP30 sensor, which had a range of 0-60000 ppb and varying accuracy levels: 1 ppb (0-2008 ppb), 6 ppb (2008-11110 ppb), and 32 ppb (11110-60000 ppb).

In the monitored classrooms, the sensors were integrated on one panel (hereafter referred to as the "IAQ sensor") and were all connected to a central unit from which data is saved on a SD card, with a logging interval of 5 minutes. The IAQ sensors were mostly placed on the teachers' desk for data collection.

4.7.4 Data analysis

During data cleaning, it was found that although the IAQ sensors functioned properly for most of the six-week period, some devices occasionally had gaps in data collection. These interruptions, which lasted up to two days, were likely caused by teachers accidentally unplugging the sensors and then reconnecting them later. Additionally, the IAQ sensor in Classroom 504 of School 5 (equipped with MAC-A) malfunctioned shortly after installation and could not be repaired, resulting in no data for that room. Moreover, certain days were excluded from the analysis, such as during the Sinterklaas break on December 6th, 2023, and instances when teachers forgot to turn the MACs on. This resulted in the exclusion of 30 out of a possible 420 classroom days of data, or 7% of the total expected dataset.

Further data trimming was performed based on the classroom schedules, removing unoccupied hours from the analysis. The IAQ parameter concentrations were compared between the ON and OFF periods for each classroom using Mann-Whitney *U*-tests. Additionally, the average concentrations across all classrooms were compared between the ON and OFF periods using Wilcoxon signed-rank tests. All analyses were conducted using IBM SPSS 28.0, with a significance level set at $P < 0.05$.

4.8 Results and discussion

The median and interquartile range of the daily average concentrations of the four IAQ parameters of each classroom during the ON and OFF periods are presented in **Table 4.7**. For $PM_{2.5}$, the mean concentration in each classroom ranged from 0.87 to 3.76 μg/m^3 during the ON period, and from 2.22 to 10.36 μg/m^3 during the OFF period, representing an approximate twofold reduction when the MACs were turned on. Similarly, for PM_{10}, mean concentrations ranged from 1.88 to 8.45 μg/m^3 during the ON period and from 3.48 to 16.20 μg/m^3 during the OFF period, also indicating a twofold decrease. In contrast, CO_2 concentrations remained fairly consistent, ranging from 777.2 to 1277.9 ppm during the ON period and from 786.6 to 1302.8 ppm during the OFF period. Likewise, TVOC concentrations were similar between the two periods, ranging from 544.5 to 7105.9 ppb during the ON period and from 537.5 to 5758.8 ppb during the OFF period. Overall, $PM_{2.5}$ and PM_{10} concentrations were consistently lower during the ON period across all classrooms, while CO_2 and TVOC levels showed no clear trend, fluctuating between the ON and OFF periods depending on the classroom. Additionally, the range of daily average $PM_{2.5}$ and PM_{10} concentrations was narrower during the ON period, unlike CO_2 and TVOC, which had similar ranges in both periods.

The results of the Mann-Whitney *U*-tests, as presented in **Table 4.7**, indicate that $PM_{2.5}$ and PM_{10} concentrations were significantly lower during the ON period compared to the OFF period across all monitored classrooms, except for classroom 203. This significant reduction was observed regardless of the type of MAC used or whether the classroom began with the ON or OFF period. Such results indicate good aerosol removal performance of the selected MACs to remove aerosols in primary school classrooms, which align with the findings of the previous tests conducted in the lab and the university classroom [4]. However, the differences in CO_2 and TVOC concentrations between the ON and OFF periods are also found to be significant in most of the classrooms. Yet unlike $PM_{2.5}$ and PM_{10}, for CO_2 and TVOC, the concentrations can be both higher or lower during the ON period compared to the OFF period, varying among the classrooms.

Hence, to further confirm that the reduction of $PM_{2.5}$ and PM_{10} during the ON period was primarily due to the operation of MACs instead of other factors (e.g., variations in classroom conditions), a Wilcoxon signed rank test was performed. This test compared the classroom-averaged concentrations of each IAQ parameter between the ON and OFF periods, using the data from **Table 4.7** as paired samples. The results, presented in **Table 4.8**, clearly show that the differences between the ON and OFF periods are statistically significant only for $PM_{2.5}$ and PM_{10}, reinforcing the conclusion that the MACs were effective in reducing aerosol concentrations. Furthermore, the Wilcoxon test results indicate that the MACs had no significant impact on CO_2 concentrations, as expected, given that CO_2 levels are primarily influenced by human respiration and ventilation, not air cleaning devices. Interestingly, there was also no significant reduction in TVOC concentrations, even though MAC-A includes an activated carbon filter, which is typically designed to capture VOCs.

TABLE 4.7 Median and interquartile range of the daily average concentrations of the IAQ parameters in the classrooms and the comparison between the ON and OFF periods.

School	MAC	$PM_{2.5}$ [µg/m³]			PM_{10} [µg/m³]			CO_2 [ppm]			TVOC [ppb]		
		ON[a]	OFF[a]	P[b]	ON	OFF	P	ON	OFF	P	ON	OFF	P
1	MAC-B	0.6 (0.4-0.8)	1.8 (1.0-3.1)	< 0.001	4.5 (3.4-5.7)	7.1 (5.7-9.1)	< 0.001	1100 (940-1273)	1199 (1069-1379)	< 0.001	1047 (487-1976)	1241 (685-2293)	< 0.001
	MAC-C	1.1 (0.9-1.6)	3.3 (2.1-4.7)	< 0.001	5.3 (4.0-6.9)	9.6 (7.3-13.1)	< 0.001	1033 (893-1241)	1102 (941-1243)	< 0.001	898 (558-1240)	1060 (595-1652)	< 0.001
	MAC-A	1.2 (0.9-1.9)	2.9 (1.8-4.5)	< 0.001	4.7 (3.4-6.7)	8.6 (6.8-11.8)	< 0.001	890 (783-1073)	1040 (909-1235)	< 0.001	953 (469-1281)	1071 (634-1861)	< 0.001
2	MAC-B	2.0 (1.1-3.8)	2.5 (1.9-3.8)	< 0.001	6.0 (4.3-8.3)	10.7 (8.6-14.8)	< 0.001	839 (728-923)	776 (698-843)	< 0.001	659 (391-1534)	445 (255-676)	< 0.001
	MAC-C	1.4 (0.9-2.2)	2.5 (2.0-3.2)	< 0.001	7.0 (5.5-9.1)	15.3 (12.1-18.9)	< 0.001	1242 (946-1525)	988 (830-1189)	< 0.001	2254 (1237-3705)	1519 (794-2646)	< 0.001
	MAC-A	2.3 (1.1-4.0)	2.3 (1.7-3.3)	0.040	5.9 (3.5-10.0)	9.1 (6.9-11.6)	< 0.001	752 (686-823)	757 (680-837)	0.518	372 (244-557)	442 (257-745)	< 0.001
3	MAC-B	1.0 (0.0-3.0)	4.0 (2.0-7.0)	< 0.001	2.0 (0.0-4.0)	4.0 (2.0-8.0)	< 0.001	850 (735-955)	834 (733-923)	0.024	3630 (1563-7043)	2196 (1309-3369)	< 0.001
	MAC-C	2.0 (1.0-4.0)	3.0 (2.0-5.0)	< 0.001	3.0 (1.0-5.0)	5.0 (3.0-7.0)	< 0.001	937 (830-1189)	896 (654-1072)	< 0.001	1792 (863-3327)	941 (346-2127)	< 0.001
	MAC-A	1.3 (1.0-2.4)	3.2 (2.1-5.1)	< 0.001	5.5 (4.1-7.4)	9.8 (7.4-13.1)	< 0.001	1135 (961-1356)	1327 (1050-1548)	< 0.001	1812 (770-2717)	3123 (2096-6060)	< 0.001
4	MAC-B	1.2 (0.9-2.2)	2.5 (1.6-4.0)	< 0.001	7.6 (5.3-10.2)	8.6 (6.5-11.6)	< 0.001	873 (748-985)	896 (748-984)	0.460	807 (493-1513)	764 (354-1427)	0.002
	MAC-C	0.9 (0.6-1.5)	1.8 (1.1-2.8)	< 0.001	3.5 (2.3-5.1)	5.3 (3.8-7.5)	< 0.001	1144 (903-1373)	1136 (937-1326)	0.660	1633 (800-2995)	2323 (1010-4417)	< 0.001
	MAC-A	1.3 (1.0-2.4)	3.2 (2.1-5.1)	< 0.001	5.5 (4.1-7.4)	9.8 (7.4-13.1)	< 0.001	1135 (961-1356)	1327 (1050-1548)	< 0.001	1812 (770-2717)	3123 (2097-6060)	< 0.001
5	MAC-B	1.0 (0.0-3.0)	8.0 (3.0-16.0)	< 0.001	2.0 (1.0-4.0)	10.0 (5.0-17.0)	< 0.001	720 (569-954)	830 (648-1010)	< 0.001	923 (477-1584)	630 (287-1343)	0.648
	MAC-C	1.0 (0.0-2.0)	6.0 (3.0-10.8)	< 0.001	1.0 (0.0-3.0)	6.0 (3.0-11.0)	< 0.001	1047 (909-1207)	1159 (967-1324)	< 0.001	547 (386-824)	683 (470-1044)	< 0.001
	MAC-A[b]	-	-	-	-	-	-	-	-	-	-	-	-

a Concentration: median (interquartile range). / b P-value of Mann-Whitney U-tests. / c No data due to sensor error.

TABLE 4.8 Comparison of IAQ parameters between ON and OFF periods with Wilcoxon signed rank tests.

IAQ parameter	ON[a]	OFF[a]	P[b]
$PM_{2.5}$ (µg/m^3)	1.2 (1.0-1.55)	3.0 (2.5-3.5)	0.001
PM_{10} (µg/m^3)	5.0 (2.8-5.9)	8.9 (5.8-9.9)	< 0.001
CO_2 (ppm)	985 (847-1135)	1014 (833-1169)	0.158
TVOC (ppb)	1000 (770-1812)	1066 (670-2228)	0.925

a *Concentration: median (interquartile range).*
b *P-value of Wilcoxon signed rank tests.*

Nonetheless, due to the fact that no other filtration was adopted for the outdoor air coming into the monitored classrooms (via either natural ventilation or mechanical ventilation), as well as that the IAQ sensor used in this study was not able to differentiate the source of the aerosols detected, how good the selected MACs were at reducing respiratory aerosols cannot be determined. Still, a general conclusion can be drawn that the MACs effectively removed all kinds of aerosols in the classrooms. Moreover, the significant differences found in CO_2 and TVOC for individual classrooms might be due to the great variation of the concentrations throughout the day.

4.9 Conclusions and recommendations

In this study, a field investigation was conducted in five Dutch primary schools, building on the findings of a prior experimental study that determined the types of mobile air cleaners (MACs) to be used, as well as their optimal settings and placements within classrooms. A total of 45 classrooms were equipped with MACs, and 15 of these classrooms were monitored over a six-week period. During this time, the MACs were alternately turned on for three weeks and off for another three weeks, allowing for a comparison of indoor air quality under both conditions.

The results showed that, despite the limited space in many classrooms preventing the MACs from being placed exactly as determined in the experimental study [4], they still performed effectively. By maintaining one key rule – placing one MAC in the front and one in the back, with the air supply directed towards the occupied zone – the devices successfully reduced $PM_{2.5}$ and PM_{10} concentrations when turned on compared to the off state.

Although measuring indoor air quality (IAQ) at only one point in the classroom (near the teacher) is not fully representative of the whole space [7], it was sufficient for this pilot study to demonstrate the MACs' effectiveness. However, to assess whether MACs can clean the air uniformly throughout the classroom, future studies should include more sampling points.

For better determining the cleaning effect of the MACs on respiratory aerosols rather than all aerosols in the air, it is recommended to also monitor the outdoor PM concentrations at each school close to the school buildings, simultaneously with the indoor measurements. In addition, since respiratory aerosols that linger in the air can be as small as 0.3-0.5 μm, future studies should consider monitoring $PM_{1.0}$ concentrations.

Acknowledgements

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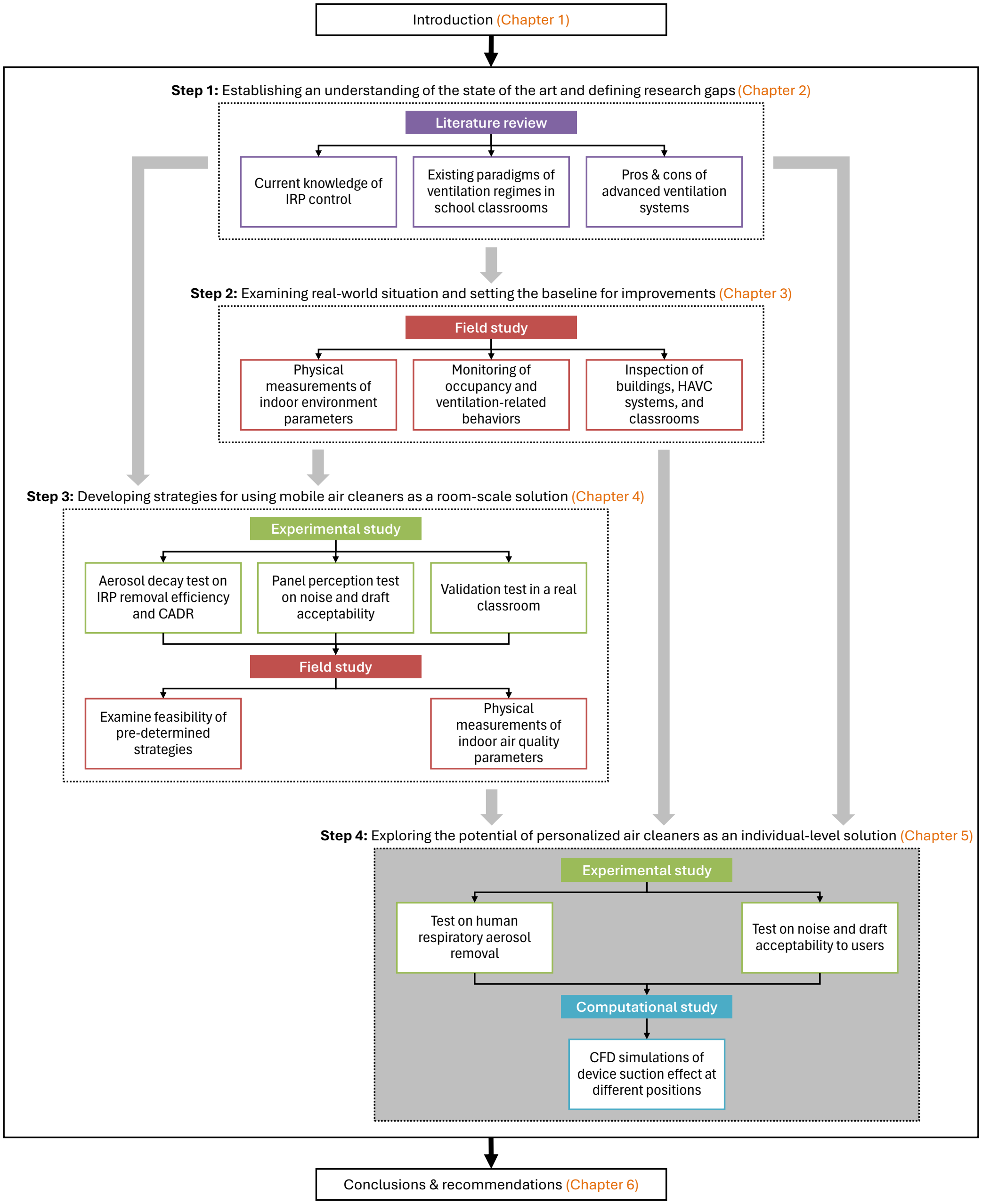

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TOC

5 Exploring possibility

Personalized air cleaners as an individual localized exhaust

Feasibility of a personalized air cleaner as a localized exhaust for short-range respiratory aerosol removal in classroom settings: A pilot study

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ABSTRACT

In this study, the feasibility of a personalized air cleaner (PAC) as a localized exhaust for short-range respiratory aerosol removal in a classroom setting was explored, aiming to combining the strengths of personalized exhaust systems and mobile air cleaners. The PAC's respiratory aerosol removal efficiency, along with noise and draft acceptability, was experimentally evaluated using human subjects, while computational fluid dynamics (CFD) simulations were employed to assess the impact of PAC positioning on suction efficacy. Experimental results showed that the PAC significantly reduced aerosol concentrations by 40%-51%, especially for particles under 1.0 μm, attributed to strong air recirculation in a confined setup. CFD simulations identified vertical positioning as the most promising; however, the PAC's suction effect was highly localized and diminished rapidly with distance, hardly reaching the occupant's breathing zone at full-room scale. Compared to other PE systems, the PAC operates at a lower airflow rate, yet increasing airflow may lead to unacceptable noise levels, as observed in the perception tests. Other modifications, such as a larger suction surface or closer placement to occupants, warrant consideration but require careful planning and design optimization. Overall, the PAC demonstrated potential as a localized air cleaning solution, while further comprehensive studies are needed to better understand the performance of PAC in real-world situations, as well as to optimize its design.

KEYWORDS personalized air cleaner, localized exhaust, classroom, respiratory aerosol removal, suction effect, perception evaluation

5.1 Introduction

The COVID-19 pandemic has highlighted the critical role of proper ventilation and air cleaning in maintaining healthy indoor air quality (IAQ). In densely populated school classrooms, the proximity of students and prolonged contact increases the risk of cross-infections through the spread of pathogen-laden respiratory particles [1-3]. Studies suggest that implementing proper ventilation and air-cleaning strategies in school classrooms can significantly mitigate the airborne transmission of respiratory particles (also called respiratory aerosols), thereby reducing the risk of infection among students and teachers [4,5]. Given the current situation in school classrooms, further improvements are needed not only to better prepare for future crises but also to provide a safe indoor environment daily [6-8].

Respiratory aerosols can transmit via both long-range and short-range routes, each with distinct characteristics and implications for infection control [9]. Short-range transmission of respiratory aerosols often occurs during close contact (within 1-2 m) between indoor occupants, involving direct inhalation of particles, normally with a size smaller than 50 μm [10-12]. Long-range transmission of respiratory aerosols, on the other hand, involves the spread of smaller particles (typically less than 5 μm) over greater distances, often carried by indoor airflows [13,14]. Previous studies have shown that conventional room-based ventilation or air-cleaning methods can effectively control the long-range transmission of respiratory aerosols, which are often treated as steady-state conditions [9,15,16]. The short-range transmission of respiratory aerosols, conversely, is a highly dynamic process that is more affected by the human microenvironment and the interaction of breathing flows [13,17,18]. Hence, different manners of ventilation or air-cleaning are needed, especially for indoor spaces like school classrooms, where close contact is common and short-range transmission may prevail [19,20,21].

Personalized ventilation (PV) and personalized exhaust (PE) systems have been widely proposed for addressing the short-range transmission of respiratory aerosols [12,18,22]. While both aim to improve IAQ and reduce airborne infection risks, they function differently and offer distinct advantages. PV systems provide clean, cool, and controlled air directly to the occupants' breathing zone, enhancing inhaled air quality and thermal comfort while reducing energy consumption [23,24,25]. Extensive studies have demonstrated their significant reduction in the inhalation fraction of respiratory aerosols, thereby lowering the infection risk [26-29]. However, the effectiveness of PV systems can be influenced by pollution source locations and airflow rates, with higher flow rates sometimes leading to increased mixing of pollutants [9,30]. In contrast, PE systems focus on directly removing exhaled contaminants from the vicinity of the infected individuals, thereby reducing the intake fraction of pollutants for the healthy ones, and their efficacy has also been well-proven [31-34]. Additionally, PE systems can be particularly beneficial in high-risk environments, such as hospital wards and aircraft cabins, by creating a microclimate with cleaner air around each occupant [32,35]. To date, PV systems have garnered the most research interest, while PE systems are much less discussed. However, based on the existing evidence, PE systems have already shown a better ability to remove respiratory aerosol and reduce infection risk, sometimes even at lower airflow rates, when compared with PV systems under the same conditions [9,34]. In addition, unlike PV systems that require equal airflow rates for every occupant to ensure safe IAQ conditions, PE systems are more flexible as they quickly remove the exhaled air, which is of great significance when the infected status of individuals is unknown [27].

Although the performance of PV and PE systems has long been acknowledged, they are not yet widely implemented in practice. One reason for this is the necessity to integrate these systems with existing room ventilation systems, which may not be feasible in many buildings with ceiling-mounted ventilation installations [36]. School classrooms, often relying on natural ventilation and characterized by limited free space, pose additional challenges for implementing PV or PE systems [2,37]. This also explains why previous studies have primarily focused on specialized indoor environments such as hospital wards or aircraft cabins, where the demand for contaminant removal is high, and integrated ventilation system designs are more viable. The outcome of such studies, however, is hardly applicable to school classrooms due to the significant differences in indoor settings and occupants' activities. Moreover, while studies in offices can serve as a closer reference, the typically discussed desk-based PV systems [23,24] may obstruct students' sightlines, making them unsuitable for teaching and learning activities [38]. Therefore, specific design is needed for school classrooms, yet relevant studies are limited. Conceição et al. [39] designed a desk-type PV system for duo-student desks, with two air terminal devices (ATDs) above the desk facing the trunk area, and two ATDs below the desk facing the leg area. The PV system was first evaluated with a single occupant [39], and then double occupants with a specific location near a window with solar radiation [40], via both computational fluid dynamics (CFD) simulations and experimental tests. It was also assessed numerically for a full-scale classroom with multiple occupants [41]. However, such evaluations focused on the thermal aspects, namely thermal comfort, and draft risk, while for IAQ, only CO_2 concentration was included. Overall, the results have indicated that the desk-type PV system can help maintain acceptable thermal comfort levels, while the relative position of the airflow to the body and the air velocity at the ATDs are important for the distribution of clean air and local draft discomfort. Katramiz et al. [38], on the other hand, developed a chair-based PV-PE system with clean air supplied from an upward outlet located on the front-row seatback, and exhaled air extracted from the top of the own seatback. The inlet of the PV-PE system was integrated with the air supply of the background displacement ventilation on the floor, while the extracted exhaled air was exhausted towards the ceiling. It is revealed that the directing effect of the PV flow and the shielding effect of the PE flow together resulted in an air-curtain effect, which significantly decreased the occupants' exposure to respiratory aerosols. Furthermore, the strength of such an effect was dominated by the PE airflow rate, underscoring the crucial role of PE systems in aerosol control.

Nonetheless, the proposed designs were developed based on existing background mechanical ventilation systems, making them impractical for many schools soon. Meanwhile, driven by the COVID-19 pandemic, a new type of personalized device for IAQ control has emerged: the personalized air cleaner (PAC). For instance, Guiot et al. [42] developed a stand-alone PAC using UV-C to deliver clean air to individual occupants. Tested numerically in an office setting, the PAC was positioned on the desk, directing air upward toward the occupant's breathing zone at a velocity of 0.65 m/s. The results have proven the effectiveness of the PAC in shielding occupants from indoor air contaminants, particularly under conditions of natural ventilation (opening window) or no ventilation. It thus sheds insights into potential applications in school classrooms, where alternative utilization of PACs, such as locally exhausting exhaled aerosols, akin to a PE system rather than a PV system, can be further explored.

Therefore, this study aims at exploring: 1) as a localized exhaust, the PAC's efficiency for removing short-range respiratory aerosol, as well as its acceptability regarding noise and draft for the occupants, in a classroom setting; and 2) the impact of the PAC's positioning on its suction effect.

5.2 Methods

5.2.1 Study design

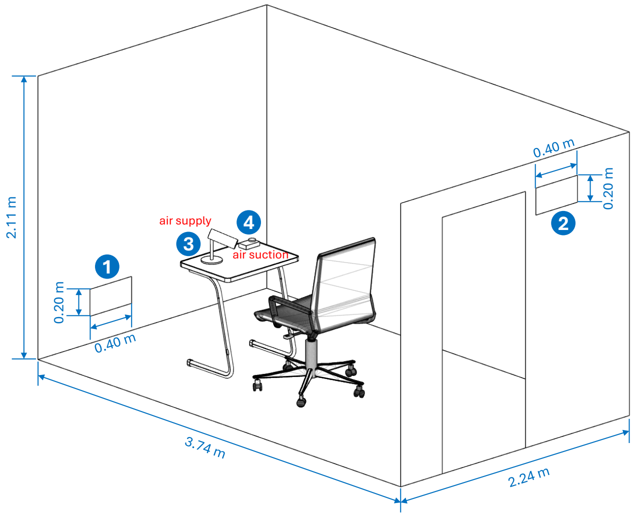
It should be noted that the present study is a pilot study to first explore the feasibility of a novel device, i.e., a PAC. Hence, the research methods were selected accordingly to serve such a purpose. This study consisted of two components: 1) experimental tests: a group of human subjects was recruited to first assess the noise and draft caused by a pre-selected PAC to determine suitable settings for practical use, and then to be the source of respiratory aerosols to evaluate the aerosol removal efficiency of the PAC; and 2) CFD simulations: based on the results of the experimental tests, the suitable settings were modelled under various conditions to identify the PAC's suction effect under different positioning.

5.2.2 Experimental tests

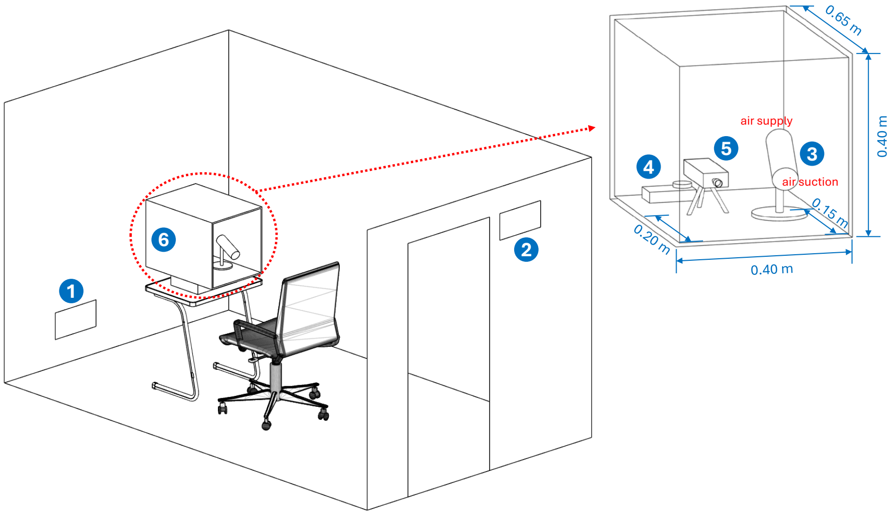
5.2.2.1 Experimental setup

Experimental facilities

The experiments were performed within a test chamber of the SenseLab at the Delft University of Technology [43]. The test chamber measures 3.74 (l) × 2.24 (b) × 2.11 (h) = 17.68 m^3, with one door and no windows. Ventilation is provided by an air handling unit equipped with an H14 HEPA filter, typically operating at an airflow rate of 160 m^3/h. The air supply grille (0.4 m × 0.2 m) is located at the bottom of the back wall, while the air exhaust grille (0.4 m × 0.2 m) is at the top of the front wall, functioning based on overflow. The test chamber's interior was arranged to simulate a study environment, with a desk and chair placed at the center of the room. The experiment setup is illustrated in **Figure 5.1**.



a)



b)

FIG. 5.1 Experiment setup in one of the test chambers of the SenseLab: (a) perception test; (b) aerosol removal test.

Note: 1 – ventilation air inlet grille; 2 – ventilation air outlet grille; 3 – personalized air cleaner; 4 – CO_2/ temperature/RH data logger; 5 – particle counter; 6 – cardboard box.

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Subjects

In total, 16 undergraduate and graduate students (seven female and nine male) from the Faculty of Architecture and the Built Environment at the Delft University of Technology were recruited as subjects, all in good health. The power level (1-β error probability) was calculated to be 0.6, via a post-hoc analysis giving an effect size of 0.5, a significance level of 0.05, and a sample size of 16. The average age of the subjects was 22.1 years (standard deviation 3.1 years). All the subjects were informed in advance not to smoke or use strong perfume/skin care products on the days of the experiments. This study was approved by the Human Research Ethics Committee (HREC) of the Delft University of Technology on November 15th, 2023 (Case ID: 3555).

Selection of personalized air cleaner

Same to the selection procedure taken in our prior study on mobile air cleaners [16], to identify a PAC suitable for individual use in a school classroom, over 300 relevant products available on the market were evaluated. As a result, only seven air cleaners were classified to be desk-based. Although claimed desk-based, many of these air cleaners presented a size exceeded the practical dimensions for placement on a student desk. After excluding air cleaners with dimensions larger than 30 cm (deemed to be impractical for individual student desk placement), only two products remained. Subsequently, the more suitable one, considering factors such as air cleaning technology (not using UV-C), noise level, cost, etc., was selected. The PAC tested in this study is cylindrical, with a size of 7 cm (diameter) × 15 cm (length). It uses an electrostatic filter for aerosol removal, with dirty air being drawn in from one end and clean air being expelled from the other end via an axial fan. The PAC has two settings, level 1 and level 2, corresponding to different fan speeds. Its nominal maximum clean air delivery rate (CADR) is 18 m^3/h. The PAC has a stand and was always positioned in reverse during the experiments, with the suction side facing the subjects to immediately exhaust exhaled air in the vicinity.

Perception test

In our previous study [16], it was found that the noise generated by mobile air cleaners was the most significant factor negatively impacting user perception of these devices. During a pre-test, the sound pressure levels of the empty test chamber, the PAC operating at level 1, and the PAC operating at level 2, were measured using a Norsonic sound analyzer (model: Nor140) for a duration of 2 minutes each. During the pre-test, the PAC and sound analyzer were placed on the desk, at 20 cm. The results were 30.6 dB(A), 48.8 dB(A), and 70.4 dB(A), respectively. Subsequently, a perception test was first performed to assess the subjects' perception of noise and draft caused by the PAC, based on which an aerosol removal test was then conducted, with the more suitable setting of the device.

It should be noted that the experimental tests are solely to test the functionality of the PAC as a localized exhaust without considering extra configurations. Hence, during the tests, a desk-based positioning was chosen for the PAC. For the perception test, the PAC was placed on the top-left corner of the desk, and one subject was seated in the chair, as shown in **Figure 5.1(a)**. Subjects were asked to rate their perception of noise, temperature, and draft on two scales: intensity and acceptability, assuming they had to study under such indoor environmental conditions. The points on the scales were determined based on the questionnaires used in a prior study also conducted in the test chambers in the SenseLab [44], which were adopted from international standards such as ISO 7730 [45] and were proven to be suitable for subjects' perceptual assessments on indoor environmental quality. The scales are described in detail as follows:

Intensity:

- For noise and draft, a 5-point scale was used, ranging from "no noise" to "very loud noise" and from "no draft" to "very strong draft," respectively.
- For temperature, a 4-point scale was used: "cold," "slightly cold", "slightly warm," and "warm."

Acceptability:

- A 4-point scale was used for all three parameters: "clearly unacceptable," "just unacceptable", "just acceptable," and "clearly acceptable."

Aerosol removal test

For the aerosol removal test, the PCE-PCO 1 particle counter [46] was employed, which measures the particle counts of six size channels: <0.3 μm, 0.3-0.5 μm, 0.5-1.0 μm, 1.0-2.5 μm, 2.5-5.0 μm, and 5.0-10.0 μm. The counting efficiency is 50% for the <0.3 μm channel and 100% for all other channels. While working, the particle counter actively draws air in and uses light scattering to measure both liquid and solid particles. During the test, the ventilation in the test chamber was continuously on to exclude the particles from other sources with the H14 HEPA filter. Consequently, to assure that the particle counter only measures particles generated from human respiration and not intervened by the room airflow caused by the ventilation, the particle counter was put inside a cardboard box on top of the desk, against the ventilation inlet, as shown in **Figure 5.1(b)**. The particle counter was placed 20 cm from the edge, in the direction of the exhaled air stream, to capture as many particles as possible. Such a setup was adapted from a prior study using the PCE-PCO 1 particle counter to measure respiratory particles in the test chamber [47], and was shown to be rational.

The PAC was also placed in the box, 15 cm from the edge, as shown in **Figure 5.1(b)**. Subjects were instructed to put their faces into the box and breathe normally. They could also use the lever of the chair to adjust the height. In addition, during both the perception test and the aerosol removal test, the CO_2 concentration, air temperature, and relative humidity were measured, using a HOBO data logger (model: MX1102A). For the perception test, the HOBO data logger was placed on the top-right corner of the desk, while for the aerosol removal test, it was positioned inside the box, behind the particle counter (**Figure 5.1**). The results showed that the during the tests, the air temperature and the relative humidity in the test chamber remained rather stable, with a mean temperature of 20.1 °C (± 0.8 °C) and a mean relative humidity of 43.5% (± 5.8%).

5.2.2.2 Test conditions and procedures

For the experimental tests, three conditions were designed:

- Condition 0 (C0): PAC turned off (baseline condition)
- Condition 1 (C1): PAC operating at level 1
- Condition 2 (C2): PAC operating at level 2

For the perception test, all three conditions were tested. Upon arrival at the lab, each subject was asked to rest for 10 minutes in the waiting area and complete the informed consent form. The subject then entered the test chamber and received instructions regarding the perception questionnaire. During the test, the subject was exposed to each condition for 2 minutes in the order of C0, C1, and C2, with a 1-minute break between each condition. The subject could complete the questionnaire at any time during each condition. After completing the test, subjects were requested not to discuss their results with others.

For the aerosol removal test, two conditions were tested: C0 and C1. C1 was chosen over C2 because it showed better results in the perception test, as presented in Section 3.1. Like the perception test, each subject was asked to rest for 10 minutes before entering the test chamber. Then the subject was instructed on how to breathe inside the box. Each test started with C0, followed by C1, and each condition lasted for 1 minute. During each condition, the subject was asked to breathe normally for 1 minute inside the cardboard box as the maximum single-measurement interval of the particle counter, with the aerosol concentration being continuously monitored. A 2-minute break was provided between the two conditions, during which the subject moved away from the box.

The above mentioned time intervals in the tests were chosen according to previous studies carried out in the test chambers, such as [44][47], and have been tested in several pre-tests.

5.2.2.3 Data analysis

The normality and the homogeneity of variances of the data were first examined. For the perception test, differences among the three conditions were assessed using one-way analysis of variance (ANOVA), followed by the Games-Howell test for post-hoc comparisons between each pair of conditions. For the aerosol removal test, the difference between C0 and C1 was assessed using a paired-samples *t* test. All data analyses were performed in IBM SPSS 28.0. The significance level was set at 0.05 ($P < 0.05$).

5.2.3 **CFD simulations**

5.2.3.1 Computational domain and geometry

The computational domain of the CFD simulations replicated the same test chamber where the previous experimental tests were performed, with dimensions of 3.74 m (length, defined as the x-direction) × 2.24 m (width, defined as the y-direction) × 2.11 m (height, defined as the z-direction). The ventilation inlet grille is on the back wall, 0.5 m to the left edge and 0.2 m from the bottom; the outlet grille is on the front wall, 0.5 m to the right edge and 0.2 m from the top; both measure 0.4 m (width) × 0.2 m (height). As the first exploration, in this study, the background ventilation was not considered in the simulations, with the intention to investigate the effect of the PAC on the room airflow individually. Although the ventilation system was not employed, infiltration through the grilles was considered. A sitting female manikin was placed in the center of the room, with a height of 1.26 m.

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The female was sitting behind a student desk, of which only the surface was included in the model, with dimensions of 0.65 m (length) × 0.45 m (width) × 0.025 m (height), and 0.74 m above the floor. The PAC was simplified as a cylinder of 0.07 m (diameter) × 0.15 m (length). The geometry of the model is shown in **Figure 5.2**.

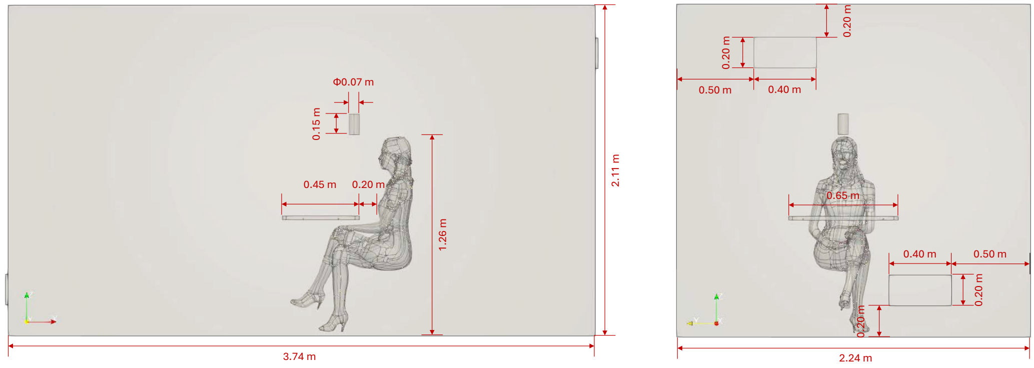

FIG. 5.2 Geometry of the model for CFD simulations (PAC at position P1): left – view of the x-z plane; right – view of the y-z plane.

To investigate the effects of the PAC's position – including relative distances and angles between the PAC and the occupant – on its range of suction within the proximity of the occupant, six position combinations were determined for the simulation:

1. x-direction: one position aligned with the edge of the desk, 0.2 m from the occupant.
2. y-direction: two positions within the desk's length: 1) center: aligned with the occupant on the central line, 2) side: 0.325 m from the central line of the desk, on the left end.
3. z-direction: one position above the occupant's head, 0.5 m from the desk (1.26 m from the floor).
4. Angles: three orientations: 1) vertical, 2) horizontal, and 3) 45°.

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It is worth noting that the selection of the positions was based on the feasibility of deploying such a device in a real classroom: the height of the PAC was determined to not block the sightline of the student, and the horizontal positions were within the dimensions of the desk. Moreover, previous studies have also indicated the advantage of top-PE over other types of systems, such as shoulder-PE and chair-PE [31,33]. In addition, the setup was assumed to be symmetrical on the left and right sides of the occupant, and thus only one side was included. The detailed positions of the PAC are specified in **Table 5.1**, and are illustrated in **Figure 5.3**.

TABLE 5.1 Description of the PAC's positions for simulation.

Position	x-direction (distance from occupant) [m]	y-direction	z-direction (distance above desk) [m]	Angle
P1	0.2	center	0.5	vertical
P2	0.2	center	0.5	horizontal
P3	0.2	center	0.5	45°
P4	0.2	side	0.5	vertical
P5	0.2	side	0.5	horizontal
P6	0.2	side	0.5	45°

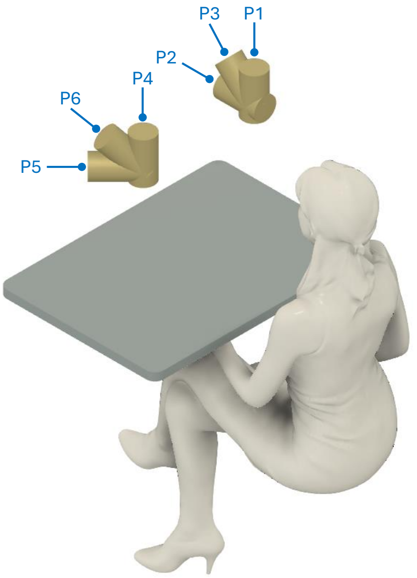

FIG. 5.3 Illustration of the PAC's positions for simulation.

5.2.3.2 Governing equations

The simulation utilized the incompressible Reynolds-Averaged Navier-Stokes (RANS) equations to model the airflow, and the standard k-ε turbulence model was used for turbulence closure. An enhanced wall treatment was applied in all geometries within the domain [48][49]. According to the measurements of air temperature in the test chamber during the experimental tests, it was assumed that the room temperature stayed constant and thus its variation was assumed negligible. As mentioned in previous sections, as a pilot study, the present CFD simulations were to first identify the suction effect of the PAC at different positioning, and thus only the air velocity was focused on. Accordingly, the governing equations included:

Continuity

$$\frac{\partial \overline{U_j}}{\partial x_j} = 0 \tag{5.1}$$

Momentum

$$\overline{U_j}\frac{\partial \overline{U_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\frac{(\mu+\mu_t)}{\rho}\frac{\partial \overline{U_i}}{\partial x_j}\right] \tag{5.2}$$

where $\overline{U}_i$ and $\overline{U}_j$ are the time-averaged velocity components, ρ is the density, $\overline{P}$ is the time-averaged pressure, μ is the dynamic viscosity, μ_t is the turbulent viscosity.

Turbulent viscosity

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5.3}$$

where μ_t is the turbulent viscosity, with C_μ a constant equal to 0.09. The turbulence kinetic energy k and the turbulence dissipation rate ε are obtained from solving their respective transport equations:

Turbulent kinetic energy (k)

$$\overline{U_j}\frac{\partial \overline{k}}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\frac{(\mu+\mu_t)}{\rho\sigma_k}\frac{\partial k}{\partial x_j}\right]+P_k-\varepsilon \tag{5.4}$$

Dissipation rate (ε)

$$\overline{U_j}\frac{\partial \overline{\varepsilon}}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\frac{(\mu+\mu_t)}{\rho\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}P_k-C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{5.5}$$

with P_k the turbulent production term, and σ_k, σ_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ model constants, which are equal to 1.0, 1.3, 1.44, and 1.92, respectively.

5.2.3.3 Boundary conditions

According to the results of the experimental test, level 1 of the PAC was chosen for the CFD simulations. The supply surface of the PAC was defined as a velocity inlet with a measured velocity (level 1) of 0.8 m/s, while the suction surface was defined as a pressure outlet with a gauge pressure of 0.15 Pa, determined based on the measured velocity of 0.4 m/s. Both ventilation grilles were selected as pressure outlets, with a gauge pressure of 1×10^{-3} Pa, based on the measured velocity of 0.05 m/s. The measurements were conducted using a Trotec hotwire anemometer (model: BA30WP). The body of the PAC was defined as solid. Surfaces such as room walls, ceiling, floor, and the manikin were set as walls. The turbulent intensity was set as 5% [50].

5.2.3.4 Solution schemes and convergence criteria

ANSYS Fluent 2023R2 [51] was used to solve the CFD model. The velocity field and the pressure field were coupled by SIMPLEC algorithm. Convection terms are discretized via the Second Order Upwind scheme. The convergence criteria were reached when scaled residuals did not drop with further iterations or residuals of equations of continuity, momentum, and turbulence dropped to 1×10^{-5}, respectively.

5.2.3.5 Grid independence test

For the grid independence test, a simplified setup was adopted, since this setup was also used for model validation and better facilitates measurements at multiple points across the room. The PAC was mounted at the center of the back wall of the test chamber, blowing air continuously towards the interior without the manikin. In addition, to better observe the decay in velocity, the PAC was set to operate at level 2. Accordingly, the velocity at the supply surface of the PAC (velocity inlet) increased to 1.2 m/s, and the gauge pressure at the suction surface of the PAC and the grilles (pressure outlets) increased to 0.29 Pa and 2×10^{-3} Pa, respectively, with all the other settings remained the same.

For this simulation, unstructured meshes were created using ANSYS Fluent Meshing. To eliminate the impacts of grids on the simulated results, three meshes were tested, namely the coarse mesh, the nominal mesh, and the fine mesh. Refinements were made in the regions of interest. The details of the three meshes are listed in **Table 5.2**. The dimensionless wall distances (y^+) of the meshes were around 1 to account for the viscous effects of the flow [52][53]. Velocity magnitude (u), turbulent kinetic energy (k), and dissipation rate (ε) were compared at the points shown in **Figure 5.4**, with the results displayed in **Figure 5.5**. It can be observed that the differences between the nominal and fine meshes are significantly smaller than those between the coarse and nominal meshes. Hence, the nominal mesh was selected.

TABLE 5.2 Information on the different meshes.

Mesh	Number of cells	Height of the first cell (y^+)
Coarse	15048639	1.43
Nominal	23673562	1.39
Fine	37647436	1.36

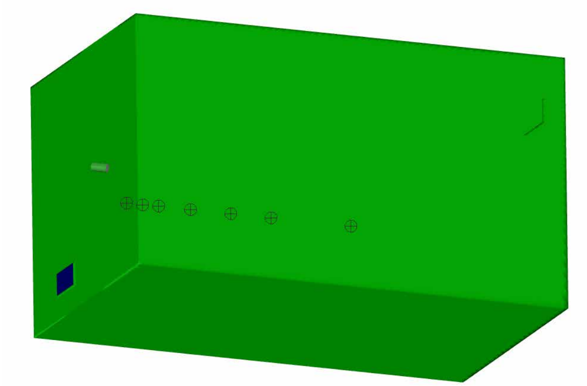

FIG. 5.4 Points for mesh comparison.

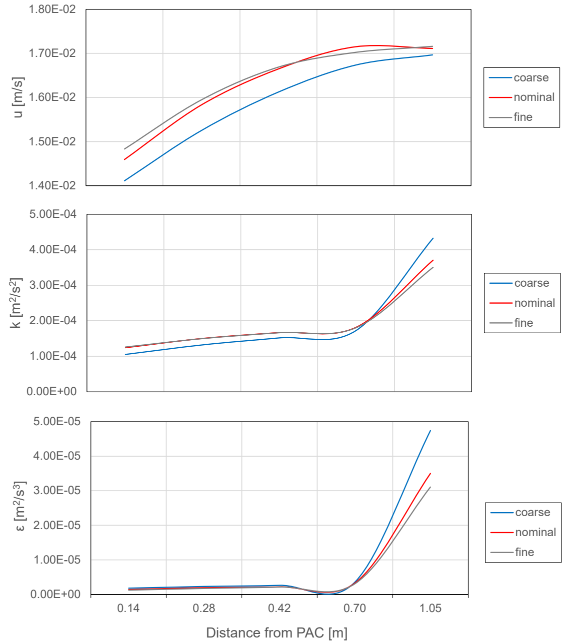

FIG. 5.5 Grid independence test: velocity magnitude (u), turbulent kinetic energy (k), and dissipation rate (ε).

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5.2.3.6 Model validation

The setup of the model validation was the same as the grid independence test, as mentioned in **Section 5.2.3.5**. The CFD model was validated by comparing the simulated velocity magnitude with the velocity measured in the test chamber using Dantec anemometers (model: 54T033), at the following positions:

1. Seven positions along the x-direction: 0.14 m (equal to two times the diameter of the PAC, hereafter referred to as 2d), 0.28 m (4d), 0.42 m (6d), 0.70 m (10d), 1.05 m (15d), 1.40 m (20d), and 2.10 m (30d).
2. Three positions along the y-direction: the central position aligned with the PAC, the left position 0.21 m (3d) to the left of the PAC, and the right position 0.21 m (3d) to the right of the PAC.
3. Three positions along the z-direction: the middle position aligned with the PAC, the bottom position 0.28 m (4d) below the PAC, and the top position 0.28 m (4d) above the PAC.

This arrangement resulted in a total of 63 measurement points, as illustrated in **Figure 5.6**. The results are presented across three planes along the z-direction: the bottom, middle, and top planes. As shown in **Figure 5.7**, the simulation results showed good agreement with the measurements. On the bottom plane, the mean difference between the measurements and the simulations is 0.029 m/s, with a standard deviation of 0.016 m/s and a maximum deviation of 0.037 m/s. On the middle plane, the mean difference between the measurements and the simulations is 0.046 m/s, with a standard deviation of 0.046 m/s and a maximum deviation of 0.150 m/s. On the top plane, the mean difference between the measurements and the simulations is 0.020 m/s, with a standard deviation of 0.013 m/s and a maximum deviation of 0.025 m/s. The slight discrepancies observed can be explained by the fact that the PAC used an axial fan, where the radial velocity does not distribute evenly, but rises from low at the hub, peaks near the blade tips, and then drops sharply beyond the tips [54]. In contrast, the CFD model simulated the velocity as uniform across the radius of the fan.

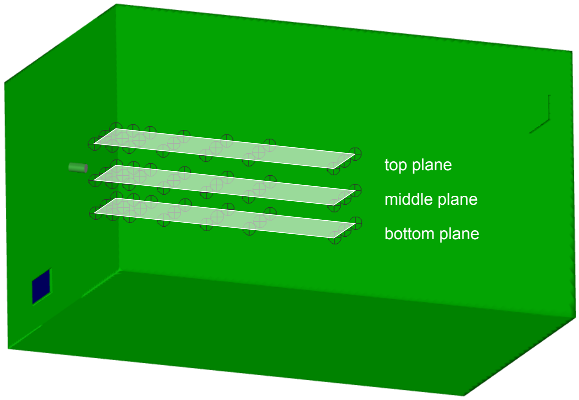

FIG. 5.6 Points for model validation.

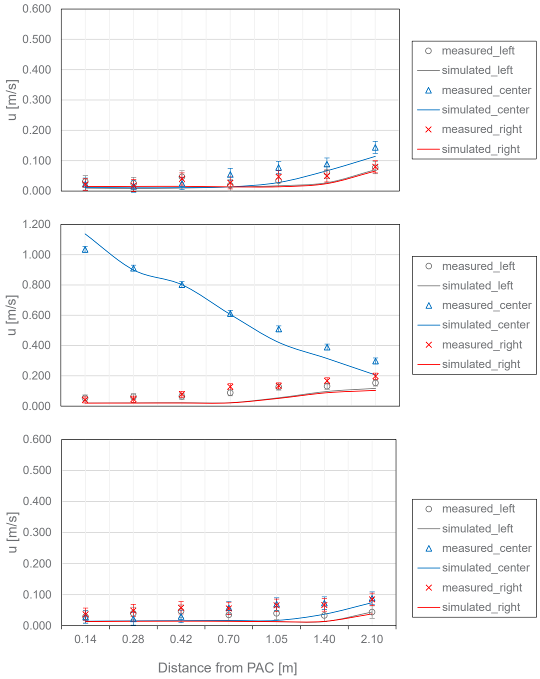

FIG. 5.7 Comparison of the velocity magnitude (u) between simulation and measurement results: (a) top plane; (b) middle plane; (c) bottom plane.
Note: the error bars of the measured values represent the instrument accuracy of ±0.02 m/s.

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5.3 Results

5.3.1 Experimental tests

5.3.1.1 Subjects’ perceptions of the personalized air cleaner

The subjects’ perceptions of noise, temperature, and draft are shown in **Figure 5.8**. For noise, when the PAC was turned off, all ratings of intensity ranged from “no noise” to “slight noise”, and all subjects found it acceptable. When the PAC was operating at level 1, the intensity ranged from “slight noise” to “loud noise,” with 81% of the subjects perceiving the noise as between “slight noise” and “moderate noise,” and 63% considered it acceptable. At level 2, the noise intensity increased, with 88% of the subjects finding it between “loud noise” and “very loud noise,” and all subjects rated it as unacceptable. For temperature, the subjects’ thermal sensation was slightly warm, and most of the time, it was clearly acceptable. For draft, the intensity ranged from “no draft” to “slight draft,” with an increase in the average rating from C0 to C2. Still, it remained acceptable for the subjects throughout.

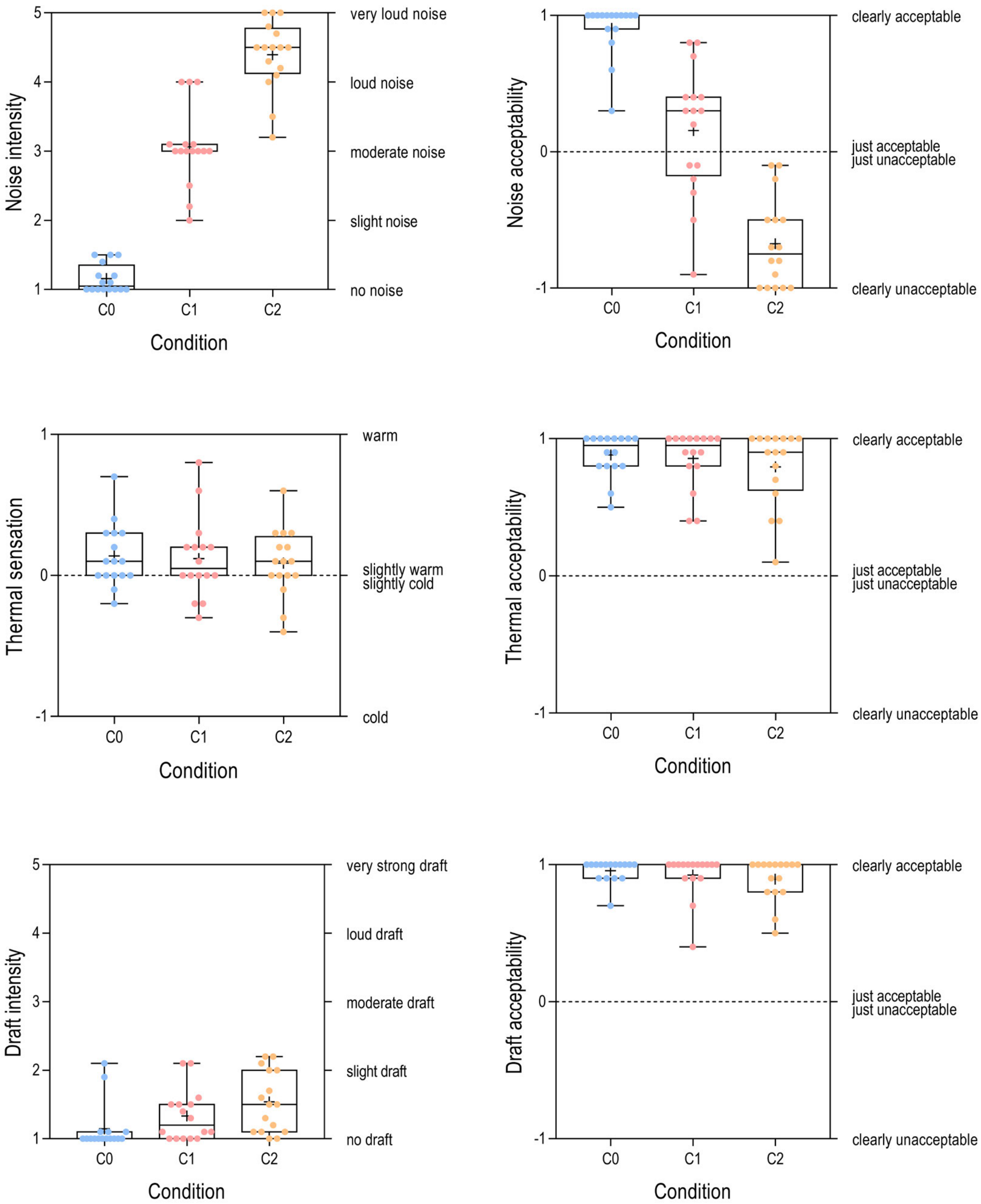


FIG. 5.8 Subjects' perception of noise, temperature, and draft.

Note: C0 – personalized air cleaner off; C1 – personalized air cleaner operating at level 1; C2 – personalized air cleaner operating at level 2.

Such results are also reflected in the statistical analyses. The results of the one-way ANOVA tests and the post-hoc Games-Howell tests are presented in **Table 5.3**. For noise, both the differences in intensity and acceptability among the three conditions were significant. Moreover, the noise intensity increased significantly from PAC off to PAC operating at level 1, and from level 1 to level 2, while for noise acceptability, the trend was the opposite. For temperature, no significant difference was found among the conditions for both sensation and acceptability. For draft, the intensity varied significantly, due to the significant difference between C0 and C2, while for acceptability, no significant difference was observed.

TABLE 5.3 Differences in subjects' perceptions of noise, temperature, and draft.

Perception aspect	Parameter	F (P)[a]	t (P)[b]		
			C0 vs C1	C0 vs C2	C1 vs C2
Noise	Intensity	**202.68 (< 0.01)**	**-1.91 (< 0.001)**	**-3.24 (< 0.001)**	**-1.33 (< 0.001)**
	Acceptability	**81.33 (< 0.01)**	**0.75 (< 0.001)**	**1.58 (< 0.001)**	**0.83 (< 0.001)**
Temperature	Sensation	0.16 (0.850)	0.02 (0.976)	0.05 (0.816)	0.03 (0.940)
	Acceptability	0.67 (0.518)	0.03 (0.923)	0.09 (0.527)	0.06 (0.756)
Draft	Intensity	**4.14 (0.022)**	-0.19 (0.308)	**-0.39 (0.023)**	-0.21 (0.342)
	Acceptability	0.82 (0.447)	0.03 (0.771)	0.06 (0.351)	0.03 (0.844)

a *F: the F-statistic from the one-way ANOVA test. P-values less than 0.05 are marked in bold.*
b *t: the test statistic from the Games-Howell test (post-hoc). P-values less than 0.05 are marked in bold.*

5.3.1.2 Aerosol removal performance of the personalized air cleaner

The result of the particle counts of distinct size bins are shown in **Figure 5.9**. It was observed that during breathing, most of the respiratory aerosols are small, with a size less than 1.0 μm, and notably, particles with a size of <0.3 μm predominated. Conversely, particles with a size of 2.5-5.0 μm exhibited the lowest concentration. Moreover, when the PAC was operating at level 1, the concentrations of respiratory aerosols were consistently lower compared to when the PAC was off, with a much narrower range. **Table 5.4** presents the results of the paired-samples *t* tests, along with the reduction percentages of particle counts from C0 to C1. The reduction percentage was calculated using the formula: (particle count at C0 - particle count at C1)/particle count at C0. Accordingly, the differences between C0 and C1 were all significant, showing the efficacy of the PAC. In general, the reduction of respiratory aerosols ranged from 40% to 50%, when the PAC was operating at level 1, with size 0.5-1.0 μm showing the highest reduction and size 1.0-2.5 μm the lowest.

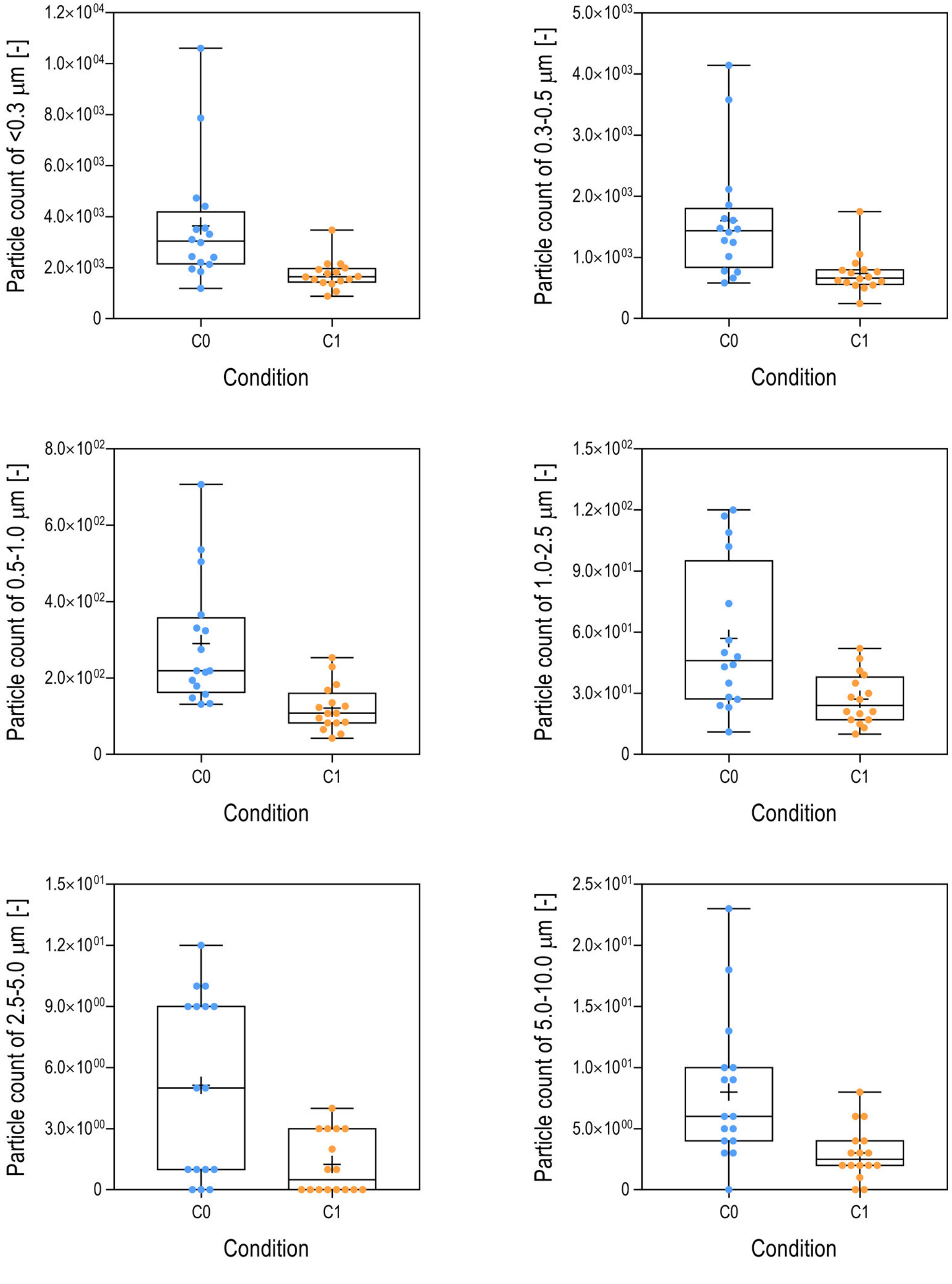


FIG. 5.9 Total particles count of respiratory aerosols during 1 minute interval. C0 – personalized air cleaner off; C1 – personalized air cleaner operating at level 1.

TABLE 5.4 Differences in the particle counts of respiratory aerosols between the personalized air cleaner on and off.

Particle size [μm]	Reduction [%][a]	t^b	P^c
<0.3	42 (25)	3.76	**0.002**
0.3-0.5	44 (28)	4.20	**< 0.001**
0.5-1.0	51 (26)	4.45	**< 0.001**
1.0-2.5	38 (39)	3.87	**0.001**
2.5-5.0	45 (76)	3.98	**0.001**
5.0-10.0	42 (43)	3.43	**0.004**

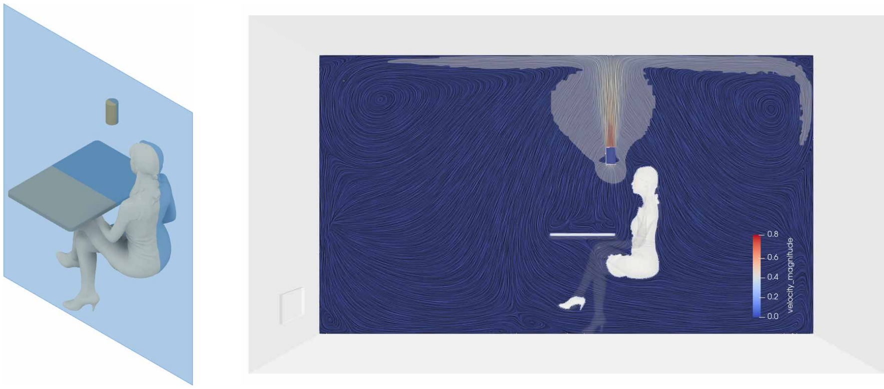
a *Mean (standard deviation).*
b *t: t-statistic from the paired-samples t test.*
c *P-values less than 0.05 are marked in bold.*

5.3.2 CFD simulations

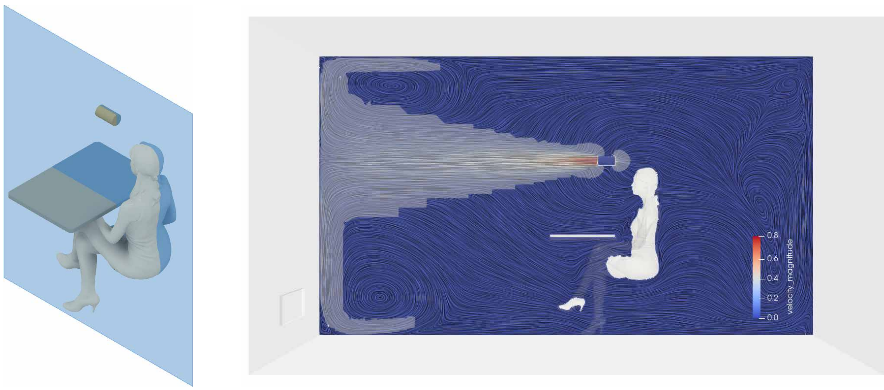
The simulation results are presented as contour plots depicting the velocity magnitude distribution of the PAC at positions P1-P6, as presented in **Figure 5.10**. The blue plane in each geometry represents the cross section corresponding to the contour shown in the next column. The highlighted areas of the contours represent regions where the velocity magnitude exceeds the threshold of 0.02 m/s. The results illustrate that, across all positions, the suction effect of the PAC was quite limited, with the low threshold of 0.02 m/s being rarely reached in the breathing zone of the manikin.

For P1 (vertical, central), as shown in **Figure 5.10(a)**, the suction effect is strong and localized directly in front of the PAC. High-velocity contours are evident close to the device, but the velocity decreases sharply, failing to reach the 0.02 m/s threshold at the breathing zone. This position offers the most concentrated suction flow but is still insufficient for effective aerosol capture from the manikin. For P2 (horizontal, central), as shown in **Figure 5.10(b)**, the suction zone in this position is wider but less intense. While air is drawn horizontally, the rapid decrease in velocity means the suction effect does not extend to the manikin's breathing zone, resulting in a lower efficacy compared to P1. For P3 (45° angle, central), as shown in **Figure 5.10(c)**, the angled configuration provides an asymmetric suction pattern that draws air both downward and horizontally. Although this creates a broader capture area, the 0.02 m/s threshold is still not reached at the manikin's breathing zone, indicating limited effectiveness. For P4-P6 (Side), as shown in **Figure 5.10(d)(e)(f)**, when the PAC is positioned to the side, the suction zone shifts laterally. However, the distance between the PAC and the breathing zone of the manikin further reduces the suction effect.

In addition, the supply side of the PAC plays a crucial role in shaping the overall air distribution within the room. In all positions, the air expelled from the PAC creates high-velocity zones close to the supply outlet, leading to a more pronounced airflow in those regions. The expelled air spreads out across the room, establishing a broader airflow pattern that can affect general air quality. However, despite this wider distribution, the supply airflow does not impact the suction effect at the manikin's breathing zone, as the suction velocity remains below the 0.02 m/s threshold across all configurations.



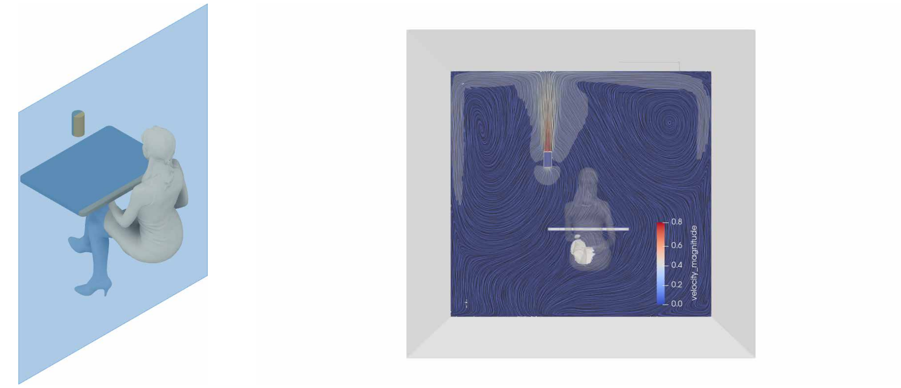
a)



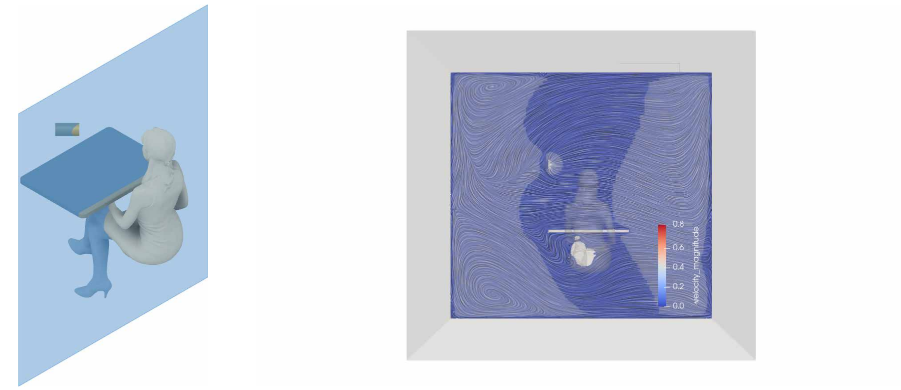
b)

FIG. 5.10 Geometries and contours of velocity magnitude of the PAC at different positions: (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, and (f) P6.
Note: the blue planes represent the cross section corresponding to the contours. The highlighted parts represent the region where the velocity magnitude is higher than 0.02 m/s.

c)

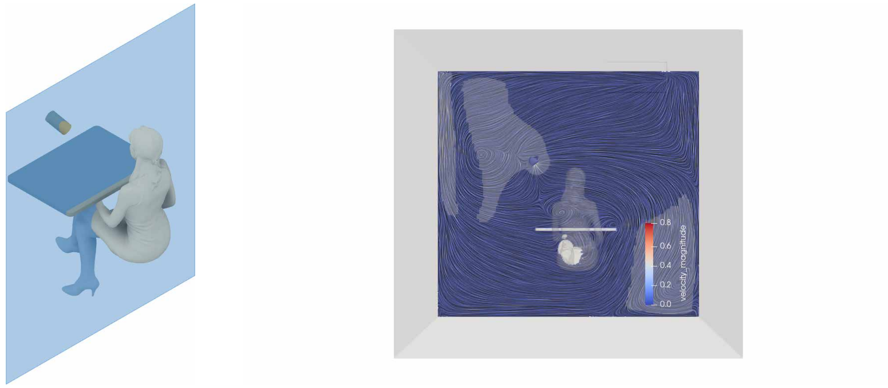


d)



e)

FIG. 5.10 Geometries and contours of velocity magnitude of the PAC at different positions: (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, and (f) P6.
Note: the blue planes represent the cross section corresponding to the contours. The highlighted parts represent the region where the velocity magnitude is higher than 0.02 m/s.



f)

FIG. 5.10 Geometries and contours of velocity magnitude of the PAC at different positions: (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, and (f) P6.
Note: the blue planes represent the cross section corresponding to the contours. The highlighted parts represent the region where the velocity magnitude is higher than 0.02 m/s.

5.4 Discussion

5.4.1 Comparison of experimental and simulation results

The experimental and simulation results provided contrasting views on the performance of the PAC in aerosol removal. The experiment showed significant aerosol reduction, with the PAC achieving particle removal efficiencies ranging from 38% to 51% depending on particle size. Specifically, the highest reduction was observed for 0.5-1.0 µm particles (51%), and the lowest for 1.0-2.5 µm particles (38%) (**Table 5.4**). This substantial aerosol removal is due to the confined nature of the experiment, where the PAC and the subject's respiration were enclosed within a cardboard box. As shown in **Figure 5.10**, it can be inferred from the velocity contours of the PAC's supply side that it can lead to stronger air recirculation and higher airflow velocities in a limited space, thus effectively enhancing the PAC's aerosol removal performance.

In contrast, the CFD simulations were conducted in a much larger domain – the entire test chamber, where the airflow dispersion occurred more freely compared to the box, leading to a much weaker recirculation effect (**Figure 5.10**). Consequently, the suction effect of the PAC in the simulation did not match the high removal rates seen experimentally, as the velocity magnitudes in the manikin's breathing zone remained below the 0.02 m/s threshold in most configurations. While such results may suggest that the PAC could struggle to exhaust exhaled aerosols effectively at an actual classroom scale, it is important to recognize that the simulations did not account for human breathing. Studies have shown that exhaled aerosols tend to follow the upward stream caused by the thermal plume of human body [55][56], making them more likely to be captured by the PAC, potentially leading to better performance than simulated. Additionally, factors like room temperature, relative humidity, breathing mode, and human activity can significantly influence aerosol dispersion [18][57], indicating the need for more comprehensive studies to fully assess the PAC's performance in real-world scenarios.

5.4.2 Influence of PAC positioning on suction effect

The positioning of the PAC also showed certain impact on its suction effect. Through the CFD simulations conducted in this study, six different PAC positions were examined, varying in height, lateral distance, and angle relative to the occupant. These positions were selected based on practical classroom constraints, ensuring the PAC did not obstruct the student's sightline while remaining within the desk's dimensions.

Among the central configurations, as illustrated in **Figure 5.10**, the vertical positioning (P1) directly above the occupant's head proved to be the most effective in terms of creating a concentrated suction zone, compared to the horizontal and angles positions (P2 and P3). The simulations showed that when the PAC is vertically aligned, it produced a stronger, more focused suction flow directed toward the manikin. This finding is significant when considering real-world scenarios, as discussed previously, where the thermal plume generated by the human body can cause exhaled aerosols to rise [55][56]. In such cases, a PAC positioned vertically could potentially leverage this upward flow to enhance aerosol capture. With proper distance to the occupant, the removal efficiency might increase considerably. Comparable results have been observed in previous studies on PE systems [31][33].

Meanwhile, the side positions (P4-P6), as presented in **Figure 5.10**, with further distance from the manikin, showed even weaker suction effect, regardless of the angles of the PAC. Hence, for applications in real-world classrooms, such positioning is less feasible than the central configurations, given the current setup of the PAC.

5.4.3 Design implications

The PAC's limited suction effect can be attributed to the rapid decay in airflow velocity at the suction side. Previous studies on localized air exhaust systems have shown that their velocity fields follow the inverse square law: $u \propto \frac{1}{d^2}$, where u represents the velocity magnitude and d is the distance from the suction surface [58][59]. Moreover, the velocity decay rate is also inversely proportional to the area of the suction surface [58][59]. This explains why suction velocities drop sharply beyond the immediate vicinity of the device, making it difficult to extract air in the breathing zone, even at short distances (20 cm from the manikin).

Therefore, to achieve effective exhaust for respiratory aerosols with devices like the PAC, several design modifications can be explored. First, increasing the airflow rate would enhance the suction effect and allow the PAC to cover a larger area. To make an estimation, based on the equation in Ref. [60], for the PAC to be approximately 20 cm from the occupant's breathing zone, the suction velocity needs to reach at least 2.31 m/s to achieve the 0.02 m/s threshold in the breathing zone. To reach such suction velocity, the supply velocity would need to be even higher. However, as observed in the experiment, increasing the velocity from 0.8 m/s (level 1) to 1.2 m/s (level 2) already resulted in unacceptably high noise levels, making further increases impractical. Second, expanding the surface area of suction intake would allow the device to draw in more air from the surrounding space. Again, according to Ref. [60], for the 0.02 m/s threshold to reach the breathing zone, the PAC's diameter would need to be at least 16.8 cm – more than double its current size. Correspondingly, such a design would require more space, which might be impractical in densely occupied classrooms. Third, reducing the distance between the device and the occupant could enhance the PAC's suction effect towards the breathing zone with the current setup. Based on Ref. [60], the distance would need to be less than 8.6 cm to achieve the 0.02 m/s threshold. Yet, placing the device too close to students may disrupt learning activities.

In summary, while these modifications could improve the performance of PAC devices, they introduce new challenges, such as noise, space constraints, and potential interference with classroom dynamics. As such, alternative solutions for personalized exhaust systems of respiratory aerosols need to be explored to balance effectiveness and practicality in real-world classroom settings.

5.4.4 Comparison with PE systems

In contrast to the findings of the present study, several existing studies have demonstrated the efficacy of PE systems for removing respiratory aerosols. To facilitate a more detailed comparison, **Table 5.5** summarizes key information from relevant studies. It is evident that the PAC used in this study shares similarities with the top-PE system investigated in other works, particularly in terms of the suction surface area and distance from the occupant. Previous studies reported maximum airflow rates ranging from 10 L/s to 29 L/s, significantly higher than the capacity of the PAC (3–5 L/s). An exception to this is Ref. [32], where a wearable headset with a small exhaust nozzle exhibited lower airflow rates, but this is an outlier compared to the other setups.

The higher airflow rates reported in previous studies may explain their more promising results in aerosol removal. However, given the moderate size of PE systems, such high airflow rates are likely to produce unacceptably high noise levels – a factor that has not been thoroughly investigated in prior research. This is understandable, as many previous studies were focused on environments such as healthcare consulting rooms or aircraft cabins, where noise control may not be a top priority. However, low noise levels are critical in school classrooms to maintain conducive conditions for teaching and learning, as researchers have already highlighted that noise is a significant distraction for children in school, often affecting their learning and comfort [61].

Furthermore, previous studies typically incorporated total-volume mechanical ventilation systems, often using mixing ventilation. In several cases, including Refs. [31], [35], and [38], the PE system was combined with a PV system. Such setups can significantly influence airflow patterns throughout the room and within the occupants' breathing zones, leading to results that differ from setups using a single PAC in an unventilated room. Therefore, further exploration is needed to investigate the combined effects of PACs with other ventilation systems to optimize their performance in real classroom environments.

TABLE 5.5 Comparison of studies on personalized exhaust (PE) systems.

Ref.	Type of PE	Suction surface area	Airflow rate [L/s]	Distance from occupant [m]	Background ventilation regime	Indoor setting
present study	top-PE	Φ = 7 cm	3-5	0.20	none	classroom
[31]	top-PE/ shoulder-PE/ chair-PE	Φ = 12 cm/ 8 cm × 8 cm/ 8 cm × 8 cm	13-29	0.15/ not specified/ not specified (both shoulder-PE and chair-PE are chair-based)	mixing	healthcare consulting room
[32]	wearable headset	Φ = 3 cm	0.24-0.5	0.02-0.06	mixing	hospital ward
[33][34]	top-PE/ shoulder-PE	Φ = 10 cm/ Φ = 10 cm	10-20	0.12/ 0.06	mixing/ displacement	healthcare consulting room
[35]	side-PE (on both sides of head)	8 cm × 13 cm	6-10	not specified (seat-based)	mixing	aircraft cabin
[38]	shoulder-PE	30 cm × 1 cm	4-10	not specified (chair-based)	displacement	classroom

5.4.5 Limitations

Several limitations of this study should be acknowledged:

Firstly, the sample size of the experimental tests was relatively small, with a power level (1-β) of 0.6. For future research, a power level of 0.8 would be recommended, which leads to at least 26 subjects. Secondly, the aerosol removal tests were conducted in a confined space (the cardboard box), which likely enhanced the PAC's performance through increased air recirculation. These results may not fully translate to larger, more open environments like school classrooms, where airflow dispersion is much less constrained. Thirdly, the CFD simulations focused on the velocity fields and did not account for other factors such as human breathing, particle dispersion, thermal plume, etc. As a result, the simulation results did not thoroughly depict the performance of aerosol removal for the PAC. Fourthly, only one PAC model with specific airflow and suction characteristics was tested in this study. Future research should explore other PAC designs with different airflow rates, suction areas, and filtration technologies to determine if they can offer improved performance under similar conditions. Lastly, this study did not investigate how the PAC might perform in conjunction with other ventilation strategies, such as mechanical or natural ventilation systems. These combined approaches may enhance overall aerosol removal in real-world classroom settings.

5.5 Conclusions

Previous studies have demonstrated that personalized exhaust (PE) systems are highly effective in mitigating the short-range transmission of respiratory aerosols. Meanwhile, mobile air cleaners (MACs) have proven effective at controlling respiratory aerosols in classroom settings, offering a flexible and cost-effective solution without the need for extensive installations. In this paper, a pilot study was conducted to explore the feasibility of combining the strengths of both the PE system and MAC, specifically by using a personalized air cleaner (PAC) as a localized exhaust for short-range respiratory aerosol removal in a classroom setting. The PAC's efficiency for aerosol removal, as well as its perceptual acceptability for the occupants, were tested experimentally, while the impact of the PAC's positioning on its suction effect was investigated via CFD simulations. The conclusions are drawn as follows:

The experimental results first showed that when the PAC operated at its maximum fan speed, the resulting noise level was deemed unacceptable by the subjects, highlighting the importance of sound considerations for the real-world application of PACs. Consequently, only the moderate fan speed was used in the subsequent tests and simulations. The results of the aerosol removal tests demonstrated that the PAC significantly reduced aerosol concentrations, achieving reductions of 40% to 51%, particularly for smaller particles (less than 1.0 μm). This high performance, however, was attributed to the strong air recirculation within the confined test setup.

In CFD simulations, the vertical positioning of the PAC showed better suction effect compared to horizontal or angled placements. However, the PAC's suction effect was highly localized and diminished rapidly with distance. Even at optimal positioning, the velocity of air drawn by the PAC did not reach the occupant's breathing zone, indicating limited efficacy in a larger, classroom-sized environment. Nonetheless, given the multiple factors that can influence the dispersion of respiratory aerosols, further investigations are needed to better understand the performance of the PAC in real-world scenarios.

Compared to other PE systems showing high efficiency, the key difference in the tested PAC lies in its airflow rate, as the PAC operates at a relatively lower level. However, simply increasing the airflow rate to achieve better suction effect is not a feasible solution, as this will increase the noise level, which was observed to be unacceptable for the occupants in the experimental test. Other modifications include a larger suction surface or a short distance from the occupant. However, they may also lead to new problems, and hence new ways of design or optimization are needed.

In addition, exploring the integration of PACs with other types of ventilation systems may provide a more comprehensive approach to aerosol removal, optimizing their effectiveness in real-world classroom settings.

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6 Conclusions and recommendations

6.1 Introduction

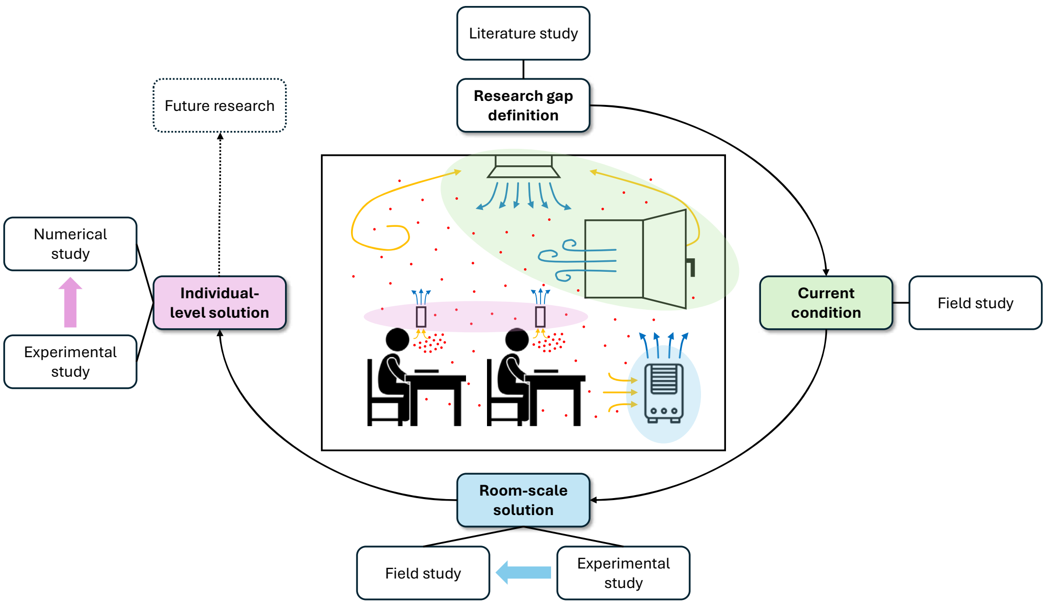

FIG. 6.1 Research framework and key steps of this PhD research.
Note: red dots represent infectious respiratory particles.

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In response to the WHO and UN's call to uphold children's right to breathe "clean" air in their daily environments, and considering the challenges posed by the COVID-19 pandemic on maintaining healthy indoor air quality (IAQ) conditions, this PhD research was carried out to address the following research question:

Which ventilation and air cleaning strategies can be used to effectively control the spread of infectious respiratory particles in school classrooms?

This research question was further divided into four sub-research questions, which were addressed individually by the studies presented in **Chapters 2-5**. **Figure 6.1** shows the field of focus and the key steps of this PhD research. In the beginning, the research context and background were established, and the research gaps were defined, via a literature review. This literature review mapped the knowledge on the features and control of the spread of IRPs, identified the existing design paradigms and actual performance of ventilation and IAQ conditions in school classrooms, as well as sought possible solutions among advanced ventilation systems. Following this, the current conditions in Dutch schools during the pandemic were investigated through a field study. This field study examined not only the sufficiency of ventilation as pandemic control and prevention measures evolved, but also the associated thermal conditions in classrooms. Based on the outcome of the field study, different ventilation and air cleaning strategies were developed. At the room scale, mobile air cleaners (MACs) were chosen to be a solution for long-range IRP control. Given the wide variety of products available, certain criteria were established to guide the selection process. The selected MACs were then evaluated in an experimental study assessing both aerosol removal efficiency and user perception. Subsequently, several recommendations were made for effectively using MACs in classroom settings for IRP removal, which were further tested in a field study to assess their feasibility in real-world environments. At the individual level, personalized air cleaners (PACs) were determined to be a solution for short-range IRP control. Since a novel application of the PAC was proposed, namely as a localized exhaust, its potential was first examined via an experimental study, assessing first the occupant acceptability, followed by the actual respiratory aerosol removal ability. Subsequently, the impact of the PAC's positioning on its suction efficacy was assessed via a computational study, leading to recommendations for further modifications to improve the PAC's performance.

In this chapter, the key findings from each step are summarized to provide detailed answers to the sub-research questions. This leads to a comprehensive response to the main research question, followed by a discussion of the study's limitations. Finally, this chapter concludes with practical implications and recommendations for future research.

6.2 Answers to research questions

6.2.1 Answers to sub-research questions

1 Sub-research question 1: **What do we know about the ventilation regimes in school classrooms and the control of infectious respiratory particles?**

In summary, as illustrated in **Figure 6.2**, airborne transmission of IRPs can occur over both long-range and short-range, each requiring distinct ventilation methods for effective control. Long-range airborne transmission can be managed with conventional room-scale ventilation systems, although evidence on optimal configurations is limited. Schools often rely on natural or mixing ventilation, which often falls short of requirements that are primarily based on occupant comfort. Short-range transmission, however, calls for innovative ventilation solutions within occupants' immediate proximity, such as personalized ventilation systems. The details are demonstrated as follows.

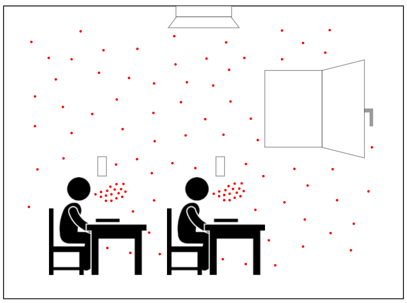

FIG. 6.2 Main focus of Chapter 2: existing knowledge on 1) airborne transmission of infectious respiratory particles, 2) ventilation regimes and IAQ conditions in school classrooms, and 3) advanced ventilation methods such as personalized ventilation.
Note: red dots represent infectious respiratory particles.

First, it is important to recognize that airborne transmission of IRPs is one of the dominant routes for cross-infection of respiratory diseases like COVID-19 [1-4]. IRPs typically consist of small particles (< 100 μm) produced during human respiratory activities, including breathing, speaking, sneezing, and coughing [1-4]. These particles can directly reach the breathing zone of another person within close contact (< 1-2 m), or remain suspended and travel further through the air, resulting in two distinct ways of airborne transmission, i.e., short-range and long-range airborne transmission, respectively [5-7]. Previous studies have demonstrated that conventional room-scale ventilation systems can effectively control long-range transmission airborne transmission of IRPs. However, the optimal ventilation rates and air distribution patterns are still unclear, especially for non-nosocomial environments [8-11]. Natural ventilation through openable windows and mixing (mechanical) ventilation, commonly used in school classrooms, fall into this category. However, such ventilation regimes are in general based on assumptions like steady-state conditions and the well-mixing model, which do not accurately reflect the nature of short-range airborne transmission [5,12]. Short-range transmission should be treated as a transient and dynamic process, which requires more precise control and responsive measures [5,6,13].

Second, current standards and guidelines for ventilation in school classrooms primarily focus on perceived air quality and are often shaped by energy-saving demands [14-17]. CO_2 concentration is frequently used as an indicator of human-generated pollution, yet it is not a reliable proxy for IRPs [18-20]. As a result, existing ventilation designs may fall short of effectively reducing the spread of IRPs in classrooms. Meanwhile, with the required minimum ventilation rates set relatively low, many school classrooms in practice fail to meet even these standards, leading to widespread reports of IAQ-related issues affecting health, comfort, and student performance [21-23]. Therefore, it is suggested that ventilation design in classrooms should shift from a comfort-based approach to one focused on health and infection control. A more flexible and adaptable ventilation strategy is required to address IRP pollution effectively at both the occupant and room levels.

Third, to better tackle the short-range airborne transmission of IRPs, personalized ventilation, including personalized air supply (PS) systems and personalized air exhaust (PE) systems, has been proposed in prior research [24-27]. These systems can provide localized protection by ensuring healthy IAQ conditions within proximity for each occupant [5,28]. Furthermore, previous studies have also revealed the advantages and disadvantages of PS and PE systems. PS systems aim at providing clean and cool air to the occupants to enhance both IAQ and thermal comfort, while PE systems focus on directly and efficiently removing exhaled contaminants [29]. However, existing designs are often developed for high-risk indoor environments, such as hospital wards or aircraft cabins. They cannot be directly applied to school classrooms due to significant differences in spatial layout and function, occupant types, and activities. Therefore, further investigation is necessary to determine the appropriate ways to implement personalized systems and devices for children in classroom settings.

2 Sub-research question 2: **What is the ventilation sufficiency of existing ventilation regimes and the current IAQ conditions in school classrooms?**

In short, as shown in **Figure 6.3**, during the COVID-19 pandemic, classroom windows and doors were kept open for maximum outdoor air supply. Before the national lockdown, the classrooms were used with full occupancy, where the CO_2 concentrations were high, with insufficient ventilation rates per person. After the lockdown, student occupancy was reduced by half to maintain safe social distancing, where significant decreases in CO_2 concentrations and increases in ventilation rates per person were observed. Nonetheless, such improvement was solely due to the reduction in occupancy. Besides, thermal conditions in the classrooms were also found to be unsatisfactory. The details are outlined as follows.

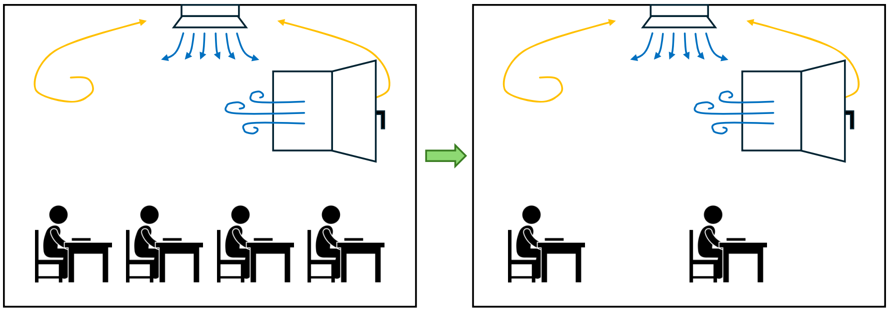

FIG. 6.3 Main focus of Chapter 3: ventilation (and thermal) conditions in school classrooms before and after the pandemic lockdown.

As mentioned in **Chapter 3**, the selection of schools considered diversity across several factors, including types of secondary education, urban or rural locations, and year of construction. Meanwhile, within each school, classrooms were chosen to represent a variety of ventilation regimes. However, during the field study, most schools opted to keep classroom windows and doors open throughout school hours to ensure maximum outdoor air supply, since it was recommended in the media as an important pandemic control and prevention measure. Such practice, exposing the indoor environments to uncontrollable outdoor conditions, resulted in mechanical ventilation systems equipped in a few classrooms – especially mechanical air supply and balanced mixing ventilation – not operating as designed, making them no different from using natural ventilation alone.

Before the lockdown, the classrooms were allowed to operate at normal student occupancy levels. Results showed that they struggled to achieve the required level of ventilation rate per person prescribed in standards and guidelines [19,30], as evidenced by unacceptably high indoor CO_2 concentrations observed during occupied hours [19]. After the lockdown, due to social distancing requirements, student occupancy was reduced to about half of its previous level in the classrooms, where significantly lower indoor CO_2 concentrations and higher ventilation rates per person were achieved. Nonetheless, analyses showed that such difference between pre- and post-lockdown periods was mainly associated with the decrease in occupancy, rather than other factors such as ventilation practices.

Moreover, thermal conditions in the classrooms were unsatisfactory during both the pre- and post-lockdown periods, failing to meet the desired level [19]. Before the lockdown, the school visits were mainly conducted during the heating season, and classroom temperatures were generally cold, likely due to the constant practice of keeping windows and doors open. After the lockdown, indoor temperatures increased with the seasons, yet unacceptably low and high levels were observed in several classrooms. Such thermal conditions are likely to cause discomfort for students.

To conclude, with maximized natural ventilation being ensured (and mechanical ventilation being hindered where available), ventilation remained insufficient in most of the studied classrooms according to standards and guidelines [19,30], often accompanied by challenges in maintaining desirable thermal conditions. While other non-ventilation related pandemic control measures, such as reduced occupancy, did improve the ventilation rate per person, this is not a sustainable long-term solution due to the limited space and staff available in schools. Therefore, more controllable and flexible strategies are needed to improve IAQ and thermal comfort in school classrooms.

3 Sub-research question 3: **How to use mobile air cleaners to effectively control infectious respiratory particles in school classrooms at a room scale?**

To summarize, as presented in **Figure 6.4**, a comprehensive strategy was developed for the effective use of MACs in classrooms to control long-range airborne transmission of IRPs. This strategy begins with selecting appropriate devices, with attention to technical specifications such as nominal efficiency, CADR, airflow patterns, and noise levels, as well as affordability. Key factors for achieving optimal CADR include an upward air supply from the MACs and a placement oriented toward the occupied zone within the room. It is also important to employ at least two devices to ensuring efficient clean air delivery throughout the space, especially in large rooms. In addition, combining MACs with mechanical ventilation is likely to enhance IRP removal. Nonetheless, aiming for higher CADR often results in increased noise levels, which can exceed acceptable limits and disrupt occupant comfort. Therefore, finding a balance between device efficiency and occupant comfort is essential. When implemented in real-world settings, adjustments are often needed due to limited space and available power outlets. However, following certain general guidelines can still ensure effective MAC performance.

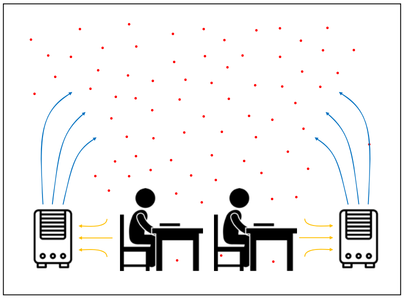

FIG. 6.4 Main focus of Chapter 4: a comprehensive strategy for using mobile air cleaners to control long-range airborne transmission of infectious respiratory particles in school classrooms, from selection to operation.
Note: red dots represent infectious respiratory particles.

a *Which strategies are recommended for mobile air cleaners in classroom settings to ensure both efficient IRP removal and acceptable perception by occupants?*

As mentioned in **Chapter 1**, this sub-research question is further divided into two questions. Hence, detailed answers to each are provided as follows.

First, due to the wide variety of MACs available on the market, it is necessary to establish a set of criteria to guide the selection process. After reviewing all available products, it is concluded that for small- and medium-sized floor-standing MACs: 1) HEPA and electrostatic filters are the recommended air cleaning technologies; 2) filter efficiency should be H13 and higher; 3) a total CADR (nominal) of 1000 m^3/s is necessary for a classroom with 30 students, to achieve a desirable clean airflow rate of 8.5-10 L/s per person, as suggested in Ref. [30-32]; 4) noise levels should be minimized, with the lowest level below the threshold specified in Ref. [19] for classrooms. Based on these criteria, eight MACs were selected, of which seven were tested.

The results of the aerosol removal test indicated that the MACs equipped with high-efficiency filters (H13) were all capable of removing IRPs in a classroom setting homogeneously, regardless of the air cleaning technology used (either HEPA or electrostatic). The most important factor for achieving a satisfying CADR is the airflow pattern induced by the MAC, i.e., how contaminated air is drawn in and clean air is expelled. MACs with an upward (either vertical or angled) air supply can distribute clean air more effectively throughout the room compared to those with a horizontal air supply. Additionally, the placement of the devices is crucial, as it significantly affects air distribution. Ideally, the supply airflow should be directed toward the occupied zone as much as possible for optimal results.

The laboratory test findings mentioned above were further validated in a real-world test conducted in a university classroom. This classroom test also revealed that as room size increases, using multiple (i.e., at least two) MACs became necessary to ensure effective clean air delivery throughout the entire space. Furthermore, the results demonstrated the benefits of combining MACs with mechanical ventilation, which achieved a higher CADR compared to the laboratory tests, where no background ventilation was used. However, further research is needed to determine the optimal configuration for integrating ventilation systems and air cleaning devices to maximize their effectiveness.

Furthermore, noise and draft are two important factors that can hinder the feasibility of using MACs in classrooms, as they can cause discomfort for students or even impair academic performance. According to the panel perception test participated by PhD students, at the higher settings necessary to achieve adequate CADR, the noise levels often exceeded the prescribed threshold [19]. However, panel assessments varied across different MACs and conditions. In contrast, air velocities generally met the requirements for avoiding draft discomfort [33], with positive feedback from the panel. This highlights the importance of involving user feedback to optimize MAC usage in classrooms, minimizing compromises between device performance and occupant comfort.

b *What is the feasibility of applying these strategies in real school classrooms?*

As a follow-up to the experimental study, a field study was carried out in real-world primary school classrooms to assess the feasibility of implementing the pre-determined strategies.

Challenges arose during the installation of MACs in the classrooms, as many were crowded and cluttered, leaving limited space for the devices. Additionally, a common issue was the lack of sufficient power outlets. As a result, the placement of the MACs had to be adjusted in each classroom, and extension cords and splitters were required to connect all the necessary devices. Nonetheless, it was ensured that in each classroom, one MAC was positioned at the front and one at the back, with the air supply directed toward the occupied area.

Despite the challenges in placing the MACs exactly as planned in the experimental study and potential errors from incorrect operation by teachers or students, the MACs managed to significantly reduce the particle concentrations in the classrooms. Indeed, a more comprehensive investigation with a larger sample size is needed to fully understand the feasibility of using MACs in school classrooms for IRP removal, yet as a pilot study, the findings can prove their effectiveness in real-world settings.

4 Sub-research question 4: **What is the potential of personalized air cleaners to control infectious respiratory particles in school classrooms within individual proximity?**

In brief, as illustrated in **Figure 6.5**, a novel way of using the PAC was proposed, namely, as a localized air exhaust to capture the exhaled particles within the proximity of each occupant. The PAC demonstrated efficient removal of respiratory particles in confined spaces, which was attributed to the air circulation caused by its supply airflow. In a larger space, the vertical position showed better performance than the others. However, the PAC's suction effect was generally limited, diminishing rapidly with distance. Moreover, only the lower PAC setting was suitable for real-life classroom use, as the higher setting produced unacceptably high noise levels, as reported by participants. Hence, modifications are needed to improve the performance of the PAC. The details are given as follows.

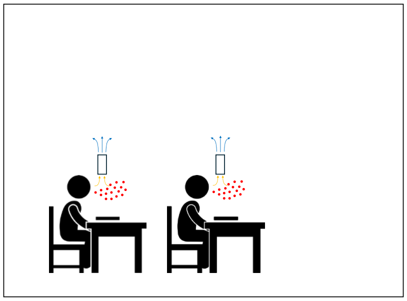

FIG. 6.5 Main focus of Chapter 5: possibility of using a personalized air cleaner to locally exhaust infectious respiratory particles in a classroom setting.
Note: red dots represent infectious respiratory particles.

To date, PACs are not yet commonly available. Even the smallest MACs are often still too large to be considered feasible for personalized use by each student in classrooms. The PAC tested in this study was selected after a market screening and is appropriately sized, featuring an electrostatic filter of high efficiency for particles (H13). Normally, as an air cleaning device, the PAC is used to supply filtered air to the breathing zone of the occupant, i.e., with the air supply side facing the user. However, as discussed in **Chapters 1** and **5**, previous studies on personalized ventilation have indicated that compared to personalized air supply systems, personalized air exhaust systems have the strength to efficiently remove exhaled contaminants, with their performance being unaffected by the airflow rates of nearby devices. Accordingly, in this study, the PAC was determined to be used as a localized air exhaust, meaning with its suction side facing the user.

As observed in the studies presented in **Chapter 4**, user perception plays a crucial role in the feasibility of using air cleaning devices in a study environment. Therefore, the acceptability of the PAC regarding noise and draft was first tested, with a panel of university students. Like the test on MACs, when the PAC was operating at a higher level, the noise was found to be unacceptably high. Hence, only the lower level was suitable for further evaluation. The aerosol removal test was performed with the suction side of the PAC facing the subjects, and all instruments were housed within a refined box to minimize the influence of ambient air. The results showed that at the lower level, the PAC was able to reduce the number of particles exhaled by the subjects by 40% to 51%, with higher efficiency for smaller particles.

Such promising results, however, were likely attributed to the air recirculation caused by the supply air flow of the PAC within the box, as the CFD simulations yielded less favorable outcomes. As a preliminary exploration, the simulations primarily focused on the velocity profile at the suction side of the PAC. Six different positions of the PAC were examined, all of which were carefully selected to ensure applicability in real-world classrooms. However, it was noted that with a lower setting, such positioning was too far from the occupant to let the PAC's suction effect reach the breathing zone. Nevertheless, the central position with a vertical placement demonstrated better results compared to the other positions. In real-life scenarios, this position would also have a greater potential to leverage the rise of exhaled particles caused by the thermal plume of the human body, leading to enhanced capture of IRPs.

Indeed, further modifications are necessary to achieve optimal performance for personalized air cleaning devices like the PAC. When compared to other designs of personalized exhaust systems, which demonstrated high efficiency, the PAC exhibited a significantly lower airflow rate. However, as concluded from the perception test, simply increasing the airflow rate would lead to unacceptable noise levels. While alternative solutions, such as increasing the suction surface area or reducing the distance from the occupant, may enhance removal efficiency, they could also introduce new challenges. Therefore, careful configurations are essential.

To conclude, the concept of using the PAC as a localized exhaust for IRP removal in a classroom setting showed good potential, yet new designs focused on both efficiency and user acceptability are needed to ensure its feasibility for real-world applications.

6.2.2 Answer to main research question

Which ventilation and air cleaning strategies can be used to effectively control the spread of infectious respiratory particles in school classrooms?

To sum up, from the literature review, it was understood that for controlling long-range and short-range airborne transmission of IRPs, distinct ways of ventilation, namely at both room-scale and individual level, are required (**Chapter 2**). From the field study, it was observed that existing ventilation regimes in school classrooms were insufficient, necessitating both room-scale and individual-level solutions (**Chapter 3**). Consequently, MACs were selected to address long-range IRP transmission, leading to the establishment of a systematic strategy, from selection to operation, for classroom usage (**Chapter 4**). Meanwhile, PACs were proposed to minimize short-range IRP transmission as a localized exhaust, for which the feasibility was examined, and further modifications were suggested (**Chapter 5**). The detailed ventilation and air cleaning strategies for IRP control in school classrooms, based on key findings from the previous chapters, are summarized in **Table 6.1**.

TABLE 6.1 Summary of different ventilation and air cleaning methods in school classrooms.

Solution for long-range IRPs		Solution for short-range IRPs	Findings
Ventilation regime	Mobile air cleaner	Personalized air cleaner	
Natural ventilation	No	No	• Used in most classrooms • Largely dependent on outdoor conditions, normally not controllable • Difficult to provide sufficient ventilation when the classroom is fully occupied • Can cause thermal discomfort due to warm or cold outdoor temperature
Mechanical ventilation	No	No	• Used in certain newly built classrooms • Common types are mechanical supply, mechanical exhaust, and mixing ventilation • Was not able to be assessed independently due to the commonly opened windows and doors during the pandemic
Natural ventilation + mechanical ventilation	No	No	• Same as natural ventilation alone • Mechanical systems not functioning as designed as they were overpowered by natural ventilation
No	Small- and medium-sized floor-standing MACs	No	• A large variety available • Selection criteria including air cleaning technology, induced airflow pattern, CADR, noise level, etc. • Can effectively remove IRPs • Important to have an upward air supply • Important to configure the distribution of clean air across the occupied area through strategic placement • Multiple devices should be adopted, especially for large spaces, to achieve adequate CARD level • High noise levels are a major problem that is hard to avoid; hence users' perception should be studied in advance
Mixing ventilation	Small- and medium-sized floor-standing MACs	No	• Combining mixing ventilation can help MACs reach higher CADR • Strategic configuration of airflow pattern is required to maximize the effectiveness of both
No	No	Used as a localized exhaust	• Not yet a mature product • Can potentially be used to locally capture IRPs with a setting acceptable for users • Design modifications are needed to improve the performance to a satisfactory level

When the COVID-19 pandemic first broke out, it posed immense challenges to society. One of the most pressing challenges was how to keep schools safe for children and protect them from the risk of cross-infection. Children are vulnerable to their surroundings, yet they spend long hours each day in crowded classrooms with peers who are exposed to various people and environments outside of school.

During the pandemic, no effective solution was available, leading to school closures and a shift to remote learning, which negatively impacted students' mental and physical health [34,35]. Hence, this PhD research was initiated to seek solutions to improve the ways of ventilation and air cleaning in school classrooms. Responding to the urgency of the situation, the study focused on practical strategies that could be implemented immediately or in the near future. Although the pandemic is no longer a major threat, the findings of this research still stand meaningful. The knowledge and experience gained during the hard times can offer important insights, not only for improving IAQ under normal conditions but also for better preparation for future challenges.

In fact, as addressed in the literature study (**Chapter 2**), prior research has extensively demonstrated that airborne respiratory particles are one of the dominating routes for cross-infection of not only COVID-19 but many other severe diseases [36-39]. Therefore, minimizing the spread of IRP should not only be prioritized during pandemic outbreaks but should also be carefully considered daily to ensure occupant health, particularly in densely occupied school classrooms with vulnerable individuals. Over the years, researchers have devoted significant efforts to understanding the mechanisms and features of IRPs and the critical role of ventilation in their control, providing valuable insights for this study. The key knowledge learned is that airborne transmission of IRPs occurs both in proximity between occupants during close contact and over longer distances throughout the entire indoor space. Correspondingly, different ventilation strategies are required to address the distinct characteristics of each transmission type [1-4].

In the Netherlands, it has been observed that most classrooms rely solely on openable windows for ventilation [40,41]. Some newer buildings are equipped with mechanical ventilation systems, which typically include mechanical air supply (exhaust via infiltration), mechanical air exhaust (using windows or passive grilles for outdoor air supply), and a combination of both mechanical air supply and exhaust (usually in the form of mixing ventilation). During the pandemic, a common recommendation for schools was to keep all windows and doors open [42]. While this ensured maximum ventilation capacity, it disrupted the balance of the designed airflow rates for the mechanical systems, particularly in classrooms using mechanical supply and mixing ventilation. Consequently, it was observed in the field study (**Chapter 3**) that in these classrooms, the mechanical ventilation systems were overpowered by natural ventilation, resulting in conditions indistinguishable from classrooms relying solely on natural ventilation (**Table 6.1**). This made it infeasible to assess the performance of the mechanical systems independently. However, the necessity of opening windows somehow implied the inadequacy of existing mechanical systems to meet ventilation needs during the pandemic.

This is likely because current design paradigms are comfort-based, and often use recirculation for energy saving [14]. In fact, such an issue is not new, as insufficient ventilation and poor IAQ conditions have long been documented in school classrooms worldwide prior to the COVID-19 pandemic, even when mechanical ventilation systems were used independently [22,43-46].

From the field study (**Chapter 3**) it was also concluded that, under the existing ventilation regimes in classrooms during the pandemic – primarily natural ventilation – the ventilation rate was insufficient to meet current standards and guidelines [19,30], let alone effectively control IRPs. Such ventilation practice, relying solely on outdoor conditions, can also lead to discomfort issues [33]. Consequently, there is a pressing need for more controllable methods of managing indoor environments in classrooms. Given the urgency for improvements, it is not feasible to immediately install or renovate the entire system due to the time and costs involved. Therefore, more flexible and affordable solutions are considered.

Based on the findings of the literature review (**Chapters 2**) and the field study (**Chapter 3**), strategies for controlling the spread of IRPs and improving IAQ in school classrooms have been developed, beginning with the long-range airborne transmission, for which the proposed solution is air cleaning devices. Among all sorts of air cleaning devices, MACs were considered for their flexibility and affordability. Although MACs are already widely available and highly developed, their use in school classrooms remains uncommon. Based on the experimental and field studies presented in **Chapter 4**, a comprehensive strategy was developed for utilizing MACs in classrooms to effectively remove IRPs and enhance IAQ, detailing everything from selection to operation, as summarized in **Table 6.1**. This strategy is not limited to specific brands or scenarios, providing guidance for a variety of users and indoor settings. In the meantime, the noise generated by MACs can pose a significant issue that hinders their practical usage, which is hard to mitigate unless the fan level can be reduced. Therefore, combinations of MACs with other types of ventilation or air cleaning methods should be further explored.

Following **Chapter 4**, the solution proposed for controlling short-range IRP transmission is a PAC, which is not yet widely available. Given the promising performance of personalized exhaust systems in removing exhaled contaminants, as demonstrated in previous studies [26,27,47], and the advantages of air cleaners being flexible for implementation [48], the PAC was proposed to leverage the strengths of both. Hence, the potential of using the PAC as a localized exhaust for IRPs in a classroom setting was explored, as addressed in **Chapter 5**. As shown in **Table 6.1**, it was found through the experiment that the noise and draft at a moderate setting of the PAC were acceptable to the subjects, alongside decent results of respiratory aerosol removal within a refined space. However, the simulation results revealed the limited effectiveness of the PAC in a room-scale environment, with a more realistic distance to the occupant. Thus, for the PAC to be feasible for practical use in classrooms, further modifications are needed. This requires a comprehensive design that considers the PAC's efficiency, user comfort, and the overall functionality (e.g., teaching and learning) of the space.

6.2.3 Limitations

Due to the constraints of time and resources, this PhD research has the following limitations which need to be acknowledged.

When addressing the main research question, the initial step was to understand the mechanisms and features of IRP dispersion and examine the characteristics of ventilation in school classrooms during the pandemic. This was accomplished through a literature review (**Chapter 2**) and a field study (**Chapter 3**), respectively.

For the literature review, it needs to be noted that it was conducted at the early stage of the pandemic, limiting its inclusion of the rapidly emerging studies in recent years. Nevertheless, it covered essential information on relevant topics to guide the follow-up studies, which, in the meantime, have reflected the updates in knowledge.

For the field study, first, although the schools selected represented a degree of diversity in Dutch secondary education, they lacked samples from specific groups, such as private schools and special education institutions, where characteristics of indoor settings, systems, and occupancy may differ significantly. Second, the school visits were conducted only during the heating and intermediate seasons, leaving out conditions during the summer months. Although the incidence of infectious respiratory diseases is generally higher during the heating season [49-51], warmer temperatures in summer could significantly affect indoor environmental conditions, as well as occupants' perceptions and behavior. Including data from warmer seasons would provide a more comprehensive, year-round profile of ventilation and IEQ in classrooms. Third, the study did not include subjective assessments from children (and teachers), which could have offered valuable insights into occupant preferences and needs, complementing the physical measurements for developing solutions [23,52,53]. Fourth, the initial selection of classrooms was based on the diversity of ventilation regimes they were equipped with. However, the practice of keeping windows and doors open strongly hindered the operation of mechanical ventilation systems. As a result, this study was unable to fully address the features and performance of the various ventilation regimes used in school classrooms.

The next step in answering the main research question was to develop effective strategies for ventilation and air cleaning to control IRPs in classrooms. Accordingly, a room-scale solution was proposed in the form of MACs (**Chapter 4**), and an individual-level solution in the form of the PAC (**Chapter 5**). A limitation shared by both studies is that they focused mainly on using the MACs or PAC individually, without exploring their combination with other ventilation or air cleaning methods. However, this study design choice was intentional, as the aim was to assess the feasibility of using these devices alone for IRP removal in classrooms with limited ventilation, as observed in **Chapter 3**. Future research could follow to explore the advantages and disadvantages of various combinations of ventilation and air cleaning methods, helping to expand the strategies outlined in **Table 6.1**.

For the study on MACs (**Chapter 4**), additional limitations were identified. First, the panel perception assessment conducted in the laboratory setting involved only eight adults, which is a small sample size and may not accurately reflect children's perceptions of indoor environmental conditions, rendering the results potentially unrepresentative [54]. This limitation was partially addressed in the follow-up field study, where subjective evaluations from different stakeholders were collected; however, since this part was conducted by other research teams as part of a joint project, it is not included in the current study. Second, the investigation of MACs was conducted over a short duration, whereas real-life use may last for years. Factors such as maintenance costs and efficiency degradation over time are also crucial for assessing the feasibility of MACs in school classrooms, and thus should be addressed in future research. Third, in the field study, the particles measured could not be distinguished as originating from human respiration or other sources (e.g., outdoor air), preventing a conclusive evaluation of IRP removal for the MACs. Therefore, specific methods should be considered for further investigation into the performance of MACs in removing IRPs in real-life settings.

For the study on the PAC (**Chapter 5**), only one type of PAC was investigated, as it was the only suitable model available. First, it was determined based on previous research that the PAC was used as a localized air exhaust; hence, the performance of using the PAC in the normal way – as a localized air supply, was not explored. Second, aerosol removal tests were conducted in a confined space (a cardboard box), which likely enhanced the PAC's performance due to increased air recirculation; thus, these results may not accurately reflect performance in larger, more open environments like school classrooms, where airflow dispersion is less constrained. Third, the CFD simulations primarily focused on velocity fields and did not consider other important factors, such as human breathing, particle dispersion, and thermal plumes, leading to an incomplete understanding of the PAC's aerosol removal performance. Nonetheless, as an initial exploration of using the PAC as a localized exhaust, this study highlights the potential of this type of device, with future research aimed at optimizing its design and enhancing its feasibility.

Beyond the above-mentioned limitations, it should also be pointed out that, although the aim of this PhD research is to provide healthy IAQ conditions for children in school classrooms, it did not examine whether the proposed strategies can actually reduce the infection risk of COVID-19 or other respiratory diseases. Therefore, further investigations over extended periods in real-world classrooms on the incidence of respiratory infectious diseases among children and teachers should be carried out to validate the ventilation and air cleaning strategies developed in a laboratory setting or via computational approaches.

6.3 Practical implications

The key outcomes of this PhD research are:

1. Highlighting the inadequacies of current ventilation systems in school classrooms, particularly during pandemic conditions, for IRP control.
2. Creating a flexible, evidence-based strategy for selecting, placing, and operating MACs in school classrooms for long-range IRP removal.
3. Investigating the potential of PACs as a localized solution for controlling short-range IRP transmission.
4. Suggesting combining air cleaning technologies like MACs and PACs with mechanical ventilation systems can provide a more holistic approach to managing IAQ.
5. Emphasizing the need for updated school ventilation and IAQ guidelines, advocating for a shift from comfort-based to health-focused ventilation designs.

Accordingly, the practical implications of this PhD research are provided as follows.

School managers are offered actionable strategies to improve IAQ in classrooms. The findings show that relying solely on natural ventilation is inadequate for controlling IRPs, especially in crowded classrooms. School managers can consider integrating MACs as a flexible and cost-effective solution to enhance air quality without significant infrastructural changes. Practical guidance on selecting and operating these devices is provided in the study, helping to ensure effective use while balancing noise levels and airflow. Additionally, school managers are encouraged to plan for ventilation upgrades where feasible, ensuring long-term resilience against the risk of airborne diseases.

Facility managers, tasked with the maintenance and operation of school ventilation systems, will benefit from the detailed insights provided in this research. The study reveals that during pandemic conditions, proper operation of mechanical ventilation systems can be affected by the continuous opening of windows, reducing their effectiveness. Facility managers should explore strategies to optimize mechanical systems to ensure they perform as intended, even under such constraints. The research also outlines best practices for deploying MACs, emphasizing factors like filter efficiency, clean air delivery rate, and device positioning. PACs offer another potential solution, and facility managers should keep an eye on further developments in this area for future classroom implementations.

Policymakers and public health officials can use the findings of this study to revise and update ventilation guidelines for schools, particularly considering the lessons learned during the COVID-19 pandemic. Current standards, which focus primarily on comfort and energy efficiency, should be expanded to include the control of airborne infectious particles. A recent example of this shift is the newly released ASHRAE standard, *Control of Infectious Aerosols* (ASHRAE 241-2023) [55]. The study supports the need for more robust IAQ monitoring protocols and the integration of air cleaning technologies like MACs as a standard practice in schools. Public health officials could also advocate for funding initiatives to help schools acquire and maintain air cleaning devices, ensuring that schools are better equipped to manage both everyday IAQ and future health crises.

For product developers in the air cleaning industry, this research points to several opportunities for innovation and refinement. The study demonstrates the effectiveness of MACs in removing IRPs, yet existing products are mostly designed for household use, which in some cases need to be adjusted for classroom use. Moreover, user interfaces tailored for home users can sometimes create challenges for school users. Hence, there is a continued need for MACs to be specifically designed for classroom environments. Additionally, the limited availability of PACs presents a market opportunity. Developers should focus on creating quieter, more efficient, and user-friendly PAC designs that can be easily implemented in school environments. The research encourages the exploration of hybrid solutions, where MACs and PACs work in conjunction with existing ventilation systems, offering an untapped potential for product development.

Students and teachers, although not directly involved in the decision-making process, are the primary occupants of classrooms and are at the frontline of experiencing indoor air quality. The outcomes of this study provide valuable insights for both groups, helping them understand the importance of IAQ and its impact on health and learning. Teachers can learn how to properly operate and manage ventilation and air cleaning devices, ensuring a safe and comfortable classroom environment throughout the day. The study also emphasizes the importance of feedback from teachers and students regarding device performance – educating them on how their input can shape the implementation of IAQ solutions. For students, a better understanding of the importance of IAQ can encourage healthy behaviors and improve awareness of how environmental factors affect their well-being and academic performance.

6.4 Recommendations for future research

As previously laid out, this PhD research serves as a pathfinder to seek solutions for effectively controlling IRPs in school classrooms. Future research can build on these findings to develop more comprehensive strategies. The recommended directions address individual solutions for long-range and short-range airborne transmission of IRPs, combinations of the two approaches, and validation for real-world cross-infection mitigation, which are further addressed in the following sections.

6.4.1 Investigating different room-scale mechanical ventilation regimes

The mechanical ventilation system (fully controlled, with both airflow inlet and outlet) most commonly used in school classrooms is mixing ventilation (MV). It is a traditional way of ventilating, designed to introduce supply air at high velocity to thoroughly mix with the indoor air, ensuring even distribution of temperature and contaminants throughout the space [56]. MV systems are commonly used in classrooms due to their simplicity and effectiveness in maintaining consistent indoor conditions [57]. The problem often observed in mixing ventilation systems is inadequate ventilation rates. However, achieving a level sufficient for effective IRP control may significantly increase energy consumption or even exceed the maximum capacity of existing systems. Additionally, it has been observed that increasing the ventilation rate in MV does not necessarily result in a proportional reduction in particle concentrations [58]. Hence, other types of mechanical ventilation systems should be considered for improving IAQ in school classrooms, such as displacement and stratum ventilation.

Displacement ventilation (DV) works by supplying cool, fresh air at a low velocity near the floor. As this air gets heated by the thermal plume of occupants, it rises to displace warmer, contaminated air, which is then exhausted from the ceiling. This process promotes improved air quality and thermal comfort in the occupied zone [56]. Stratum ventilation (SV), on the other hand, operates by using multiple levels or strata of air, typically with cooler air supplied at lower levels and warmer air naturally stratifying above. This method facilitates targeted temperature control and improved air quality by maintaining distinct thermal layers in a space [56]. Extensive studies have shown that DV and SV systems are more effective than MV systems in reducing indoor air contaminants, especially for DV systems, which have the advantage of maintaining better air quality in the breathing zone [58-60]. Moreover, both DV and SV systems have demonstrated a strong ability to enhance thermal comfort while reducing energy consumption compared to mixing ventilation [61-63].

Although studies have examined the performance of DV and SV systems in school classrooms, they represent only a few examples from modern educational settings [61-63]. Besides, these studies primarily focused on thermal comfort and energy savings rather than IRP control. Therefore, future research is needed to investigate the capability of DV and SV systems for IRP removal in classroom environments, with particular attention to airflow configurations (such as the placement of airflow inlets and outlets) and airflow rates. This can be done first through CFD simulations to address enough trials, then through testing in a laboratory environment, and eventually being validated in the field.

6.4.2 Optimizing design of personalized air cleaning devices

As demonstrated in **Chapter 5**, the setup of using the PAC as a localized exhaust for efficiently removing IRP and maintaining good IAQ for each individual has its strength over other personalized systems such as PV and PE. Hence, future research should first aim to establish a more comprehensive understanding of the performance of PACs. First, more realistic CFD simulations should be performed, incorporating important factors such as dispersion of particles from human breathing and room temperature and relative humidity. Potential modifications could

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then be explored, for instance, an increase in the suction surface area or a shorter distance from the occupant, together with an increase in the airflow rate. From there, a prototype can be developed and examined for both efficiency and acceptability. Ultimately, the prototype should be evaluated in real-world environments.

Furthermore, in recent years, personalized environmental control systems (PECS) have gained increased interest. The concept of PECS emphasizes individual control over not only IAQ but also other IEQ aspects, such as thermal comfort, visual comfort, and acoustics, within the immediate surroundings of each occupant. It is indeed important to treat the IEQ condition holistically, for their interaction effects on health and comfort. Hence, the potential for combining different personalized systems should be explored. For example, Shinoda et al. [64] developed a PECS prototype that provided personalized control over heating, cooling, and ventilation, and ensured good thermal comfort and ventilation effectiveness for the occupants. However, acoustics and visual comfort were not considered. Moreover, noise and odors from the system were found to pose a problem for the users. Zhang et al. [65,66] created an individually controlled noise-reducing device (ICND) which achieved significant improvement in overall acoustics in a classroom setting. This device, with a canopy-like design, could potentially be integrated with personalized air cleaning systems and other types of PECS to enhance overall IEQ in school classrooms.

6.4.3 Exploring combinations of different ventilation and air cleaning methods

As summarized in **Table 6.1**, in this PhD research, the proposed solutions were examined individually. However, great potential lies in the combination of both room-scale and individual-level solutions. For instance, previous studies on PV and PE systems were often conducted in indoor settings with ambient mechanical ventilation (including both MV and DV). The promising performance in reducing infection risk well indicated the potential of such a combination [25,27,67]. Furthermore, aligned with the findings in **Chapter 4**, studies have demonstrated that combining MACs with mechanical ventilation can further improve IAQ in school classrooms, which can sometimes even benefit from energy saving [68,69]. Nonetheless, further investigations are needed to establish proper strategies for such combined solutions. Specifically, for different types of ventilation systems and air cleaning devices, the control of integrated airflow should be carefully considered. Additionally, the effects of corresponding noise and drafts need to be evaluated to ensure occupant comfort. Other combinations, such as MACs with PACs, or mechanical ventilation systems with both MACs and PACs, also remain to be explored.

6.4.4 Validating effects of ventilation and air cleaning strategies on real-world cross-infection

In response to the last point in **Section 6.2.3**, investigation over extended periods on the effects of ventilation and air cleaning interventions on real-world cross-infection of respiratory diseases among children and teachers is crucial to validate their efficacy. To date, few studies have addressed this, likely due to the lack of data because of worldwide school closures and the limited incidence of infected children after school reopening [70]. One example is the retrospective cohort study conducted by Buonanno et al. [71] in Italian schools (from pre-schools to high schools) to identify the association between ventilation and SARS-CoV-2 transmission. The results showed that in classrooms with mechanical ventilation systems, the infection risk among students was significantly lower than in those with only natural ventilation. In addition, increased ventilation rates per person is associated with reduction in infection risk. This study serves as a pioneer validation for the importance of adopting mechanical ventilation systems with higher ventilation rates for minimizing the spread of IRPs and reducing infection risk in school classrooms. With more systems and devices being examined and further strategies proposed, future research is needed to better understand their application on actual mitigation of cross-infection among occupants in real-world classrooms.

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Appendices

APPENDIX A

Supplementary materials for Chapter 3

A.1 Technical questionnaire of the school building(s)

1. How many different ventilation regimes does the school consist of?
2. Describe the building (part) in which the first ventilation regime is located (if your school consists of several building parts/buildings, only fill in the data for the first building part, on the following pages you can enter the data about the other building parts).
3. What is the year of construction of the building?

4. Which school years are (mainly) taught in this building?
   - ☐ 1
   - ☐ 2
   - ☐ 3
   - ☐ 4
   - ☐ 5
   - ☐ 6
   - ☐ All grades

5. What is the total area of the building?
6. What is the total floor area of the building?
7. How many floors does the building have?
8. What is the height of the building in meters?
9. How many classrooms are there in the building?

10. How many canteens and/or other sitting areas are there in the building?
11. How many teachers' rooms and / or offices are there in the building?
12. How many kitchens are there in the building?
13. How many libraries and / or media libraries are there in the building?
14. How many toilets and showers are there in the building?

15. How is the building ventilated?
- Natural ventilation - open windows
- Natural ventilation - open windows and doors
- Mechanical - exhaust air only
- Mechanical - both exhaust and air supply
- Mechanical - displacement ventilation

16. Is there mechanical ventilation in the building?
- ☐ Yes, the whole building
- ☐ Yes, in some areas of the building
- ☐ No

16.1. If the answer of "Is there mechanical ventilation in the building?" is not "No", then please answer this question: What is the date of the last maintenance of the mechanical ventilation system?

16.2. If the answer of "Is there mechanical ventilation in the building?" is not "No", then please answer this question: How is the mechanical ventilation system controlled?

- ☐ Manual (on / off) - centralized
- ☐ Manual (on / off) - local
- ☐ Automatically
- ☐ CO_2 controlled
- ☐ Other

16.2.1. If the answer of "How is the mechanical ventilation system controlled?" is "Other", then please answer this question: Specify how the mechanical ventilation system is controlled.

16.3. If the answer of "Is there mechanical ventilation in the building?" is not "No", then please answer this question: Where does the supply of the ventilation system take place?
- ☐ Roof
- ☐ Front
- ☐ Ground
- ☐ Other

16.3.1. If the answer of “Where does the supply of the ventilation system take place?” is “Other”, then please answer this question: Specify where the supply of the ventilation system takes place.

16.4. If the answer of “Is there mechanical ventilation in the building?” is not “No”, then please answer this question: What is the height of the ventilation system measured in meters from the ground?

17. Are the doors between the different areas generally open?

- ☐ Yes
- ☐ No
- ☐ Partly

18. What type of air handling unit is present in the building?

- ☐ 100% fresh air
- ☐ Recirculation
- ☐ Passive cooling with outside air
- ☐ Two-duct system with recirculation
- ☐ Other

19. If the answer of “What type of air handling unit is present in the building?” is “Other”, then please answer this question: Specify the type of air handling unit.

19.1. Is the toilets exhaust system running continuously to provide basic ventilation in the building?

- ☐ Yes
- ☐ No
- ☐ No exhaust system in toilets

20. Is there a heating system in the building?

- ☐ Yes, throughout the building
- ☐ Yes, in some areas of the building
- ☐ No

20.1. If the answer of “Is there a heating system in the building?” is not “No”, then please answer this question: What type of heating system is available in the classrooms? (multiple answers possible)

- ☐ Radiator and / or convector
- ☐ Floor heating
- ☐ Ceiling heating
- ☐ Wall heating
- ☐ Air conditioner cabinets

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- ☐ Air supply through ceiling
- ☐ Air supply through wall
- ☐ Ventilation floor

21. Which heat recovery systems are used? (Multiple answers possible)

- ☐ Plate heat exchanger
- ☐ Rotating heat exchanger
- ☐ Evaporation-condensation pipe
- ☐ Twin coil unit
- ☐ Others
- ☐ No

21.1. If the answer of “Which heat recovery systems are used?” is “Other”, then please answer this question: Specify which heat recovery systems are used.

22. Is there a cooling system in the building?

- ☐ Yes, throughout the building
- ☐ Yes, in some areas of the building
- ☐ No

22.1. If the answer of “Is there a cooling system in the building?” is not “No”, then please answer this question: What type of cooling system is available? (multiple answers possible)

- ☐ Floor cooling
- ☐ Ceiling cooling
- ☐ Wall cooling
- ☐ Air conditioning cabinets
- ☐ Air supply from ceiling
- ☐ Air supply through wall
- ☐ Ventilation floor

A.2 Interview with school facility manager

1st school visit (October to December 2020):

1) What are the available ventilation regimes in the school building(s)?
2) If applicable, are the mechanical ventilation system still operating? If so, at what capacity? If not, why?
3) In particular, how are the classrooms ventilated?
4) At the school level, how are the windows and doors inside the classrooms operated, regarding the COVID-19 pandemic control and prevention?
5) Is there any other action taken insides the school buildings in order to enhance ventilation in the classrooms?
6) What is the maximum occupancy of students in the classrooms?
7) Are there any COVID-19 pandemic control and prevention measures implemented in the classrooms? (e.g., 1.5 m distance between the students)
8) What is the timetable of the classrooms? How long are the lessons? How long are the breaks and how are the breaks arranged? (e.g., Are students required to leave/stay in the classroom during the break?)
9) How often are the classrooms cleaned?

2nd school visit (March to June 2021):

1) Comparing to the pre-lockdown period, has anything been changed regarding the ventilation of the classrooms?
2) Comparing to the pre-lockdown period, has anything been changed regarding the operation of windows and doors in the classrooms?
3) What is the maximum occupancy of students in the classrooms?
4) Comparing to the pre-lockdown period, are there any different COVID-19 pandemic control and prevention measures implemented in the classrooms?
5) Comparing to the pre-lockdown period, has anything been changed with the timetable (regarding both the lessons and the breaks)?
6) Compared to the pre-lockdown period, has anything been changed for cleaning?

A.3 Classroom checklist

1. Indoor Characterization

1.1. On which floor is the classroom location (0= ground floor): ________________

1.2. Basic information:
Total floor area: ___________ m^2
Total volume: ___________ m^3
Ceiling height: ___________ m

1.3. Contrast of window frames
- ☐ Light-colored window frames with light-colored wall
- ☐ Light-colored window frames with dark-colored wall
- ☐ Dark-colored window frames with light-colored wall
- ☐ Dark-colored window frames with dark-colored wall

1.4. Windows frames
- ☐ Metal
- ☐ Wood
- ☐ PVC
- ☐ Aluminum
- ☐ Other (specify) ______________________________

1.5. Can the windows be open?
- ☐ No
- ☐ Yes
- ☐ If yes, can they be adjusted?
- ☐ All
- ☐ Some (estimate % of openable windows)
- ☐ But occupants are not allowed to open them

1.6. Type of glazing
- ☐ Single glazing
- ☐ Double glazing
- ☐ Triple glazing
- ☐ Other (specify) __________________

1.7. Type of lighting

☐ Natural
☐ Artificial
☐ Mixture

1.8. Type of artificial lighting

☐ Fluorescent
☐ Compact fluorescent
☐ Incandescent
☐ Halogen
☐ Other (specify) ______________________

1.9. Is the artificial light turned on at this moment?

☐ Yes
☐ No

1.10. Is there any reflection on the surface of the desks?

☐ Yes
☐ No

1.11. Solar shading devices

☐ None
☐ External
☐ Internal
☐ Both

1.12. Do solar shading devices hamper the use of windows or decrease the ventilation capacity?

☐ Yes
☐ No

1.13. Control of the shading devices

☐ No control (fixed)
☐ Individual
☐ Automatic
☐ Automatic with individual by-pass
☐ Other (specify) ____________________________

1.14. Room ceiling surface

- ☐ Concrete
- ☐ Paint
- ☐ Wallpaper
- ☐ Synthetic material
- ☐ Mineral fiber tiles
- ☐ Wood fiber tiles; cork tiles
- ☐ Wood
- ☐ Gypsum/plaster
- ☐ Other (specify) ______________________________

1.15. Room wall covering

- ☐ Concrete
- ☐ Paint
- ☐ Wallpaper
- ☐ Porous fabrics including textiles
- ☐ Stone/ceramic tiles
- ☐ Wood/cork
- ☐ Gypsum/plaster
- ☐ Other (specify) ______________________________

1.16. Room floor covering

- ☐ Concrete
- ☐ Carpet
- ☐ Synthetic smooth (linoleum, vinyl, ...)
- ☐ Laminate parquetry
- ☐ Stone/ceramic tiles
- ☐ Wood/cork
- ☐ Other (specify) ______________________________

1.17. Are there any major indoor sources of noise?

- ☐ No indoor sources of noise
- ☐ Occupants (distracting conversations)
- ☐ Neighbors
- ☐ Machines (photocopiers, computers, printers)
- ☐ Vibration from fans, ducts, supply grilles or vents
- ☐ Elevators
- ☐ Other (specify) ________________________

1.18. Can you hear outdoor noise sources?

☐ No outdoor noise sources
☐ Traffic
☐ Train
☐ Airplane
☐ People
☐ Yes (specify) ________________________

2 Humidity Problems

2.1 Visible mould growth in the room

☐ No
☐ Yes
- Where ____
- Extent (diameter)____________________________ (m)

2.2 Other damp/mould symptoms

☐ No
☐ Yes
  - ☐ Water leakage
  - ☐ Noticeable mould odor
  - ☐ Visible damp spots on walls, ceiling or floor
  - ☐ Bubbles or yellow discoloration of plastic floors
  - ☐ Blackened wood floor

2.3 Visible leak / crack in the room

☐ No
☐ Yes
- Where ____
- Extent (number, length, width) ___________________

2.4 Tendency for formation of condensation on windows

☐ No
☐ Yes
  - ☐ Inside
  - ☐ Outside
  - ☐ In- between the glazing

2.5 Others (Please specify)

3 Indoor Climate Characterization

3.1 Heating terminal units

- ☐ Hot water radiators or convectors
- ☐ Electrical radiators or convectors
- ☐ Floor heating
- ☐ Warm air flow
- ☐ Other (specify) ______________________________

3.2 Are heaters located below windows?

- ☐ No
- ☐ Yes

3.3 Is there noise absorption present?

- ☐ No
- ☐ Yes
  - ☐ Ceiling tiles
  - ☐ Wall panels
  - ☐ Baffles
  - ☐ Other:_____________________

3.4 How is the classroom ventilated?

- ☐ Operable windows
- ☐ Other natural ventilation (e.g., passive stack)
- ☐ Hybrid/mixed model (natural + mechanical)
- ☐ Local ventilation unit (i.e., ClimaRad)

3.5 Location of grilles (passive ventilation)

- ☐ Ceiling
- ☐ Walls
- ☐ Windows
- ☐ Other (specify) ________________________________

4 Mechanical Ventilation

4.1 Designed air distribution principle

- ☐ Mixing
- ☐ Displacement
- ☐ Other (specify) _______________________

4.2 Location of air supply devices

- ☐ None
- ☐ Floor
- ☐ Windowsill
- ☐ Ceiling
- ☐ High on wall
- ☐ Low on wall
- ☐ Other (specify) ______________________

4.3 Location of air exhaust grilles

- ☐ None
- ☐ High
- ☐ Low

5 Classroom Indoor Pollution Sources

5.1 Board

- ☐ Black board with chalk
- ☐ White board with markers
- ☐ Electronic interactive board
- ☐ Flip over chart
- ☐ Other (specify) ______________________

5.2 Electronic equipment (specify the number)

- ☐ Computers/printers/photocopiers
- ☐ Projector/TV
- ☐ Other (specify) ______________________

5.3 Other appliances (specify the number)

- ☐ Air cleaners (specify type) ____________________________
- ☐ Space heaters
- ☐ Humidifiers
- ☐ Dehumidifiers
- ☐ Air fresheners
- ☐ Permanent (passive or electric plugged)
- ☐ Occasionally (spray or other)

5.4 Furniture materials

- ☐ Wood
- ☐ Plywood
- ☐ Textiles
- ☐ Metal

- ☐ Plastic laminate or composite
- ☐ MDF furniture of less than 1 year old
- ☐ Other (specify) ________________________

5.5 Are there any curtains?

- ☐ No
- ☐ Yes
- ☐ Other (specify) ________________________

5.6 Are there any rugs?

- ☐ No
- ☐ Yes
- ☐ Other (specify) ________________________

5.7 Are there any cushions?

- ☐ No
- ☐ Yes
- ☐ Other (specify) ________________________

5.8 Closet or shelves with gouaches, inks, etc. for graphic arts

- ☐ No
- ☐ Yes
- ☐ Other (specify) ________________________

5.9 Animals/Pets

- ☐ No
- ☐ Yes, stuffed
- ☐ Yes, living
- ☐ Fish/Turtle (aquariums)
- ☐ Birds
- ☐ Rodents
- ☐ Other (specify) ________________________

5.10 Number of potted plants in the room:______________

A.4 Observation form

Teacher's observation form

1) Time of the lesson: from ____:____ to ____:____
2) Number of students in the classroom: ______
3) There are ____ windows in this classroom, and ____ among them can be opened.
4) There are ____ doors in this classroom.
5) Before the course, ____ window(s) is/are open , ___ door(s) is/are open.
6) During the course, ___ window(s) is/are open, ___ door(s) is/are open.
7) Is there any mechanical ventilation operating in this classroom?

☐ Yes
☐ No
☐ I don't know

8) Did you or the students open or close any window during the course? If so, please fill in the following table:

When	Who	What	How many	
At ____:____	□ I □ student	□ opened □ closed	____ window(s)	____ door(s)
At ____:____	□ I □ student	□ opened □ closed	____ window(s)	____ door(s)
At ____:____	□ I □ student	□ opened □ closed	____ window(s)	____ door(s)

Researcher's observation form

1) Time of the lesson: from ____:____ to ____:____
2) Number of students in the classroom: ______
3) There are ___ windows and ___ doors, and ____ windows and ____ doors can be opened.
4) Before the course, ___ window(s) and ___ door(s) is/are opened.
5) During the course, ___ window(s) and ___ door(s) is/are opened.
6) Did the teacher or the students open or close any windows/doors during the lesson? If so, please answer the following questions:

- At ____:____, the teacher/students open/close ___ window(s)/ ___ door(s).
- At ____:____, the teacher/students open/close ___ window(s)/ ___ door(s).
- At ____:____, the teacher/students open/close ___ window(s)/ ___ door(s).

APPENDIX B

Supplementary materials for Chapter 4

B.1 Questionnaires for panel perception test

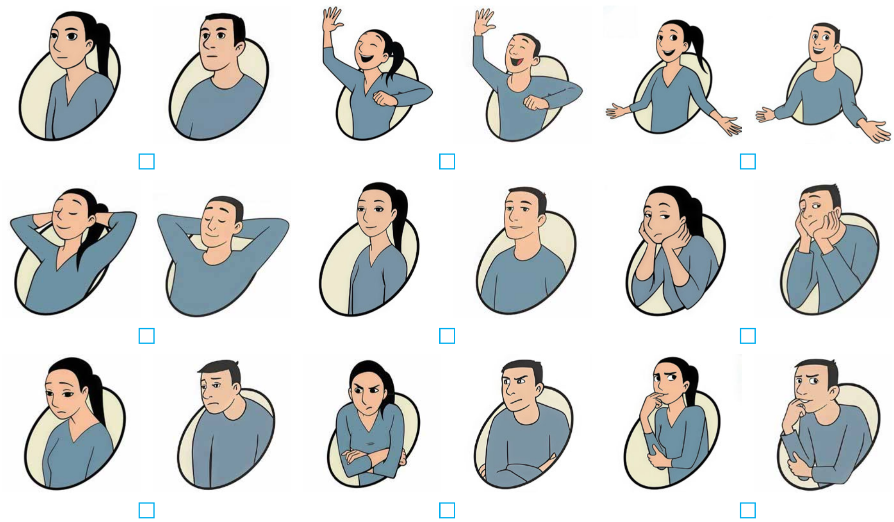
General Information

1. Age ____________ years

2. Gender

☐ male ☐ female

3. Which of the 9 images best suits how you feel at this moment?



4. Please briefly describe the type of clothing you are wearing at this moment.

Top:

Bottom:

Shoes:

Questionnaire of Sound and Air Movement Perception

Part 1. Assessment of sound

1.1 Can you hear any sound at the location where you are sitting?

☐ Yes	☐ No

(If the answer is **Yes**, please continue with question 1.2 and 1.3; If the answer is **No**, you can skip question 1.2 and 1.3)

1.2 How loud is the sound that you hear?

Quiet	☐	☐	☐	☐	Loud

1.3 What is your assessment of the sound that your hear?

☐	☐	☐	☐	☐

Part 2. Assessment of air movement

2.1 Can you feel any air movement at the location where you are sitting?

☐ Yes	☐ No

(If the answer is **Yes**, please continue with question 2.2-2.4; If the answer is **No**, you can skip question 2.2-2.4)

2.2 At which part(s) of your body do you feel the air movement? Please mark the body part(s) with “x”

2.3 How strong is the air movement that you feel?

Mild	☐	☐	☐	☐	Strong

2.4 What is your assessment of the air movement that you feel?

☐	☐	☐	☐	☐

B.2 Results of the aerosol decay test in the lab experiment

TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC1	S1	C1	A	2.229	2.202, 2.257	0.988
			B	2.252	2.218, 2.286	0.982
			C	2.237	2.209, 2.265	0.988
			D	2.205	2.181, 2.228	0.991
			E	2.170	2.151, 2.189	0.994
			F	2.200	2.182, 2.218	0.994
		C2	A	2.830	2.811, 2.849	0.998
			B	2.825	2.800, 2.849	0.996
			C	2.853	2.825, 2.880	0.995
			D	2.935	2.920, 2.950	0.999
			E	2.869	2.851, 2.887	0.998
			F	2.862	2.843, 2.881	0.998
	S2	C1	A	5.052	5.004, 5.099	0.996
			B	5.193	5.151, 5.234	0.997
			C	5.026	4.984, 5.069	0.997
			D	5.050	5.008, 5.091	0.997
			E	4.965	4.919, 5.010	0.996
			F	5.077	5.035, 5.118	0.997
		C2	A	5.217	5.187, 5.247	0.999
			B	5.387	5.358, 5.416	0.999
			C	5.205	5.173, 5.237	0.999
			D	5.212	5.187, 5.237	0.999
			E	5.155	5.129, 5.181	0.999
			F	5.227	5.204, 5.251	0.999

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TOC

TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC2	S1	C1	A	8.656	8.462, 8.851	0.989
			B	8.849	8.710, 8.988	0.995
			C	8.705	8.538, 8.873	0.992
			D	8.473	8.316, 8.631	0.993
			E	8.527	8.320, 8.733	0.987
			F	8.896	8.704, 9.087	0.990
		C2	A	5.280	5.140, 5.420	0.973
			B	4.538	4.488, 4.588	0.995
			C	4.372	4.335, 4.410	0.997
			D	4.480	4.443, 4.518	0.997
			E	4.605	4.553, 4.658	0.995
			F	4.499	4.453, 4.544	0.996
	S2	C1	A	13.213	13.012, 13.415	0.996
			B	14.672	14.426, 14.918	0.996
			C	13.312	13.112, 13.513	0.996
			D	12.886	12.675, 13.096	0.996
			E	14.281	13.946, 14.616	0.991
			F	13.008	12.801, 13.214	0.996
		C2	A	7.737	7.616, 7.857	0.994
			B	7.773	7.667, 7.879	0.995
			C	7.420	7.308, 7.533	0.994
			D	7.632	7.534, 7.730	0.996
			E	7.798	7.662, 7.934	0.992
			F	7.820	7.726, 7.915	0.996
MAC3	S1	C1	A	6.312	6.246, 6.378	0.997
			B	6.526	6.458, 6.593	0.997
			C	7.043	6.914, 7.173	0.990
			D	8.149	7.934, 8.364	0.980
			E	6.839	6.690, 6.989	0.985
			F	7.713	7.557, 7.869	0.988
	S2	C1	A	15.107	14.949, 15.265	0.999
			B	15.816	15.558, 16.075	0.997
			C	16.149	15.789, 16.508	0.994
			D	15.926	15.582, 16.271	0.994
			E	15.478	15.232, 15.724	0.997
			F	15.816	15.610, 16.021	0.998

>>>

TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC4	S1	C1	A	5.461	5.388, 5.534	0.994
			B	5.773	5.726, 5.821	0.998
			C	6.108	6.042, 6.174	0.996
			D	5.863	5.801, 5.925	0.996
			E	5.977	5.899, 6.054	0.995
			F	6.426	6.377, 6.475	0.998
		C2	A	5.960	5.902, 6.018	0.997
			B	6.375	6.311, 6.439	0.997
			C	5.930	5.855, 6.005	0.995
			D	5.876	5.780, 5.973	0.991
			E	6.057	6.006, 6.109	0.998
			F	6.518	6.430, 6.606	0.994
	S2	C1	A	13.908	13.703, 14.113	0.996
			B	14.725	14.491, 14.958	0.996
			C	14.468	14.216, 14.719	0.995
			D	14.666	14.413, 14.920	0.995
			E	14.095	13.880, 14.309	0.996
			F	13.648	13.492, 13.804	0.998
		C2	A	14.119	13.741, 14.496	0.990
			B	14.866	14.615, 15.118	0.996
			C	13.777	13.473, 14.080	0.993
			D	14.181	14.002, 14.360	0.998
			E	14.765	14.523, 15.007	0.996
			F	14.444	14.101, 14.787	0.992
		C3	A	7.296	7.225, 7.367	0.997
			B	6.811	6.730, 6.892	0.996
			C	6.866	6.818, 6.915	0.999
			D	7.221	7.162, 7.281	0.998
			E	7.402	7.308, 7.496	0.995
			F	6.757	6.803, 6.811	0.998

>>>

TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC5	S1	C1	A	6.461	6.390, 6.532	0.997
			B	6.063	5.967, 6.160	0.993
			C	6.071	5.979, 6.164	0.993
			D	6.710	6.575, 6.844	0.989
			E	6.418	6.353, 6.483	0.997
			F	6.043	5.974, 6.112	0.996
		C2	A	6.870	6.794, 6.945	0.996
			B	6.956	6.845, 7.068	0.993
			C	6.764	6.667, 6.862	0.994
			D	7.304	7.198, 7.410	0.994
			E	7.841	7.737, 7.945	0.995
			F	9.167	8.982, 9.352	0.990
	S2	C1	A	10.984	10.836, 11.132	0.997
			B	10.836	10.726, 10.947	0.998
			C	10.462	10.317, 10.608	0.996
			D	11.182	11.010, 11.354	0.996
			E	10.630	10.472, 10.789	0.996
			F	10.760	10.603, 10.917	0.996
		C2	A	12.297	12.130, 12.464	0.997
			B	12.467	12.234, 12.701	0.995
			C	11.737	11.358, 12.116	0.984
			D	14.784	14.481, 15.088	0.994
			E	13.993	13.819, 14.167	0.998
			F	13.862	13.720, 14.005	0.998

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TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC6	S1	C1	A	7.363	7.254, 7.471	0.994
			B	7.251	7.176, 7.326	0.997
			C	7.441	7.334, 7.548	0.994
			D	7.263	7.170, 7.355	0.995
			E	7.573	7.480, 7.665	0.996
			F	7.331	7.252, 7.409	0.997
		C2	A	5.961	5.864, 6.059	0.990
			B	5.830	5.764, 5.896	0.995
			C	5.645	5.576, 5.715	0.994
			D	6.097	6.015, 6.179	0.993
			E	6.027	5.952, 6.101	0.994
			F	5.789	5.731, 5.848	0.996
	S2	C1	A	14.212	14.014, 14.410	0.996
			B	15.286	15.039, 15.533	0.995
			C	14.350	14.101, 14.598	0.994
			D	13.837	13.654, 14.020	0.997
			E	15.250	14.989, 15.512	0.994
			F	14.330	14.129, 14.532	0.996
		C2	A	13.064	12.904, 13.225	0.998
			B	13.673	13.476, 13.870	0.997
			C	13.283	13.100, 13.467	0.997
			D	13.502	13.340, 13.664	0.998
			E	13.383	13.224, 13.541	0.998
			F	13.313	13.121, 13.504	0.997
		C3	A	7.973	7.862, 8.085	0.995
			B	8.290	8.182, 8.397	0.996
			C	8.022	7.909, 8.135	0.995
			D	8.315	8.182, 8.450	0.993
			E	8.373	8.239, 8.506	0.994
			F	8.332	8.214, 8.450	0.995

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TABLE B.2.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC7	S1	C1	A	9.525	9.428, 9.622	0.998
			B	9.752	9.664, 9.840	0.998
			C	9.334	9.205, 9.462	0.996
			D	9.514	9.423, 9.606	0.998
			E	9.650	9.552, 9.749	0.998
			F	9.387	9.293, 9.481	0.998
		C2	A	11.076	10.936, 11.216	0.997
			B	11.510	11.360, 11.660	0.997
			C	10.835	10.692, 10.979	0.996
			D	10.986	10.845, 11.127	0.997
			E	11.428	11.328, 11.527	0.999
			F	11.653	11.491, 11.814	0.996
	S2	C1	A	19.226	18.912, 19.541	0.996
			B	20.256	19.929, 20.583	0.996
			C	19.209	18.817, 19.600	0.993
			D	19.450	19.163, 19.736	0.996
			E	21.203	20.850, 21.557	0.996
			F	18.864	18.548, 19.181	0.995
		C2	A	19.159	18.895, 19.422	0.997
			B	20.826	20.546, 21.106	0.997
			C	18.475	18.070, 18.881	0.992
			D	19.005	18.753, 19.258	0.997
			E	19.484	19.103, 19.864	0.994
			F	18.755	18.525, 18.986	0.998
		C3	A	11.821	11.677, 11.965	0.997
			B	10.582	10.341, 10.823	0.990
			C	10.847	10.744, 10.951	0.998
			D	11.781	11.655, 11.906	0.998
			E	11.083	10.900, 11.266	0.995
			F	11.385	11.272, 11.498	0.998

a MAC: mobile air cleaner.
b S: setting.
c C: configuration.
d 95% confidence interval.

TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC1	S1	C1	A	2.135	2.101, 2.169	0.979
			B	2.290	2.258, 2.322	0.984
			C	2.262	2.234, 2.289	0.988
			D	2.229	2.205, 2.254	0.990
			E	2.190	2.169, 2.211	0.993
			F	2.236	2.216, 2.255	0.994
		C2	A	2.742	2.720, 2.765	0.996
			B	2.941	2.916, 2.966	0.996
			C	2.943	2.917, 2.969	0.996
			D	3.007	2.989, 3.026	0.998
			E	2.952	2.922, 2.982	0.995
			F	2.947	2.928, 2.966	0.998
	S2	C1	A	5.052	4.598, 4.777	0.983
			B	5.257	5.214, 5.300	0.997
			C	5.100	5.054, 5.147	0.997
			D	5.066	5.012, 5.121	0.997
			E	4.977	4.924, 5.031	0.995
			F	5.143	5.094, 5.193	0.996
		C2	A	4.884	4.819, 4.949	0.993
			B	5.370	5.342, 5.397	0.999
			C	5.282	5.250, 5.314	0.999
			D	5.225	5.193, 5.258	0.999
			E	5.142	5.113, 5.171	0.999
			F	5.296	5.266, 5.326	0.999

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TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC2	S1	C1	A	7.454	7.183, 7.725	0.968
			B	9.698	9.527, 9.868	0.994
			C	9.242	9.065, 9.418	0.993
			D	8.617	8.429, 8.806	0.990
			E	8.889	8.643, 9.136	0.984
			F	9.051	8.829, 9.273	0.998
		C2	A	5.183	5.006, 5.359	0.953
			B	4.809	4.747, 4.871	0.993
			C	4.617	4.572, 4.662	0.996
			D	4.682	4.634, 4.730	0.996
			E	4.908	4.840, 4.977	0.992
			F	4.691	4.640, 4.742	0.995
	S2	C1	A	12.114	11.721, 12.506	0.981
			B	15.379	15.124, 15.634	0.996
			C	13.827	13.597, 14.057	0.996
			D	13.144	12.879, 13.409	0.993
			E	14.341	14.000, 14.682	0.991
			F	13.289	13.041, 13.537	0.994
		C2	A	7.470	7.272, 7.668	0.980
			B	8.333	8.212, 8.454	0.995
			C	7.947	7.820, 8.074	0.993
			D	7.944	7.826, 8.063	0.994
			E	8.353	8.192, 8.515	0.990
			F	8.060	7.954, 8.165	0.996
MAC3	S1	C1	A	6.604	6.460, 6.748	0.985
			B	7.150	7.054, 7.247	0.995
			C	7.847	7.669, 8.024	0.985
			D	9.087	8.799, 9.376	0.972
			E	7.260	7.060, 7.459	0.977
			F	8.568	8.354, 8.781	0.983
	S2	C1	A	15.091	14.641, 15.541	0.988
			B	17.028	16.651, 17.405	0.994
			C	17.876	17.239, 18.423	0.989
			D	16.843	16.319, 17.367	0.988
			E	16.153	15.800, 16.505	0.994
			F	17.044	16.657, 17.431	0.994

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TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC4	S1	C1	A	4.870	4.793, 4.948	0.991
			B	5.810	5.759, 5.862	0.997
			C	6.164	6.093, 6.236	0.996
			D	5.793	5.727, 5.859	0.996
			E	5.846	5.763, 5.929	0.993
			F	6.439	6.380, 6.498	0.997
		C2	A	5.942	5.884, 6.000	0.997
			B	6.568	6.491, 6.644	0.996
			C	5.360	5.265, 5.454	0.989
			D	5.840	5.747, 5.933	0.992
			E	6.002	5.943, 6.061	0.998
			F	6.733	6.631, 6.836	0.993
	S2	C1	A	11.739	11.366, 12.111	0.981
			B	15.105	14.819, 15.391	0.994
			C	14.634	14.376, 14.891	0.995
			D	14.301	13.982, 14.619	0.992
			E	13.773	13.534, 14.012	0.995
			F	13.514	13.335, 13.693	0.997
		C2	A	14.077	13.729, 14.425	0.992
			B	15.036	14.758, 15.314	0.995
			C	12.312	11.090, 12.716	0.983
			D	14.281	14.041, 14.520	0.996
			E	14.474	14.209, 14.739	0.995
			F	14.727	14.332, 15.123	0.990
		C3	A	7.200	7.125, 7.276	0.997
			B	6.903	6.818, 6.987	0.996
			C	6.258	6.169, 6.348	0.993
			D	7.103	7.032, 7.174	0.997
			E	7.337	7.224, 7.451	0.993
			F	6.893	6.837, 6.948	0.998

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TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC5	S1	C1	A	6.476	6.393, 6.558	0.995
			B	6.053	5.955, 6.150	0.992
			C	5.457	5.355, 5.559	0.989
			D	6.481	6.323, 6.639	0.983
			E	6.270	6.182, 6.359	0.994
			F	6.078	6.021, 6.136	0.997
		C2	A	6.971	6.875, 7.067	0.994
			B	7.412	7.295, 7.529	0.993
			C	7.077	6.948, 7.205	0.991
			D	7.602	7.479, 7.725	0.993
			E	8.318	8.190, 8.446	0.994
			F	9.820	9.615, 10.025	0.989
	S2	C1	A	11.184	10.998, 11.369	0.995
			B	11.193	11.055, 11.331	0.997
			C	9.062	8.806, 9.317	0.983
			D	11.165	10.932, 11.399	0.992
			E	10.713	10.502, 10.924	0.993
			F	11.324	11.124, 11.523	0.994
		C2	A	13.038	12.790, 13.287	0.994
			B	13.873	13.616, 14.129	0.995
			C	12.985	12.510, 13.460	0.981
			D	16.490	16.094, 16.885	0.992
			E	15.279	15.052, 15.507	0.997
			F	15.010	14.838, 15.181	0.998

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TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC6	S1	C1	A	7.269	7.112, 7.427	0.986
			B	7.881	7.800, 7.962	0.997
			C	7.849	7.742, 7.956	0.995
			D	7.562	7.459, 7.665	0.995
			E	7.742	7.642, 7.842	0.995
			F	7.703	7.621, 7.784	0.997
		C2	A	6.053	5.915, 6.190	0.980
			B	6.347	6.268, 6.426	0.994
			C	5.846	5.781, 5.911	0.995
			D	6.276	6.183, 6.369	0.992
			E	6.243	6.161, 6.325	0.994
			F	5.908	5.850, 5.967	0.996
	S2	C1	A	14.225	13.853, 14.598	0.986
			B	16.565	16.278, 16.852	0.994
			C	15.471	15.237, 15.706	0.996
			D	14.669	14.454, 14.884	0.996
			E	16.214	15.899, 16.529	0.993
			F	15.526	15.247, 15.806	0.994
		C2	A	13.242	12.960, 13.525	0.992
			B	14.646	14.462, 14.829	0.998
			C	13.581	13.436, 13.726	0.998
			D	13.639	13.469, 13.810	0.998
			E	14.185	13.987, 14.383	0.997
			F	13.578	13.413, 13.742	0.998
		C3	A	7.819	7.628, 8.010	0.984
			B	9.220	9.077, 9.363	0.994
			C	8.526	8.407, 8.646	0.995
			D	8.556	8.419, 8.692	0.994
			E	8.665	8.516, 8.813	0.993
			F	8.656	8.529, 8.782	0.995

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TABLE B.2.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC7	S1	C1	A	8.206	8.127, 8.286	0.998
			B	8.539	8.452, 8.625	0.998
			C	8.558	8.488, 8.629	0.998
			D	8.674	8.631, 8.717	0.999
			E	8.422	8.358, 8.486	0.999
			F	8.646	8.594, 8.699	0.999
		C2	A	10.159	10.029, 10.289	0.997
			B	10.660	10.567, 10.753	0.998
			C	10.553	10.485, 10.622	0.999
			D	10.642	10.559, 10.725	0.999
			E	10.361	10.223, 10.500	0.996
			F	11.173	11.063, 11.282	0.998
	S2	C1	A	17.420	17.223, 17.618	0.996
			B	17.716	17.440, 17.992	0.996
			C	18.171	18.003, 18.340	0.998
			D	18.380	18.202, 18.559	0.996
			E	18.175	17.985, 18.364	0.996
			F	18.077	17.895, 18.259	0.998
		C2	A	19.392	19.165, 19.619	0.998
			B	19.823	19.611, 20.034	0.998
			C	19.128	18.902, 19.354	0.998
			D	18.931	18.749, 19.113	0.999
			E	18.436	18.051, 18.821	0.993
			F	18.641	18.465, 18.817	0.999
		C3	A	10.187	10.082, 10.292	0.998
			B	10.151	9.798, 10.272	0.989
			C	10.151	10.033, 10.270	0.997
			D	10.766	10.683, 10.849	0.999
			E	9.849	9.665, 10.033	0.993
			F	10.621	10.561, 10.680	0.999

a MAC: mobile air cleaner.
b S: setting.
c C: configuration.
d 95% confidence interval.

TABLE B.2.3 Natural decay coefficient $k_{PM,n}$ of $PM_{2.5}$.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-05-25 11:11-14:35	A	1.482	1.459, 1.505	0.970	22.8 (0.3)	43.5 (0.5)
	B	1.528	1.507, 1.549	0.977	22.8 (0.3)	42.4 (0.5)
	C	1.597	1.573, 1.622	0.971	22.7 (0.3)	43.1 (0.5)
	D	1.647	1.621, 1.672	0.972	23.0 (0.3)	41.7 (0.4)
	E	1.387	1.369, 1.406	0.978	22.8 (0.3)	42.6 (0.4)
	F	1.533	1.517, 1.548	0.988	23.0 (0.3)	42.5 (0.5)
2023-05-25 14:55-17:32	A	1.480	1.458, 1.501	0.979	23.3 (0.1)	40.5 (0.3)
	B	1.580	1.563, 1.596	0.990	23.2 (0.1)	39.5 (0.3)
	C	1.580	1.567, 1.593	0.993	23.1 (0.1)	40.1 (0.3)
	D	1.544	1.531, 1.558	0.993	23.3 (0.1)	39.0 (0.3)
	E	1.529	1.515, 1.543	0.992	23.2 (0.1)	39.7 (0.3)
	F	1.527	1.517, 1.536	0.996	23.3 (0.1)	39.5 (0.3)
2023-05-25 18:10-22:00	A	0.803	0.796, 0.811	0.984	22.8 (0.1)	39.6 (0.2)
	B	0.788	0.779, 0.797	0.979	22.8 (0.1)	38.7 (0.2)
	C	0.805	0.797, 0.813	0.983	22.7 (0.1)	39.2 (0.2)
	D	0.813	0.804, 0.822	0.980	22.7 (0.2)	38.6 (0.2)
	E	0.794	0.786, 0.802	0.982	22.8 (0.1)	38.9 (0.2)
	F	0.819	0.810, 0.827	0.982	22.7 (0.2)	39.0 (0.3)
2023-05-26 10:20-12:55	A	1.372	1.356, 1.389	0.995	23.3 (0.2)	35.4 (0.3)
	B	1.498	1.485, 1.511	0.993	23.3 (0.2)	34.5 (0.3)
	C	1.489	1.475, 1.504	0.990	23.2 (0.2)	34.9 (0.3)
	D	1.528	1.515, 1.542	0.992	23.5 (0.1)	34.0 (0.3)
	E	1.433	1.422, 1.443	0.995	23.3 (0.2)	34.7 (0.3)
	F	1.367	1.355, 1.379	0.993	23.4 (0.1)	34.4 (0.2)
2023-05-26 14:12-16:30	A	1.131	1.118, 1.143	0.987	23.1 (0.1)	33.9 (0.2)
	B	1.151	1.136, 1.166	0.981	23.1 (0.1)	33.1 (0.2)
	C	1.154	1.139, 1.169	0.981	23.0 (0.2)	33.4 (0.2)
	D	1.151	1.136, 1.166	0.981	23.0 (0.1)	33.0 (0.1)
	E	1.119	1.106, 1.132	0.984	23.1 (0.1)	33.4 (0.2)
	F	1.209	1.195, 1.224	0.995	23.1 (0.1)	33.2 (0.2)
2023-05-26 17:15-20:00	A	1.039	1.024, 1.054	0.975	23.1 (0.1)	33.9 (0.4)
	B	1.044	1.030, 1.059	0.977	23.0 (0.1)	33.1 (0.4)
	C	1.051	1.037, 1.065	0.978	22.9 (0.1)	33.5 (0.4)
	D	1.071	1.057, 1.085	0.980	22.9 (0.1)	33.1 (0.4)
	E	1.037	1.023, 1.051	0.977	23.0 (0.1)	33.4 (0.4)
	F	1.029	1.015, 1.044	0.975	23.0 (0.1)	33.3 (0.4)

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TABLE B.2.3 Natural decay coefficient $k_{PM,n}$ of $PM_{2.5}$.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-07-07 10:28-13:30	A	1.643	1.625, 1.661	0.987	23.6 (0.3)	47.8 (1.2)
	B	1.560	1.549, 1.571	0.995	22.3 (0.4)	51.6 (2.6)
	C	1.629	1.617, 1.641	0.994	23.5 (0.3)	47.0 (1.1)
	D	1.500	1.491, 1.510	0.995	23.6 (0.2)	45.8 (1.0)
	E	1.653	1.640, 1.665	0.994	23.6 (0.3)	46.5 (1.2)
	F	1.587	1.577, 1.597	0.996	23.7 (0.3)	46.8 (1.2)

a 95% confidence interval.
d mean (SD).

TABLE B.2.4 Natural decay coefficient $k_{PM,n}$ of PM_{10}.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-05-25 11:11-14:35	A	1.419	1.389, 1.448	0.945	22.8 (0.3)	43.5 (0.5)
	B	1.630	1.604, 1.656	0.970	22.8 (0.3)	42.4 (0.5)
	C	1.706	1.676, 1.736	0.964	22.7 (0.3)	43.1 (0.5)
	D	1.720	1.686, 1.753	0.957	23.0 (0.3)	41.7 (0.4)
	E	1.390	1.368, 1.412	0.969	22.8 (0.3)	42.6 (0.4)
	F	1.579	1.560, 1.599	0.982	23.0 (0.3)	42.5 (0.5)
2023-05-25 14:55-17:32	A	1.399	1.373, 1.425	0.965	23.3 (0.1)	40.5 (0.3)
	B	1.601	1.581, 1.621	0.985	23.2 (0.1)	39.5 (0.3)
	C	1.609	1.591, 1.627	0.988	23.1 (0.1)	40.1 (0.3)
	D	1.546	1.529, 1.564	0.987	23.3 (0.1)	39.0 (0.3)
	E	1.496	1.479, 1.512	0.987	23.2 (0.1)	39.7 (0.3)
	F	1.542	1.529, 1.555	0.993	23.3 (0.1)	39.5 (0.3)
2023-05-25 18:10-22:00	A	0.761	0.754, 0.768	0.985	22.8 (0.1)	39.6 (0.2)
	B	0.782	0.772, 0.791	0.975	22.8 (0.1)	38.7 (0.2)
	C	0.791	0.782, 0.800	0.978	22.7 (0.1)	39.2 (0.2)
	D	0.793	0.784, 0.803	0.976	22.7 (0.2)	38.6 (0.2)
	E	0.771	0.762, 0.781	0.975	22.8 (0.1)	38.9 (0.2)
	F	0.799	0.790, 0.808	0.979	22.7 (0.2)	39.0 (0.3)
2023-05-26 10:20-12:55	A	1.261	1.246, 1.276	0.985	23.3 (0.2)	35.4 (0.3)
	B	1.471	1.458, 1.484	0.993	23.3 (0.2)	34.5 (0.3)
	C	1.463	1.449, 1.477	0.991	23.2 (0.2)	34.9 (0.3)
	D	1.487	1.472, 1.502	0.990	23.5 (0.1)	34.0 (0.3)
	E	1.377	1.364, 1.390	0.991	23.3 (0.2)	34.7 (0.3)
	F	1.352	1.339, 1.365	0.991	23.4 (0.1)	34.4 (0.2)
2023-05-26 14:12-16:30	A	1.053	1.041, 1.065	0.985	23.1 (0.1)	33.9 (0.2)
	B	1.137	1.123, 1.150	0.984	23.1 (0.1)	33.1 (0.2)
	C	1.134	1.120, 1.148	0.983	23.0 (0.2)	33.4 (0.2)
	D	1.114	1.100, 1.128	0.982	23.0 (0.1)	33.0 (0.1)
	E	1.077	1.063, 1.090	0.982	23.1 (0.1)	33.4 (0.2)
	F	1.186	1.172, 1.201	0.984	23.1 (0.1)	33.2 (0.2)
2023-05-26 17:15-20:00	A	1.022	1.009, 1.036	0.979	23.1 (0.1)	33.9 (0.4)
	B	1.040	1.024, 1.055	0.972	23.0 (0.1)	33.1 (0.4)
	C	1.052	1.037, 1.067	0.975	22.9 (0.1)	33.5 (0.4)
	D	1.072	1.058, 1.086	0.979	22.9 (0.1)	33.1 (0.4)
	E	1.029	1.014, 1.045	0.973	23.0 (0.1)	33.4 (0.4)
	F	1.023	1.008, 1.038	0.974	23.0 (0.1)	33.3 (0.4)

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TABLE B.2.4 Natural decay coefficient $k_{PM,n}$ of PM_{10}.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-07-07 10:28-13:30	A	1.504	1.497, 1.512	0.997	23.6 (0.3)	47.8 (1.2)
	B	1.541	1.532, 1.549	0.996	22.3 (0.4)	51.6 (2.6)
	C	1.596	1.591, 1.602	0.999	23.5 (0.3)	47.0 (1.1)
	D	1.468	1.460, 1.477	0.996	23.6 (0.2)	45.8 (1.0)
	E	1.572	1.562, 1.582	0.996	23.6 (0.3)	46.5 (1.2)
	F	1.541	1.530, 1.553	0.994	23.7 (0.3)	46.8 (1.2)

a *95% confidence interval.*
d *mean (SD).*

TABLE B.2.5 Aerosol removal rate of the mobile air cleaner $k_{PM,mac}$ based on the mean value of $k_{PM,total}$ and $k_{PM,n}$.

Device[a]	Setting[b]	Configuration[c]	$k_{PM,mac}$ of $PM_{2.5}$ [h^{-1}]	$k_{PM,mac}$ of PM_{10} [h^{-1}]
MAC1	S1	C1	0.911	0.873
		C2	1.557	1.568
	S2	C1	3.758	3.693
		C2	3.933	3.850
MAC2	S1	C1	7.379	7.462
		C2	3.291	3.442
	S2	C1	12.361	12.423
		C2	6.391	6.645
MAC3	S1	C1	5.664	6.255
	S2	C1	14.379	15.250
MAC4	S1	C1	4.612	4.430
		C2	4.807	4.694
	S2	C1	12.959	12.489
		C2	13.079	12.776
		C3	5.740	5.567
MAC5	S1	C1	4.960	4.732
		C2	6.062	6.337
	S2	C1	9.493	9.399
		C2	11.758	12.897
MAC6	S1	C1	6.074	6.318
		C2	4.589	4.745
	S2	C1	13.286	14.068
		C2	12.068	12.443
		C3	6.913	7.202
MAC7	S1	C1	8.254	7.144
		C2	9.976	9.204
	S2	C1	18.774	16.609
		C2	18.161	17.714
		C3	9.870	8.876

a *MAC: mobile air cleaner.*
b *S: setting.*
c *C: configuration.*

B.3 Results of the perception of air movement caused by the mobile air cleaners

TABLE B.3.1 Body parts of the subjects for air movement perception.

Device[a]	Setting[b]	Configuration[c]	Body parts sensed air movement[d,e]
MAC1	S1	C2	face (1), neck (1)
	S2	C2	face (1), neck (2)
	S3	C2	face (2), neck (1), hands (1)
MAC2	S1	C1	face (2), hand (1), arms (1)
	S2	C1	face (3), neck (1), hands (2)
MAC3	S1	C1	-
	S2	C1	face (2), chest (1)
	S3	C1	face (1), hands (1)
MAC4	S1	C2	-
	S2	C2	face (2), chest (1), arms (1), hands (2)
MAC5	S1	C1	face (1)
	S2	C1	face (2), head (1), arms (1), hands (3), thighs (1)
	S3	C1	face (1), head (1), hands (3)
	S1	C2	arms (1)
	S2	C2	arms (1)
	S3	C2	legs (1)
MAC6	S1	C1	face (1), neck (1), shoulders (1)
	S2	C1	face (2), neck (1), shoulders (1), hands (1)
	S3	C1	face (2), neck (1), shoulders (1), arms (1), hands (1), legs (1)
	S1	C2	-
	S2	C2	face (3), head (1), neck (1), hands (2), thighs (1), ankles (1)
	S3	C2	face (2), head (1), back (1), hands (1)

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TABLE B.3.1 Body parts of the subjects for air movement perception.

Device[a]	Setting[b]	Configuration[c]	Body parts sensed air movement[d,e]
MAC7	S1	C1	face (2), head (1), neck (1), chest (1), arms (1), legs (1)
	S2	C1	face (2), neck (1), shoulders (1), arms (1), legs (2)
	S3	C1	face (3), arms (1), legs (1)
	S1	C2	face (1), head (1), arms (3), hands (1), legs (1)
	S2	C2	face (2), head (1), neck (1), arms (3), hands (1), legs (1)
	S3	C2	face (2), head (1), neck (2), arms (2), hands (1), legs (1)

a *MAC: mobile air cleaner.*

b *S: setting.*

c *C: configuration.*

d *Numbers in the parentheses show the number of subjects reported.*

e *-: none of the subjects has sensed the sound or air movement caused by the mobile air cleaners.*

B.4 Results of the aerosol decay test in the real classroom

TABLE B.4.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC1	S2	C2	A	4.623	4.549, 4.696	0.990
			B	4.537	4.483, 4.591	0.994
			C	4.520	4.462, 4.578	0.993
			D	4.563	4.505, 4.621	0.993
			E	4.920	4.877, 4.963	0.997
			F	4.536	4.474, 4.598	0.992
MAC2	S2	C1	A	11.382	11.276, 11.489	0.999
			B	11.756	11.648, 11.864	0.999
			C	11.122	10.980, 11.264	0.997
			D	11.763	11.650, 11.876	0.998
			E	11.494	11.321, 11.668	0.996
			F	11.458	11.323, 11.593	0.998
MAC3	S2	C1	A	13.055	12.920, 13.190	0.998
			B	12.472	12.360, 12.585	0.999
			C	12.312	12.149, 12.475	0.997
			D	12.482	12.375, 12.589	0.999
			E	11.280	10.954, 11.606	0.987
			F	13.205	13.051, 13.359	0.998
MAC4	S1	C1	A	10.132	9.992, 10.273	0.997
			B	10.350	10.218, 10.483	0.997
			C	9.873	9.735, 10.011	0.996
			D	10.178	10.035, 10.322	0.996
			E	10.096	9.884, 10.309	0.992
			F	10.434	10.275, 10.593	0.996
MAC5	S2	C2	A	9.422	9.283, 9.561	0.996
			B	8.658	8.571, 8.745	0.998
			C	8.317	8.180, 8.453	0.994
			D	9.403	9.199, 9.606	0.990
			E	10.603	10.401, 10.804	0.993
			F	8.955	8.833, 9.077	0.996

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TABLE B.4.1 Total decay coefficient $k_{PM,total}$ of $PM_{2.5}$.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC6	S2	C1	A	11.060	10.920, 11.200	0.997
			B	9.859	9.583, 10.134	0.987
			C	10.860	10.713, 11.007	0.997
			D	10.823	10.652, 10.994	0.996
			E	9.551	9.213, 9.889	0.978
			F	10.891	10.742, 11.041	0.997
MAC7	S1	C2	A	8.870	8.796, 8.943	0.999
			B	8.889	8.809, 8.969	0.988
			C	8.757	8.673, 8.842	0.998
			D	8.376	8.265, 8.486	0.996
			E	8.658	8.526, 8.790	0.995
			F	8.319	8.126, 8.511	0.989

a *MAC: mobile air cleaner.*
b *S: setting.*
c *C: configuration.*
d *95% confidence interval.*

TABLE B.4.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC1	S2	C2	A	5.761	5.700, 5.822	0.996
			B	5.562	5.512, 5.611	0.997
			C	5.180	5.144, 5.215	0.998
			D	5.249	5.209, 5.288	0.998
			E	5.608	5.571, 5.645	0.998
			F	5.379	5.341, 5.417	0.998
MAC2	S2	C1	A	12.471	12.342, 12.601	0.998
			B	12.943	12.808, 13.077	0.998
			C	11.765	11.647, 11.883	0.998
			D	11.966	11.843, 12.089	0.998
			E	11.893	11.661, 12.126	0.994
			F	11.797	11.693, 11.901	0.999
MAC3	S2	C1	A	13.891	13.775, 14.008	0.999
			B	13.206	13.045, 13.368	0.998
			C	12.522	12.384, 12.659	0.998
			D	12.543	12.417, 12.670	0.999
			E	11.334	10.953, 11.715	0.982
			F	13.142	13.028, 13.255	0.999
MAC4	S1	C1	A	11.803	11.664, 11.942	0.998
			B	11.957	11.838, 12.077	0.998
			C	11.107	11.000, 11.215	0.998
			D	11.293	11.157, 11.429	0.998
			E	10.878	10.640, 11.116	0.992
			F	11.365	11.232, 11.498	0.998
MAC5	S2	C2	A	10.722	10.548, 10.896	0.995
			B	10.262	10.102, 10.421	0.995
			C	9.958	9.800, 10.117	0.995
			D	11.008	10.747, 11.269	0.990
			E	12.388	12.112, 12.664	0.991
			F	10.300	10.074, 10.526	0.991
MAC6	S2	C1	A	12.657	12.478, 12.835	0.997
			B	11.186	10.794, 11.578	0.981
			C	12.439	12.210, 12.667	0.995
			D	12.282	11.939, 12.431	0.994
			E	10.325	9.919, 10.732	0.975
			F	12.739	12.465, 13.013	0.993

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TABLE B.4.2 Total decay coefficient $k_{PM,total}$ of PM_{10}.

Device[a]	Setting[b]	Configuration[c]	Location	$k_{PM,total}$ [h^{-1}]	95% CI (lower, upper)[d]	R^2
MAC7	S1	C2	A	9.334	9.173, 9.495	0.994
			B	9.444	9.322, 9.565	0.997
			C	9.303	9.181, 9.425	0.997
			D	8.975	8.822, 9.128	0.994
			E	9.078	8.903, 9.252	0.993
			F	8.767	8.547, 8.987	0.987

a *MAC: mobile air cleaner.*
b *S: setting.*
c *C: configuration.*
d *95% confidence interval.*

TABLE B.4.3 Natural decay coefficient $k_{PM,n}$ of $PM_{2.5}$.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-07-20 12:25-14:00	A	3.151	3.129, 3.172	0.997	22.9 (0.1)	52.0 (1.0)
	B	3.109	3.084, 3.135	0.996	23.0 (0.1)	50.3 (0.8)
	C	2.823	2.809, 2.838	0.998	23.0 (0.1)	51.5 (1.2)
	D	2.925	2.911, 2.940	0.998	23.3 (0.1)	49.8 (1.2)
	E	3.157	3.142, 3.171	0.999	23.3 (0.0)	50.0 (1.1)
	F	3.283	3.260, 3.306	0.997	23.2 (0.1)	50.3 (0.9)

a *95% confidence interval.*
b *mean (SD).*

TABLE B.4.4 Natural decay coefficient $k_{PM,n}$ of PM_{10}.

Time	Location	$k_{PM,n}$ [h^{-1}]	95% CI (lower, upper)[a]	R^2	T [°C][b]	RH [%][b]
2023-07-20 12:25-14:00	A	3.187	3.165, 3.210	0.997	22.9 (0.1)	52.0 (1.0)
	B	3.325	3.302, 3.348	0.997	23.0 (0.1)	50.3 (0.8)
	C	2.931	2.912, 2.949	0.998	23.0 (0.1)	51.5 (1.2)
	D	3.046	3.029, 3.063	0.998	23.3 (0.1)	49.8 (1.2)
	E	3.314	3.295, 3.333	0.998	23.3 (0.0)	50.0 (1.1)
	F	3.394	3.377, 3.411	0.999	23.2 (0.1)	50.3 (0.9)

a *95% confidence interval.*
b *mean (SD).*

TABLE B.4.5 Aerosol removal rate of the mobile air cleaner $k_{PM,mac}$ based on the mean value of $k_{PM,total}$ and $k_{PM,n}$.

Device[a]	Setting[b]	Configuration[c]	$k_{PM,mac}$ of $PM_{2.5}$ [h^{-1}]	$k_{PM,mac}$ of PM_{10} [h^{-1}]
MAC1	S2	C2	1.570	2.274
MAC2	S2	C1	8.426	8.941
MAC3	S2	C1	9.125	9.448
MAC4	S2	C2	7.091	8.197
MAC5	S2	C2	6.213	7.569
MAC6	S2	C1	7.233	8.600
MAC7	S1	C2	5.562	5.950

a *MAC: mobile air cleaner.*
b *S: setting.*
c *C: configuration.*

Curriculum Vitae

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2016-2017 Main Investigator, *Study on the Effects of Sleep Environment on Sleep Quality*, funded by State Key Laboratory Research Project, China

Academic Activities

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June 2023 Oral presentation, *Healthy Buildings 2023 Europe Conference*, Aachen, Germany

June 2022 Oral presentation, *Indoor Air 2022 Conference*, Kuopio, Finland

June 2021 Oral presentation, *Healthy Buildings 2021 Europe Conference*, Trondheim, Norway

Oct. 2020 Oral presentation, *Indoor Air 2020 Conference*, Seoul, South Korea

July 2018 Poster presentation, *Indoor Air 2018 Conference*, Philadelphia, USA

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25#07

Healthy Air for Children

Strategies for Ventilation and Air Cleaning to Control Infectious Respiratory Particles in School Classrooms

Er Ding

In response to the WHO and UN's call to ensure children's right to breathe "clean" air and the challenges posed by the COVID-19 pandemic on maintaining healthy indoor air quality (IAQ), this PhD research explores ventilation and air cleaning strategies to control the spread of infectious respiratory particles (IRPs) in school classrooms.
The study follows four key steps: (1) a literature review bridging school ventilation regimes, IRP transmission, and advanced ventilation systems; (2) a field study to evaluate real-world ventilation and thermal conditions during the pandemic; (3) an experimental investigation of performance of mobile air cleaners (MACs) followed by an in-situ validation; and (4) a combined experimental and computational study to assess personalized air cleaners (PACs) as localized exhaust for IRP removal.
Findings reveal that most classrooms rely on natural ventilation, often failing to meet IAQ standards, especially when fully occupied. With windows and doors open, ventilation rates remained inconsistent, and thermal conditions were unsatisfactory. Hence, more controllable ventilation and air cleaning approaches are needed. MACs, when appropriately selected and positioned, offer effective protection against long-range IRP transmission at room scale, while PACs are effective at mitigating localized, short-range IRP exposure, improving IAQ at an individual level.
This research offers a comprehensive set of solutions for IRP control in classrooms, with actionable insights for a variety of stakeholders. It advocates for a shift from comfort-based to health-centered paradigms. Future research should explore hybrid systems, optimize designs, and validate interventions through real-world infection risk assessments to create healthier, more resilient classrooms.

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