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Important note

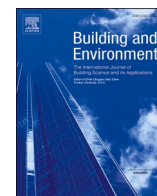
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The effect of a mobile HEPA filter system on ‘infectious’ aerosols, sound and air velocity in the SenseLab

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ABSTRACT

High efficiency air filtration has been suggested to reduce airborne transmission of ‘infectious’ aerosols. In this study the ‘air cleaning’ effect as well as the effect on sound and air velocity (draught risk) of a mobile High-Efficiency Particulate Air (HEPA) filter system was tested for different settings and positions in the Experience room of the SenseLab. From both the noise assessments by a panel of subjects and sound monitoring it was concluded that the mobile HEPA filter system causes an unacceptable background sound level in the tested classroom setting (Experience room). With respect to the air velocity measurements and draught rating calculations, it was concluded that both depend on the position and the setting of the HEPA filter system as well as on the position and height of the measurements. For the removal of aerosols simulated by air-filled soap bubbles in front of the subject, the mobile HEPA filter system performed better as compared to the ‘No ventilation’ regime, for all settings and both positions, and for some settings, even better than all the tested mixing ventilation regimes. The use of a mobile HEPA filter system seems a good additional measure when only natural ventilation options are available. Future research should focus on rooms of different sizes or shapes, as this may also play a role in the filter’s performance, noise and draught effects.

1. Introduction

Since the first outbreaks of COVID-19, it is questioned what is needed to minimize transmission of SARS-CoV-2 indoors: in the classroom, at the office, in a restaurant, at the hairdressers, in public transport, in aircraft cabins, and at the home doctor. SARS-CoV-2 has three possible transmission routes [1]:

- 1) direct transmission of virus carrying droplets when in close vicinity by coughing, sneezing or talking [2];
- 2) indirect transmission via deposited or transmitted infectious droplets via surfaces;
- 3) airborne transmission through virus carrying small airborne droplets (also named ‘aerosols’) emitted by infected individuals [3].

To reduce direct transmission from mainly large infectious droplets, physical distancing of individuals has been adopted, and for indirect transmission cleaning surfaces, washing hands and sneezing/coughing in the elbow. For people who need to or tend to come close to (possible) infected persons, personal protective equipment is used (e.g. facial

masks and protective gloves).

For the third mode of transmission, i.e. airborne transmission, recent studies (e.g. Ref. [4–8]) indicate that in spaces with insufficient and ineffective ventilation the risk seems to increase. Therefore, to decrease the risk of airborne transmission, it has been recommended (e.g. Refs. [1,9,10]): a) to provide sufficient and effective ventilation (that supplies clean outdoor air and minimizes recirculating air); and b) to supplement general ventilation with airborne infection controls such as local exhaust, high efficiency air filtration, and/or germicidal ultraviolet lights in ventilation systems.

Sufficient and effective ventilation ensures the supply of fresh air to an indoor environment or space and/or the exhaust of polluted air from the indoor space at the right time and the right place [11]. Ventilation can be established by just opening a window (natural ventilation) and/or by using a mechanical ventilation system varying from only exhaust to very advanced air conditioning systems that supply and exhaust the air. It is important to make sure that sufficient ‘clean’ air is supplied to and ‘infected’ air is immediately exhausted from the breathing zones of each individual person (without passing through the breathing zones of other persons), as efficiently as possible [12].

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Different ventilation principles are available (e.g. mixing ventilation, displacement ventilation, cross ventilation, personal ventilation) [11]. Mixing ventilation is focused on diluting the air pollutants and therefore reduces the number of 'infectious' aerosols in the air. Displacement and cross ventilation move the air horizontally or vertically through a room, replacing in theory polluted air with 'fresh' air. Moreover, personal ventilation provides each person with 'fresh' air in his/her breathing zone. While with mechanical ventilation the amount of air supplied, exhausted and/or re-used (recirculated air) can be controlled, natural ventilation, such as opening a window, is an uncontrolled form of ventilation, and is therefore not a reliable way of ventilation.

Next to air supply/exhaust, a mechanical ventilation system, central and/or local, can have other functions: cleaning (e.g. filtering), heating/cooling, humidification/dehumidification, and heat recovery. In all mechanical supply ventilation systems, cleaning of incoming air is required to 1) protect the system and to 2) supply clean air to the occupants of the building. Air cleaning in most systems comprises of filtering the air of particles (dust: 0.01–200 μm), such as cassette filters or absolute filters that remove mainly coarse particles (PM_{10} : <10 μm), and bag filters that remove fine particles ($\text{PM}_{2.5}$: <2.5 μm , which can reach the lung cells). Additionally, for cleaning of ultrafine or nanoparticles (<0.1 μm) such as bacteria and viruses, that can even pass the membrane of our lung cells, HEPA (High-Efficiency Particulate Air) and ULPA (Ultra-Low Particulate Air) filters can be used [11,13]. Another air cleaning technique that is used to 'clean' the air of viral, bacterial and fungal particles, is Ultraviolet Germicidal Irradiation (UVGI-light), in particular the UV-C part of the UV-spectrum [14].

SARS-CoV-2 has a size of around 100 nm (0.1 μm) in diameter. It does not exist 'naked', but is surrounded by or embedded in a fluid comprising mainly of water. When a person exhales, talks, or sneezes, a range of droplets are brought into the air, some very small and airborne (aerosols), others larger and heavier [15]. How much virus load a droplet contains, and how much is needed to be infected and develop COVID-19 is still being studied, which makes it difficult to estimate how much ventilation is needed to minimize the risk of airborne transmission [16], although some attempts are made [for example in [17]]. Therefore, cleaning the air in an indoor environment by a mobile HEPA filter system has been suggested as an additional measure, especially in buildings where natural ventilation is the only option, and in enclosed spaces with several occupants. Next to the 'cleaning' effect of these type of systems, the position [18], the sound and draught created are important aspects to consider.

For the visualization of aerosols, most studies have used airflow measurements or local measurements such as laser visualization of sprays and coughing (e.g. Ref. [15,19,20]). However, those techniques are not able to visualize aerosols droplets (optical cross section of 1–10 μm) in a region of several square meters. Therefore, the behaviour of aerosol droplets has been mimicked by a larger tracer, such as Air-filled soap bubbles (AFSB) with diameters in the sub-millimetre range under nearly neutrally buoyant conditions [21], providing a larger scattering cross-section, which enables regions of observation of several square meters as shown in previous studies with Helium-filled soap bubbles (e.g. Ref. [22,23]).

In this study the 'air cleaning' effect as well as the effect on sound and air velocity (draught risk) of a mobile HEPA filter system were tested for different settings (600, 800, 1000, 1200 and/or 1500 m^3/h) and positions within the Experience room of the SenseLab [24] and compared to different natural ventilation regimes. The 'air cleaning effect of the mobile HEPA filter system was tested by visualising of AFSB exhaled by a dummy manikin head and compared to different ventilation regimes of the Experience room. The sound was monitored and assessed by a panel of subjects for different settings of the HEPA filter system. Finally, to have an indication of the draught risk the system poses, air velocity was monitored at different positions and heights in the Experience room for different positions and different settings of the mobile HEPA filter system.

2. Methods

2.1. Aerosols visualization

AFSB simulating aerosols were introduced with a simulated breathing system through a manikin head in the Experience room of the SenseLab [24] (Position A in Fig. 1), simulating the exhaling of an infected person. The pathway of the bubbles was monitored by a camera with a 35 mm objective in time, for a mobile HEPA-filter system at different locations and different settings (Fig. 2). For comparison, several ventilation regimes were additionally monitored (e.g. mixing ventilation, natural ventilation and cross ventilation).

2.1.1. Experience room

The Experience room, with a volume of 68 m^3 (6.4 (l) x 4.1 (b) x 2.6 (h), was furnished with desks and chairs as typical for a classroom, but with 1.5 m distance in mind. To minimize reflection of light from background objects (mostly walls and desks), the surfaces were covered with black paper or foil (see Fig. 2a). Mixing ventilation, providing 100% outdoor air, occurs via four ceiling grilles and is exhausted through the perforated plinth on the short side of the experience room (see Fig. 2). For the natural ventilation mode, the windows, and/or the door in the Experience room were opened (Fig. 3a), allowing sunlight to come into the Experience room. The air velocity for a ventilation rate of 600 m^3/h (mixing setting) within an empty room is 0.03 m/s measured at four different points and three heights (0.2, 1.2 and 1.6 m) [25].

2.1.2. Bubble generation

The AFSB generation system, composed of a fluid supply unit (FSU) and a bubble generator, was placed outside the Experience room. The bubble generator nozzle has an orifice diameter of 1 mm [16]. The bubbles are created and supplied into a buffer, from where the bubbles are led into a 5 m long PVC-tube with an external diameter of 48 mm that is connected on one side to the ventilator (designed by TUDelft project Inspiration (<https://www.projectinspiration.nl/specification/>) and to the other side to the manikin head that is fixed on one of the chairs in the Experience room (see Fig. 2). The ventilator provided circa 0.5 L (not inhaling, only exhaling) in 1.25 s, resulting in a breathing cycle of 2.5 s (24 exhalations per minute). Normal breathing rate lies around 15 times per minute (4 s per breathing cycle) and one breath of air amounts approximately 0.5 L [26].

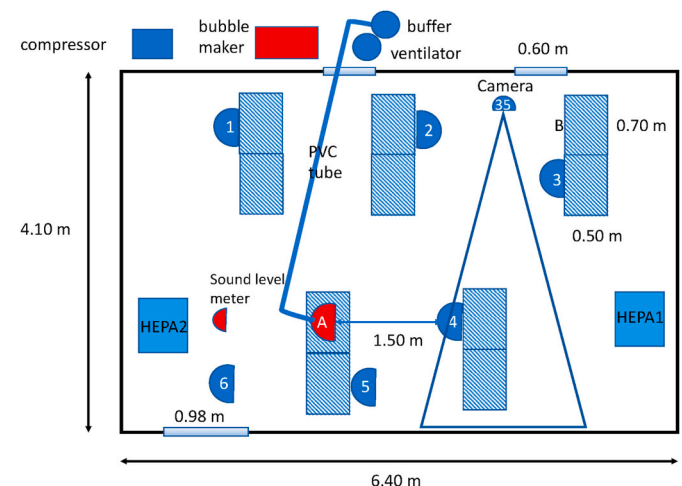


Fig. 1. Test-setup in the Experience room of the SenseLab [24]: A is infected person; B is researcher operating the computer; numbers 1–6 represent the locations of the air velocity measurements as well as the subjects (sitting on a chair (half blue circle) present in the sound assessment test.

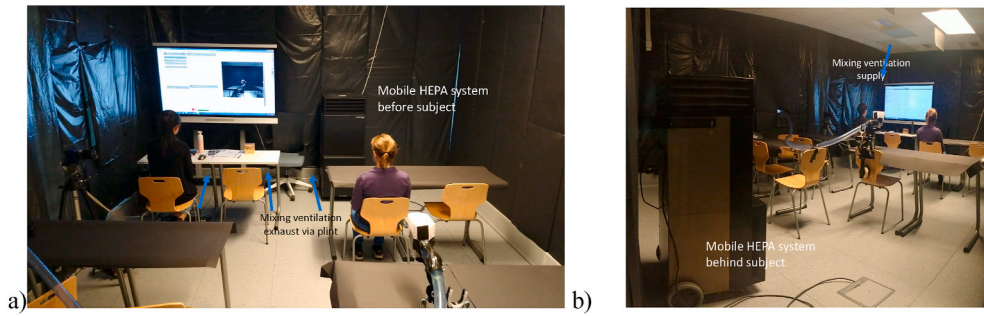


Fig. 2. Set-up in the Experience room: a) HEPA at 1 and b) HEPA at 2.

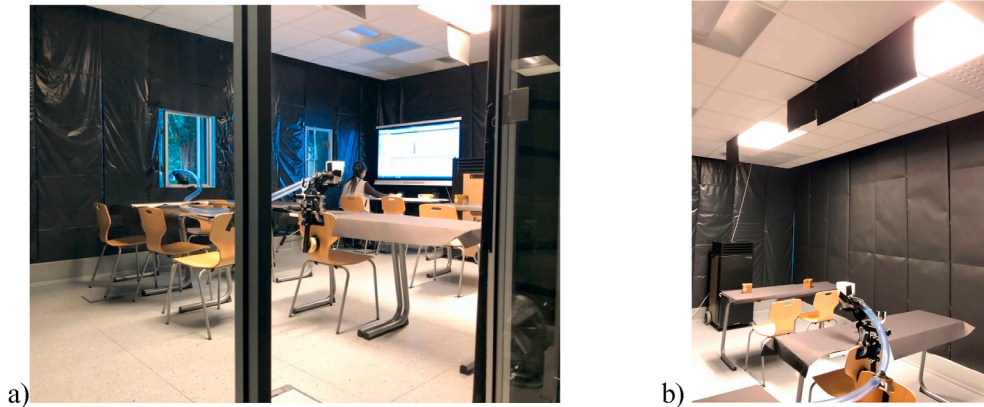


Fig. 3. a) natural ventilation: opening windows and door b) Lighting system and HEPA filter system.

2.1.3. Imaging system

The data acquisition system consisted of a LaVision *Imager sCMOS* camera (2560×2160 px², 16 bit, 6.5 μ m pixel pitch), installed on a tripod so that a measurement volume was located in front of the manikin head (see Fig. 2). The camera was equipped with a 35 mm (Nikon) lens with an aperture setting of f4. Existing LED-ceiling lighting (see Fig. 3b) illuminated the bubbles. Sequences of 1000 single-frame images were acquired during 50 s at an acquisition frequency of 20 Hz. Considering a breathing cycle of 2.5 s, 50 images would cover one breathing cycle.

2.1.4. Mobile HEPA filter system

A mobile HEPA filter system with a filter class H14, ensuring that 99.995% of the particles with a diameter of 0.1–0.3 μ m is filtered out of the passing room air, and five different airflow rate settings (1: 600, 2: 800, 3: 1000, 4: 1200 and 5: 1500 m³/h) was placed in the room. Additionally, the HEPA filter system has the possibility to heat-up the HEPA filter to 100 °C when not in use, to kill the viruses caught by the filter. Room air is sucked in on two sides in the lower part of the system, and the ‘cleaned’ air is supplied into the room from all sides of the upper part of the system and directed towards the ceiling.

Table 1
Test scheme.

Series 1		Series 2	
Conditions	Flow rate	Conditions	Flow rate
HEPA2	600 m ³ /h	mixing	1200 m ³ /h
HEPA2	800 m ³ /h	mixing	600 m ³ /h
HEPA2	1200 m ³ /h	open door	(natural ventilation)
HEPA1	1200 m ³ /h	open windows	(natural ventilation)
HEPA1	800 m ³ /h	open door + windows	(natural ventilation)
HEPA1	600 m ³ /h	closed door + windows	(no ventilation)

2.1.5. Test scheme and procedure

Two series of tests were performed (see Table 1). In each of the tests, a researcher was sitting behind the computer (see Fig. 2) to control the monitoring of the camera, and a researcher was handling the bubble maker (see Fig. 1). For each test condition, 1000 pictures were generated at 1 min, 5, and 10 min for both test series. These times were chosen for two reasons: a) to show the distribution of bubbles in time; b) assuming stable conditions for mixing ventilation at 10 min for both 600 and 1200 m³/h (with 1200 m³/h, air exchange rate of 17.6 h⁻¹ and a volume of 68 m³), it should take cc. 3.4 min to refresh the air). After each test, the ventilation was set at 1200 m³/h to clean the Experience room of the generated bubbles. The time in between tests was at least 10 min. For the light settings, two indirect and two soft light LED armatures were on. The lights in the general space of the SenseLab were off. For the tests with the windows open, some light from the outside could not be avoided (see Fig. 3a).

2.1.6. Data management and analysis

For each test, sequences of 1000 single-frame images were processed in DaVis 10.1.0. The following procedure was then performed:

- For each sequence:
 - An image showing the first maximum tracked particles of the first 200 images was created.
 - The first 10 and/or 50 images were used to determine the mean number of particles converted to a unit area of 1000×1000 pixels, for: one zone (Fig. 4) with 1171×654 pixels (divided by 0.77 for conversion to unified area); and six zones (Fig. 5), each with the same size (853×800 pixels; divided by 0.68 for conversion to unified area).
- To compare particle counts in different settings and for different zones, one-way ANOVA and t-testing were used with SPSS version 25.

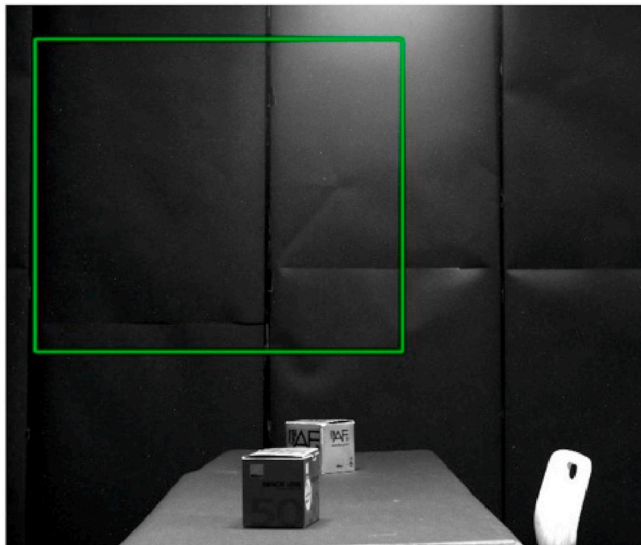


Fig. 4. Area for which the number of tracked particles was analysed.

2.2. Sound and noise assessment

A separate session was held with six subjects to test the sound/noise created by the mobile HEPA filter system for different settings. The sound level was monitored with a Norsonic Nor 140 sound analyser, while the panel of subjects assessed the sound level at three HEPA filter system settings (1: 600; 3: 1000; and 5: 1500 m³/h) with a questionnaire (Appendix A) for HEPA1 position. Fig. 1 shows the position of the six subjects (numbers 1 to 6) and the sound level meter. The percentage of dissatisfied was determined for each of the settings assessed by combining the answers 'bad' and 'very bad' to the question: "What is your assessment of that noise?"

2.3. Air velocity and draught risk

Additionally, the air velocity was monitored at 6 locations (the same as the 6 subjects for the sound evaluation) in the Experience room for different settings (1: 600, 2: 800, 3: 1000, 4: 1200 and 5: 1500 m³/h), different heights (0.2 m, 1.10 m and 1.80 m) and different locations (number 1 to 6 in Fig. 1). Air velocity was measured with a Dantec ComfortSense monitor at each position (at three different heights) for 1 min every 0.5 s, resulting in 120 measurements. The draught rating (DR), which is the predicted percentage of dissatisfied occupants resulting from draught, was calculated using the following equation [27]:

$$DR = (34 - T_l)(v_l - 0.05)^{0.62} (0.37v_lTu + 3.14) \text{ [%]}$$

With:

T_l = local air temperature (between 20 and 26 °C [°C])

v_l = local average air velocity (<0.5 m/s) [m/s]

Tu = local turbulence intensity (between 10 and 60%) [%]

If Tu is unknown, apply 40%; if $v_l < 0.05$ m/s, apply 0.05 m/s; if $DR > 100\%$, apply 100%

From the air velocity measurements, for each test the draught rating was calculated assuming a T_l of 23 °C.

3. Results

3.1. Visualization of air bubbles

Figs. 6 and 7 show an image of the maximum tracked particles of the first 200 images of each sequence for series 1 and 2, respectively. Table 2 presents the mean₁₀ and mean₅₀ counted particles based on 10 and 50 images, respectively, for test series 1 and 2. T-tests comparing particle counts between different HEPA settings and ventilation regimes (based on means of 50 images at 10 min) are presented in Table 3. Fig. 8 shows the comparison of tracked particles for different time periods with different HEPA filter system settings and ventilation regimes (based on 50 images).

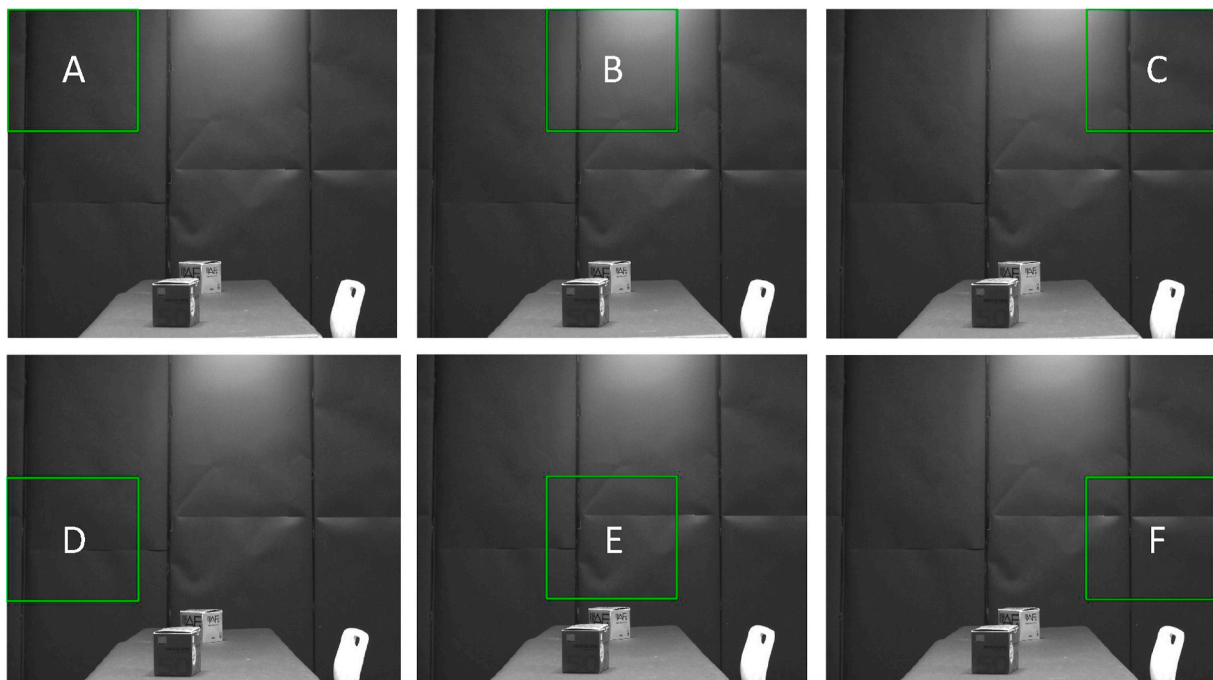


Fig. 5. Areas A-F for which the number of tracked particles was analysed for the second and third series at 10 min.

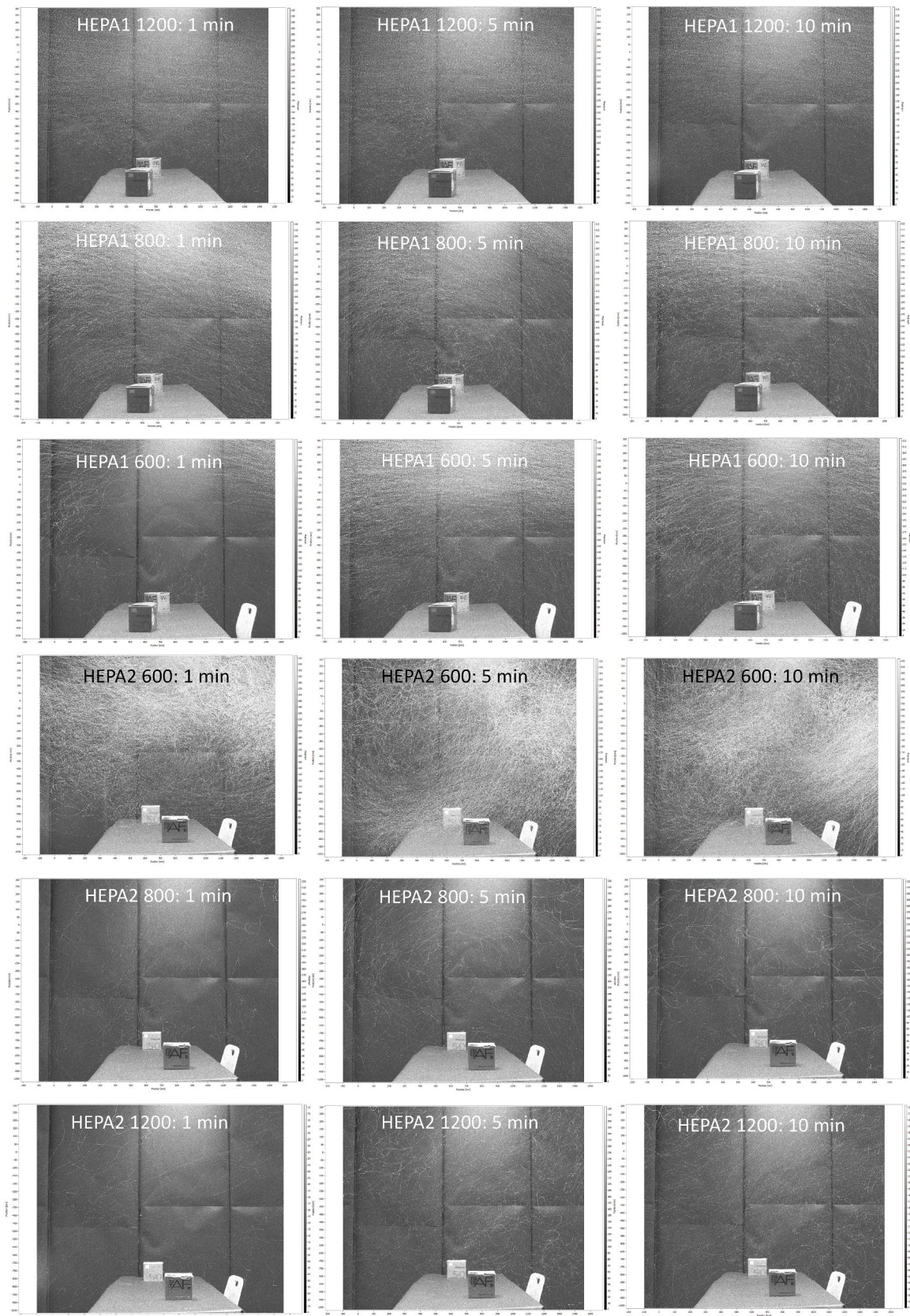


Fig. 6. Test series 1: An image showing the maximum tracked particles of the first 200 images of each sequence tested.

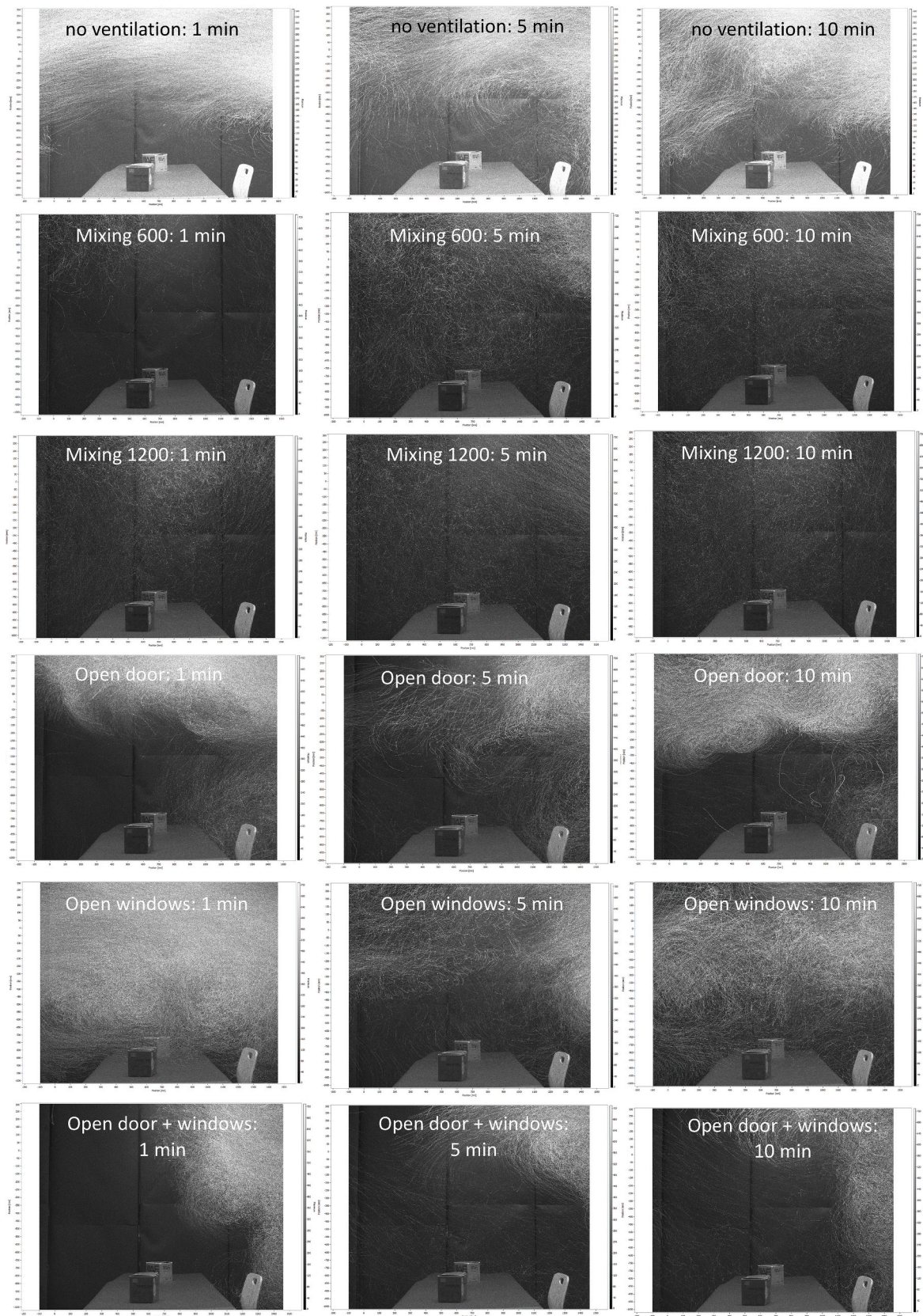


Fig. 7. Test series 2: An image showing the maximum tracked particles of the first 200 images of each sequence tested.

Table 2

Tracked particles based on 10 and 50 images for test series 1 and 2.

Settings	Time [min]	1	5	10	F ^a
No ventilation	mean ₁₀ (SD)	1479	839 (12)	1321	419*
	mean ₅₀ (SD)	(80)	810 (25)	(39)	4054*
	t-test ₁₀₋₅₀	1540	5.0*	1297	
	50(p) ^b	(57)	(27)	(27)	
HEPA2: 600	mean ₁₀ (SD)	1331	818 (17)	1340	742*
	mean ₅₀ (SD)	(38)	791 (25)	(43)	6104*
	t-test ₁₀₋₅₀ (p)	1335	4.3*	1375	
		(25)		(34)	
HEPA2: 800	mean ₁₀ (SD)	18 (1)	83 (3)	57 (3)	1784*
	mean ₅₀ (SD)	16 (3)	83 (4)	55 (3)	4734*
	t-test ₁₀₋₅₀ (p)	6.3*	−0.4	1.4	
		(0.690)	(0.699)	(0.175)	
HEPA2: 1200	mean ₁₀ (SD)	23 (3)	69 (5)	82 (3)	762*
	mean ₅₀ (SD)	23 (3)	77 (6)	75 (6)	1431*
	t-test ₁₀₋₅₀ (p)	0.4	−4.3*	4.8*	
		(0.655)			
HEPA1: 1200	mean ₁₀ (SD)	1 (1)	37 (9)	4 (1)	148*
	mean ₅₀ (SD)	3 (1)	36 (6)	3 (3)	1386*
	t-test ₁₀₋₅₀ (p)	−3.6	0.2	2.3	
		(0.001)	(0.819)	(0.026)	
HEPA1: 800	mean ₁₀ (SD)	155 (3)	174 (18)	191 (12)	20*
	mean ₅₀ (SD)	175 (17)	229 (32)	184 (12)	74*
	t-test ₁₀₋₅₀ (p)	−7.7*	−4.9*	1.8	
				(0.078)	
HEPA1: 600	mean ₁₀ (SD)	39 (1)	183 (9)	255 (15)	1162*
	mean ₅₀ (SD)	35 (3)	230 (36)	255 (12)	1372*
	t-test ₁₀₋₅₀ (p)	5.7*	−7.8*	−0.2	
				(0.869)	
Open windows	mean ₁₀ (SD)	5395	636 (27)	3047	8007*
	mean ₅₀ (SD)	(98)	703 (47)	(104)	37341*
	t-test ₁₀₋₅₀ (p)	5387	−6.0*	2925	
		(92)		(104)	
Open door	mean ₁₀ (SD)	1235	577 (24)	3071	6745*
	mean ₅₀ (SD)	(51)	577 (16)	(65)	9426*
	t-test ₁₀₋₅₀ (p)	1426	−0.2	3022	
		(144)	(0.857)	(55)	
Open door + windows	mean ₁₀ (SD)	12 (3)	165 (7)	148 (11)	1153*
	mean ₅₀ (SD)	10 (6)	186 (19)	155 (6)	2711*
	t-test ₁₀₋₅₀ (p)	0.9	−5.7*	−1.8	
		(0.395)		(0.100)	
Mixing 1200	mean ₁₀ (SD)	470 (15)	404 (12)	418 (16)	58*
	mean ₅₀ (SD)	470 (10)	401 (16)	418 (16)	298*
	t-test ₁₀₋₅₀ (p)	−0.2	0.4	−2.5	
		(0.871)	(0.696)	(0.015)	
Mixing 600	mean ₁₀ (SD)	55 (6)	877 (23)	622 (13)	7108*
	mean ₅₀ (SD)	62 (8)	851 (22)	610 (16)	29986*
	t-test ₁₀₋₅₀ (p)	−2.9	3.3	2.2	
		(0.006)	(0.002)	(0.031)	

Notes: Mean₁₀ and Mean₅₀: mean based on particle count of 10 and 50 images, respectively; SD = Standard deviation; a. results from ANOVA, comparison of counts between different times of measurement; * statistically relevant with $p < 0.001$; b. t-test between Mean₁₀ and Mean₅₀. A negative value for the t-test means that the mean particle count of the 10 images was less than for the 50 images.

Because, for most settings, the t-tests between the means with 10 and 50 images indicated no difference or a very small difference (Table 2), it was decided to use the mean₁₀ for comparison of the particle counts between the different zones (A-F) for the different HEPA settings (Fig. 9) and different ventilation regimes (Fig. 10). The 10 min sequence was chosen based on assumed steady state conditions for mixing ventilation regimes and HEPA filter system settings.

3.2. Sound and noise assessment

The sound pressure level measurement results are presented in Table 4, together with the assessments of the panel of subjects. From the assessments followed that while the HEPA system was off, three out of the six subjects noticed a sound (31 dB) at the location they were sitting, while none of them was dissatisfied with it. At the lowest setting of the HEPA system (setting 1: 600 m³/h), all subjects noticed noise (40 dB), while 2/3 were dissatisfied with that. For settings 3 and 5 (1000 and 1500 m³/h, respectively), all subjects were dissatisfied with the noise they perceived (44 and 51 dB, respectively).

3.3. Air velocity and draught

In Fig. 11, both the calculated draught rating and the measured average air velocity are presented for each setting and location of the HEPA filter system at different heights (0.2 m (feet), 1.1 m (sitting) and 1.8 m (standing) above the floor) for the six subjects (1–6).

4. Discussion

4.1. Air cleaning

4.1.1. HEPA system settings vs. ventilation regimes

The t-values in Table 3 indicate that for almost all of the HEPA settings, except for the 'HEPA2: 600', the particle count was lower in the observed area in front of the subject as compared with the 'No ventilation' regime. Moreover, for the 'HEPA1: 1200' settings the particle counts were significantly lower than for all the other settings. As shown in Table 3, for all HEPA settings fewer particles were counted than for the 'Open windows' and 'Open door' regimes, and for almost all of them, except for 'HEPA2: 600', resulted in fewer particles than the two mixing regimes (both 1200 and 600 m³/h). Three HEPA settings ('HEPA2: 800', 'HEPA2: 1200', and 'HEPA1: 1200') showed lower particle counts than all tested ventilation regimes, while the 'Open door and windows' regime (cross natural ventilation) showed the least counted particles of the other ventilation regimes tested, confirming that this is a good alternative to mixing ventilation [28].

4.1.2. Natural ventilation vs. no ventilation

From the natural ventilation regimes tested, the 'Open door' and 'Open windows' regime, showed larger particle counts than the 'No ventilation' condition (Tables 2 and 3), for the 10th minute; while for the 5th minute the opposite was seen. A possible explanation for this could be the non-steady state airflow distribution caused by both the natural ventilation regimes in relation to the both the soap bubble source and the measurement location (i.e. in front of the subject who was sitting 1.5 m from the soap bubble source). The unsteady state airflows resulting from opening a window or opening a door, can cause different concentrations of soap bubbles in time in the region where they were monitored.

4.1.3. Position of HEPA system

For the test series with the HEPA system in the different positions, statistically significant differences between the results acquired from the particle counts in front of the subject for the two HEPA filter system positions (HEPA 1 and HEPA 2) were found. However, the trends were not consistent: the HEPA filter system removed more particles in position 1 with setting 600 and/or 1200 m³/h, while it removed more particles at position 2 when the setting was 800 m³/h. Also, with regard to the setting (airflow rate), a statistically significant difference between the three settings was found, with a dependency on the position. At position 1, the HEPA filter system seemed to remove slightly more particles (bubbles) for setting 1200 m³/h, while at position 2, this occurred for setting 800 m³/h.

The fact that the trends are not consistent could be explained by the

Table 3

Comparison of particle counts between different HEPA settings and different ventilation regimes at 10 min (based on means of 50 images).

Time	No ventilation	HEPA2 600	HEPA2 800	HEPA2 1200	HEPA1 600	HEPA1 800	HEPA1 1200	Mixing 1200	Mixing 600	Open windows	Open door
HEPA2 600	11.8*										
HEPA2 800	−299.5*	−261.9*									
HEPA2 1200	−287.3*	−253.5*	17.8*								
HEPA1 600	−234.0*	−211.6*	114.0*	90.1*							
HEPA1 800	−248.4*	−224.0*	70.9*	53.0*	−29.0*						
HEPA1 1200	−313.2*	−273.0*	−98.3*	−67.0*	−146.9*	−101.6*					
Mixing 1200	−184.8*	−171.8*	165.8*	144.8*	62.8*	86.6*	191.1*				
Mixing 600	−147.7*	−140.0*	252.3*	223.4*	130.0*	152.3*	279.6*	57.8*			
Open windows	105.3*	98.6*	192.8*	191.0*	178.3*	182.9*	196.3*	165.7*	153.9*		
Open door	194.7*	177.0*	378.5*	373.2*	345.6*	353.8*	385.5*	318.3*	297.0*	5.8*	
Open door & windows	−269.5*	−238.6*	91.3*	55.0*	−51.0*	−14.5*	147.1*	−113.7*	−192.2*	−185.7*	−363.5*

Note: The numbers are t-values from t-tests; a positive number means that the particle numbers in the setting mentioned in the first column is larger than in the setting mentioned in the first row, and vice versa. * statistically relevant with $p < 0.001$.

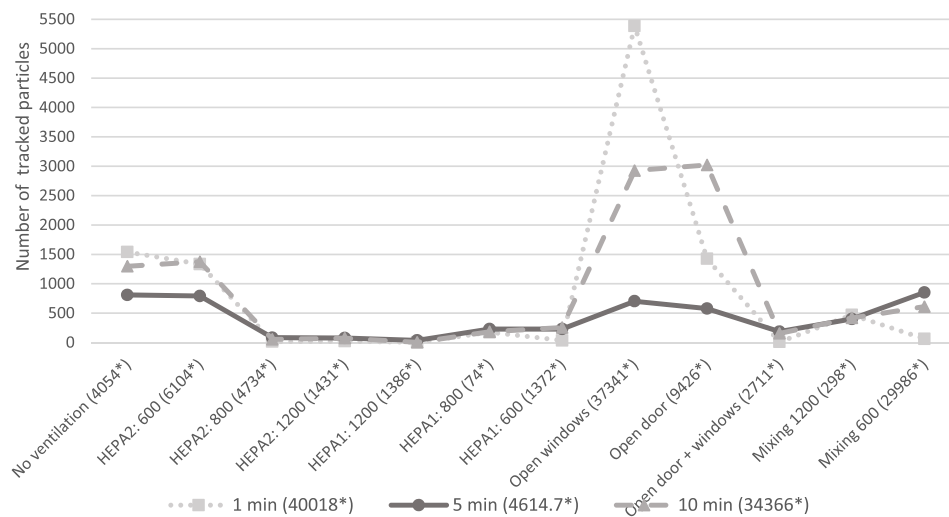


Fig. 8. Comparison of tracked particles for different time periods with different HEPA filter system settings and ventilation regimes (based on 50 images). Note: the numbers in parentheses are the F-values from ANOVA analyses; * P-value is less than 0.001.

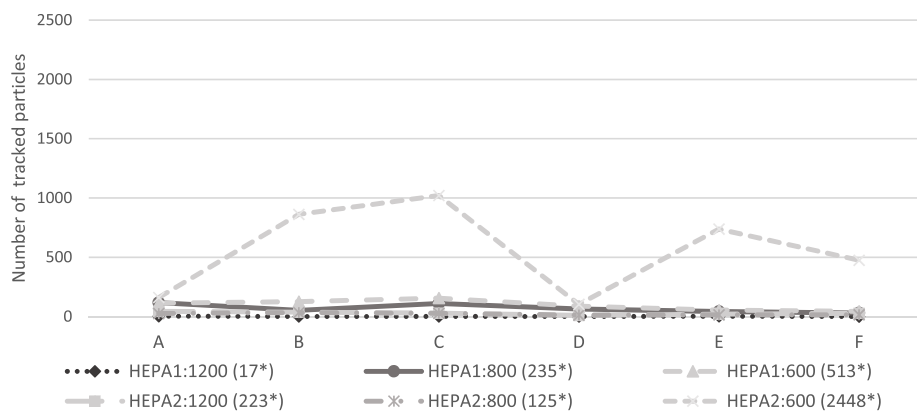


Fig. 9. Comparison of particle numbers between different zones A-F at 10 min under different HEPA settings (based on means of 10 images). Note: the numbers in parentheses are the F-values from ANOVA analyses; * P-value is less than 0.001.

position, which may create different turbulence patterns within the room due to possible obstructions (such as chairs or tables or proximity to the walls), as well as the direction of the bubbles production.

4.1.4. Zones

As shown in Figs. 9 and 10, all the p-values of the ANOVA tests were less than 0.001, which means that there are statistically significant

differences between the six observation zones (A-F) for all the HEPA filter settings (Fig. 9) and for all the ventilation regimes (Fig. 10). For both test series can be observed that particle counts in the upper zones were generally higher than that in the lower zones (Figs. 9 and 10), for all HEPA filter system settings, both positions, and all ventilation regimes, except for the 'HEPA2: 600' setting and the 'Open door and windows' regime. For the HEPA filter system tests (series 1), in general,

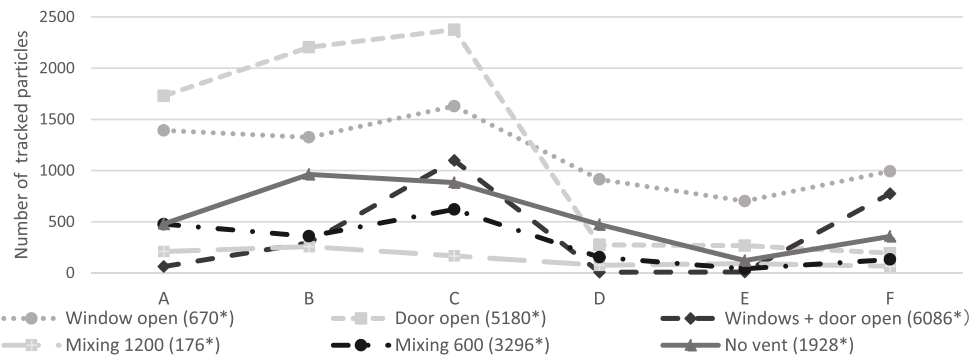


Fig. 10. Comparison of particle numbers between different zones A-F at 10 min under different ventilation regimes (based on means of 10 images). Note: the numbers in parentheses are the F-values from ANOVA analyses; * P-value is less than 0.001.

Table 4
Sound pressure level and panel assessment.

Test	HEPA off	Setting 1	Setting 3	Setting 5
Sound pressure levels measurements				
mean (dB)	31.2	39.6	44.2	50.9
SD	4.3	2.3	0.9	0.56
Panel member	a. Do you hear noise at the location you are sitting? b. What is your assessment of that noise?			
1a	no	yes	a lot	a lot
1b	–	bad	very bad	very bad
2a	a little	yes	yes	a lot
2b	normal	bad	bad	bad
3a	no	yes	yes	a lot
3b	–	good	bad	bad
4a	a little	yes	a lot	a lot
4b	normal	very bad	very bad	very bad
5a	no	yes	a lot	a lot
5b	–	bad	very bad	very bad
6a	a little	yes	yes	yes
6b	Very good	normal	bad	very bad
Mean a	No – A little	Yes	Yes – A lot	A lot
% dissatisfied ¹	0%	66%	100%	100%

1: assessments bad and very bad are considered to be dissatisfied.

particle numbers in zones B and C were the highest, while in zone D (for HEPA position 2) and zone F (for HEPA position 1) were the lowest. In addition, it can be seen that the higher the setting of the mobile HEPA filter system, the fewer particles were tracked. Fig. 10 shows that the particle count was in general the highest in zone C, no matter which ventilation regime, while the particle count was in general the lowest in zones D or F, except for ‘open windows and door’. For the ‘open windows and door’ regime, the highest numbers of particles were found in zones C and F. This could indicate that ‘natural’ induced airflow caused the particles to be re-distributed, rather than removing them. In addition, mixing ventilation reduced the number of particles more than ‘Open windows’ or ‘Open door’ regimes.

4.2. Noise

In the CEN standard EN 16798–1 [29], for noise, respectively 30, 34 and 38 dB is the maximum equivalent continuous sound level caused by building services (such as ventilation systems) recommended for classrooms with a high, normal and moderate level of expectation. In the Dutch Fresh school guidelines, levels that are even more stringent are recommended for sound caused by ventilation systems: maximum 30 dB in class A Very good, 33 dB in class B Good and maximum 35 dB in class C Acceptable [30]. Considering the measured values (40, 44 and 51 dB for respectively setting 1, 3 and 5 of the HEPA filter system), and assuming the contribution of the background level has a negligible effect on the combined noise level (meaning the measured level is caused by

the most noisy source, that is the mobile HEPA filter system) [31], it is clear that none of the settings reached even the moderate/acceptable levels recommended by the guidelines. This is confirmed by the assessments of the panel of subjects.

4.3. Draught

Air velocity, standards and guidelines (such as the Dutch Building Decree [32] and ASHRAE 55–2017 [33]) state that supply of air should not cause an air velocity greater than 0.2 m/s in the occupied zone of an area where people stay (when the operative temperature is lower than 23 °C). The occupied zone is the space between the floor and 1.8 m above the floor and more than 1.0 m from outside walls/windows, and 0.3 m from internal walls [33]. From Fig. 10 and Appendix B can be seen, that with the HEPA filter system at position 1, except for measurement location 3 at 1.8 m with HEPA setting 5 (0.21 m/s), for none of the settings and at none of the positions measured, the air velocity exceeded 0.2 m/s. While, for the HEPA filter system at position 2, for setting 3, 4 and 5, measurement location 6 at 0.2 m (resp. 0.24, 0.29 and 31 m/s) and for setting 5 measurement location 1 at 0.2 m (0.21 m/s), location 2 at 1.1 m (0.21 m/s) and location 6 at 1.1 m (0.22 m/s), the air velocity exceeded 0.2 m/s.

The feeling of draught is influenced by the air velocity, the turbulence and the temperature. With the draught rating approach [27], it is possible to predict the percentage of dissatisfied occupants resulting from draught. Therefore, the draught rating (DR) for the different settings and positions of the mobile HEPA filter system were calculated. From Fig. 10 and Appendix B can be concluded, that with the HEPA filter system at position 1, the DR exceeds 10% for measurement locations 2 and 3, for setting 3 (at 1.8 m), settings 4 and 5 (at 0.2 and 1.8 m). For measurement position 2 at 1.8 m at setting 5, the DR exceeds 20% (calculated DR is 22%), the highest for position 1. For the HEPA filter system at position 2, the calculated DR exceeds or is equal to 20% for:

- Location 1: setting 5 at 0.2 m (23%);
- Location 2: setting 5 at 1.1 m (25%);
- Location 6: setting 3 at 0.2 m (23%); setting 4 at 0.2 m (28%); setting 5 at 0.2 m (32%) and at 1.1 m (20%)

Additionally, DR exceeds 10% for:

- Setting 3: location 1 at 0.2 m, 1.1 and 1.8 m; location 2 at 1.1 m; location 5 at 0.2 and 1.8 m; location 6 at 1.1 and 1.8 m;
- Setting 4: location 1 and 5 at 0.2 and 1.8 m; location 4 at 1.8 m; location 6 at 1.1 and 1.8 m;
- Setting 5: location 1, 2 and 6 at 1.8 m; location 4 at 0.2 and 1.8 m; location 5 at 0.2, 1.1 and 1.8 m.

While, measurement position 3 has no draught ratings above 10%,

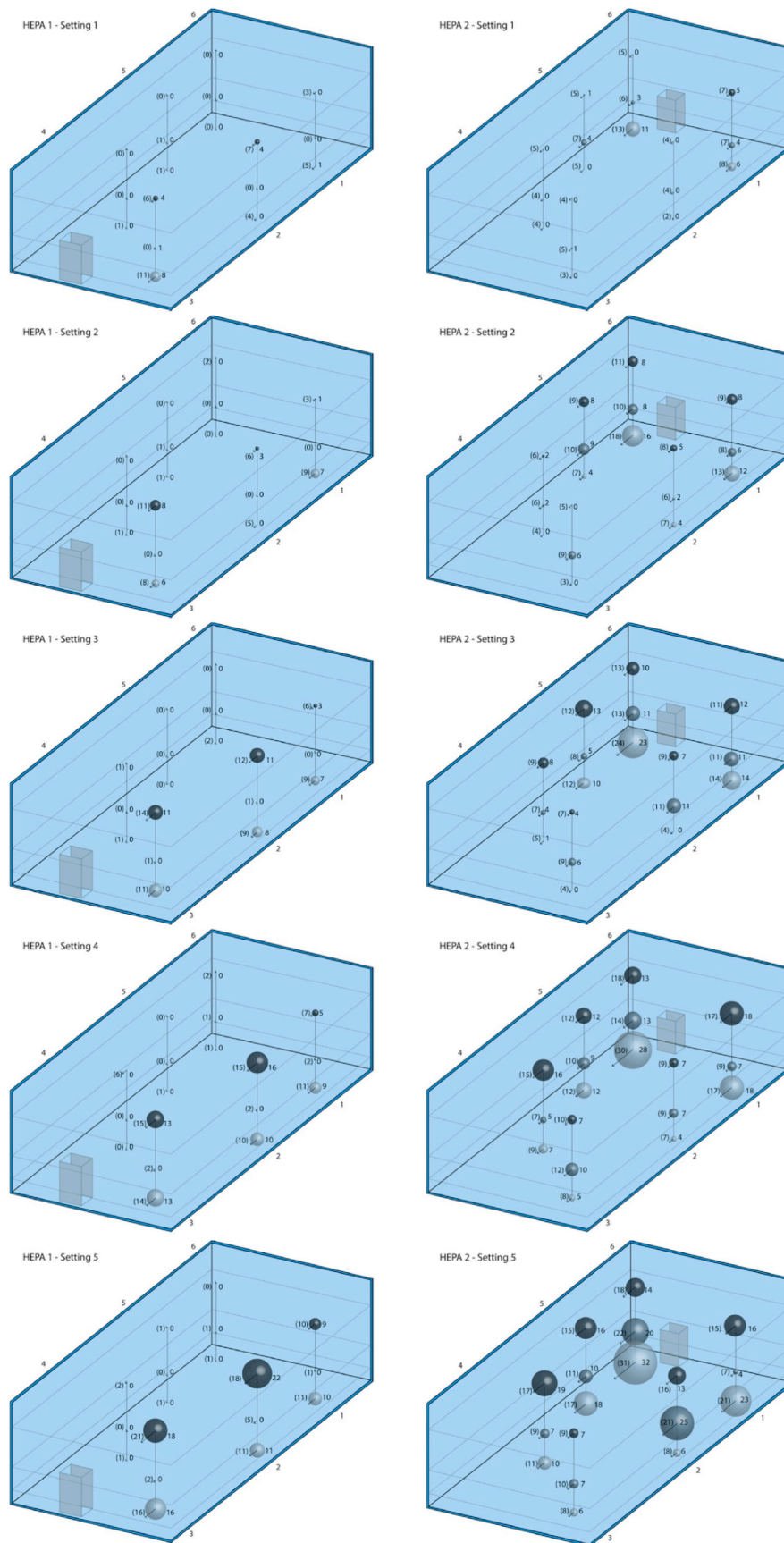


Fig. 11. Average air velocities and draught ratings at six different positions (1–6) in the Experience room, 3 heights, 5 settings of the HEPA system and two positions of the HEPA system (HEPA1&2).

position 1 and 6 clearly show the most often, and position 6 the highest draught ratings, for HEPA position 2.

4.4. Limitations

4.4.1. Lifetime of AFSB

The differences found between zones for all tested settings and regimes, indicate that in none of the conditions tested complete mixing was established (at the 10 min test sequence). For the 'Open door', 'Open windows', and 'Open door and windows' this was expected, but for the tests with the HEPA filter system the mixing ventilation regimes, it was not. Reaching complete mixing is affected by several parameters, such as the ventilation rate of the room, the local airflow distribution and in this study the lifetime of the AFSB (the 'infectious' aerosols). The lifetime of the AFSB depends, among others, on the air velocity and the turbulence in a space. Bubbles will 'live' longer in an environment with low turbulence than in one with high turbulence: the lifetime of the air-filled soap bubbles have been found to lie around 2 min in an environment with air velocities of several metres per second [34]. This could at least partly explain the differences observed between the positions of the HEPA filter system and the differences observed with mixing ventilation (e.g. HEPA1 and 2: 1200 performed better than Mixing 1200).

4.4.2. Influence of people

Due to the COVID-19 situation, during the AFSB tests and the air velocity measurements, the Experience room was not occupied, except for the researcher operating the computer. The sound assessments with a panel of six persons, was an exception. The six persons were sitting more than 1.5 m from each other, and testing was completed in 15 min. Before and after the testing, the ventilation rate of the Experience room was set at 1200 m³/h (mixing). For future studies, thermal manikins could be considered to be used as alternative to 'real' persons [35].

5. Conclusions

For the removal of aerosols simulated by AFSB in front of the subject, the mobile HEPA filter system performed better as compared to the 'No ventilation' regime, for all settings and both positions, except for the 'HEPA2 600' setting. The performance of the HEPA filter system clearly depends on its setting and position. For some settings (HEPA 1 and 2 1200 and HEPA2: 800), the HEPA filter system performed better than all the tested ventilation regimes. This might be related to the method used, i.e. the fact that the lifetime of bubbles is lower than the time needed to reach steady state conditions in combination with the higher velocities and turbulence observed for the HEPA filter system settings 3 to 5.

From both the noise assessments and sound monitoring for different settings of the HEPA filter system, it can be concluded that the mobile HEPA filter system is causing an unacceptable background sound level in the tested classroom setting (Experience room).

With respect to the air velocity measurements and the draught rating calculations, it is concluded that both depend on the position and the setting of the HEPA filter system as well as the position and height of the measurements. Setting 1 and 2 (600 and 800 m³/h) did not cause velocities higher than 0.2 m/s or draught ratings higher than 10%, for any of the positions.

Nevertheless, the use of a mobile HEPA filter system seems a good alternative to use when no ventilation options are available. It is recommended though to still reduce the time spend in an enclosed space without (natural) ventilation, and to open the windows and door, creating cross ventilation, in order to ventilate the room with 'fresh' air. Future research should focus on the performance of the HEPA filter system in rooms of different sizes or shapes, as this may also play a role in its performance, noise and draught effects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.buildenv.2020.107475>.

References

- [1] L. Morawska, J. Tang, W. Bahnfleth, P.M. Bluyssen, A. Boerstra, G. Buonanno, J. Cao, S. Dancer, A. Floto, F. Franchimon, C. Haworth, J. Hogeling, C. Isaxon, J. L. Jimenez, J. Kurnitski, Y. Li, M. Loomans, G. Marks, L.C. Marr, L. Mazzarella, A. K. Melikov, S. Miller, D. Milton, W. Nazaroff, P.V. Nielsen, C. Noakes, J. Peccia, X. Querol, C. Sekhar, O. Seppänen, S. Tanabe, R. Tellier, K.W. Tham, P. Wargocki, A. Wierzbicka, M. Yao, How can airborne transmission of COVID-19 indoors be minimised? *Environment International* 142 (2020) 105832, <https://doi.org/10.1016/j.envint.2020.105832>.
- [2] W. Chen, N. Zhang, J. Wei, H.-L. Yen, Y. Li, Short-range Airborne Route Dominates Exposure of Respiratory Infection during Close Contact, *Building and Environment*, 2020, 106859.
- [3] K.A. Prather, L.C. Marr, R.T. Schooley, M.A. McDiarmid, M.E. Wilson, D.K. Milton, Airborne Transmission of SARS-CoV-2, *Science*, New York, NY, 2020 eabf0521.
- [4] Y. Li, H. Qian, J. Hang, X. Chen, L. Hong, P. Liang, S. Li JXiao, J. Wei, L. Liu, M. Kang, Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant, *medRxiv preprint* (2020), <https://doi.org/10.1101/2020.04.16.20067728>.
- [5] S.L. Miller, W.W. Nazaroff, J.L. Jimenez, A. Boerstra, G. Buonanno, S.J. Dancer, J. Kurnitski, L.C. Marr, L. Morawska, C. Noakes, Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event, submitted to *Indoor Air*, *medRxiv preprint*, <https://doi.org/10.1101/2020.06.15.20132027>, 2020.
- [6] H. Nishiura, H. Oshitani, T. Kobayashi, T. Saito, T. Sunagawa, T. Matsui, T. Wakita, , MHL COVID-19 response Team, M. Suzuki, Closed environments facilitate secondary transmission of coronavirus disease 2019, *medRxiv preprint* (2020), <https://doi.org/10.1101/2020.02.28.20029272>.
- [7] M. Richard, A. Kok, D. de Meulder, T.M. Bestebroer, M.M. Lamers, N.M.A. Okba, M.F. van Vliessing, B. Rockx, B.L. Haagmans, M.P.G. Koopmans, R.A.M. Fouchier, S. Herfst, SARS-CoV-2 transmitted via contact and via the air between ferrets, *bioRxiv preprint* (2020), <https://doi.org/10.1101/2020.04.16.044503>.
- [8] N. Wilson, S. Corbett, E. Tovey, Airborne transmission of covid-19, *BMJ* (2020), <https://doi.org/10.1136/bmj.m3206>.
- [9] REHVA, COVID-19 guidance document, April 3 2020, <https://www.rehva.eu/activities/covid-19-guidance>, 2020.
- [10] ASHRAE, Position document on infectious aerosols, April 14, 2020, Atlanta, Georgia, USA, https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf, 2020.
- [11] P.M. Bluyssen, All You Need to Know about Air Conditioning, the How and Why of Heating, Ventilating and Air Conditioning Systems in a Nutshell, Delft Academic Press, Delft, The Netherlands, 2019.
- [12] R. Bhagat, M. Davies Wykes, S. Dalziel, P. Linden, Effects of ventilation on the indoor spread of COVID-19, *J. Fluid Mech.* 903 (2020) F1, <https://doi.org/10.1017/jfm.2020.720>.
- [13] G. Liu, M. Xiao, X. Zhang, C. Gal, X. Chen, L. Liu, S. Pan, J. Wu, L. Tang, D. Clements-Croome, A review of air filtration technologies for sustainable and healthy building ventilation, *Sustainable cities and society* 32 (2017) 375–396.
- [14] S.B. Martin, C. Dunn, J.D. Freihaut, W.P. Bahnfleth, J. Lau, A. Nedeljkovic-Davidovic, Ultraviolet Germicidal Irradiation current best practices, *ASHRAE J.* (2008). August 2008: 28–36.
- [15] L. Morawska, G. Johnson, Z. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities, *J. Aerosol Sci.* 40 (2009) 256–269.
- [16] G. Buonanno, L. Morawska, L. Stabile, Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications, *Environ. Int.* 145 (2020) 106112.
- [17] H. Dai, B. Zhao, Association of the infection probability of COVID-19 with ventilation rates in confined spaces, *Build. Simul.* 13 (2020) 1321–1327.

- [18] E.S. Mousavi, K.J.G. Pollit, J. Shermann, R.A. Martinello, Performance analysis of portable HEPA filters and temporary plastic anterooms on the spread of surrogate coronavirus, *Build. Environ.* 183 (2020) 107186.
- [19] R. Wölfel, V.M. Corman, W. Guggemos, M. Seilmaier, S. Zange, M.A. Müller, D. Niemeyer, T.C. Jones, P. Vollmar, C. Rothe, M. Hoelscher, T. Bleicker, S. Brünink, J. Schneider, R. Ehmann, K. Zwirgmaier, C. Drosten, C. Wendtner, Virological assessment of hospitalized patients with COVID-2019, *Nature* 581 (2020) 465–469.
- [20] V. Stadnytskyi, C.E. Bax, A. Bax, P. Anfinrud, The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission, *Proc. Natl. Acad. Sci. Unit. States Am.* 117 (2020) 11875–11877.
- [21] P.M. Bluysen, D. Zhang, M. Ortiz, T. de Reijer, F. Scarano, A Method to Study Airborne Transmission of SARS-CoV-2 by Soap Bubbles (Under Review), 2020.
- [22] J. Bosbach, M. Kühn, C. Wagner, Large scale particle image velocimetry with helium filled soap bubbles, *Exp. Fluid* 46 (2009) 539–547.
- [23] D.E. Faleiros, M. Tuinstra, F. Scarano, A. Sciacchitano, Generation and control of helium-filled soap bubbles for PIV, *Exp. Fluid* 60 (2019) 40.
- [24] P.M. Bluysen, F. van Zeist, S. Kurvers, M. Tenpierik, S. Pont, B. Wolters, L. van Hulst, D. Meertins, The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions, *Intell. Build. Int.* 10 (1) (2018) 5–18, <https://doi.org/10.1080/17508975.2017.1330187>.
- [25] P.M. Bluysen, D. Zhang, D.H. Kim, A. Eijkelenboom, M. Ortiz, First SenseLab studies with primary school children: exposure to different environmental configurations in the Experience room, *Intell. Build. Int.* (2019), <https://doi.org/10.1080/17508975.2019.1661220>.
- [26] K.E. Barrett, S.M. Barman, S. Boitano, H. Brooks, Ganong's Review of Medical Physiology, 24 ed., 2012, p. 619. ISBN 978-0071780032.
- [27] ISO, ISO 7730, Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, 2005. Geneva, Switzerland.
- [28] A.K. Melikov, Z.T. Ai, D.G. Markow, Intermittent occupancy combined with ventilation: an efficient strategy for the reduction of airborne transmission indoors, *Sci. Total Environ.* 744 (2020) 140908.
- [29] CEN, EN 16798-1:2019, Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics - Module M1-6, CEN-CENELEC, Brussels, Belgium, 2019.
- [30] N.L. Agentschap, Requirements specifications for fresh schools, in: Dutch: Programma Van Eisen Frisse Scholen) Publication Number 2EGOU1203, 2012. Utrecht, The Netherlands.
- [31] C.H. Hansen, Chapter 1: fundamentals of acoustics, in: B. Goelzer, H. Hansen, G. A. Sehnrdt (Eds.), Occupational Exposure to Noise: Evaluation, Prevention and Control, World Health Organization, Geneva, Switzerland, 2001.
- [32] Dutch building decree, online Dutch building decree (in Dutch: Online Bouwbesluit) (www.onlinebouwbesluit.nl).
- [33] ASHRAE, ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy, 2017. Atlanta, USA.
- [34] G.C.A. Caridi, D. Ragni, A. Sciacchitano, F. Scarano, HFSS-seeding for large-scale tomographic PIV in wind tunnels, *Exp. Fluid* 57 (2016) 190.
- [35] D. Lucina, J. Pantelic, A. Melikov, C. Sekhar, K.W. Tham, Experimental investigation of the human convective boundary layer in a quiescent indoor environment, *Build. Environ.* 75 (2014) 79–91.