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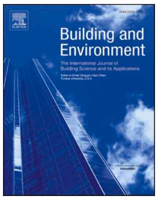

Personalized environmental control systems (PECS): A systematic review of performance evaluation methods for thermal comfort, air quality and energy

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ABSTRACT

Personalized Environmental Control Systems (PECS) can improve both comfort and energy efficiency by shifting indoor climate control toward localized, occupant-tailored comfort, unlike conventional systems that condition entire, partly unoccupied spaces uniformly. . Despite their potential, the absence of standardized assessment and reporting methods, and the diversified PECS technical specifics hinder consistent performance evaluation practices. Conducted in the framework of IEA EBC's Annex 87, this review, based on the PRISMA statement, provides a comprehensive overview of existing methods and indicators used to evaluate the performance of PECS, specifically targeting thermal and air quality domains. A novel three-layered classification approach was applied to categorize PECS types, and reviewed studies were grouped into four methodological categories: building simulation, CFD, chamber, and field studies. The review identifies methods' usage trends, benefits, and limitations. Among 302 reviewed papers, more than half (61 %) adopt controlled laboratory tests, while CFD is the most used simulation method (68.6 % of simulation studies). Field studies are a minority, highlighting the limited implementation of PECS in real-world scenarios. Simulations are cost effective in rapidly prototyping and developing PECS. However, the insights they provide into PECS performance are limited by either model resolution constraints or high complexity. Comfort evaluations do not consider individual occupant differences nor behavior inherent to PECS. It is through experiments that knowledge can be gained on realistic occupant responses. However, they can be resource intensive and require careful planning. This review provides best practice guidelines to assist researchers in improving quality reporting of their methods.

Nomenclature and abbreviations

ACE	air change effectiveness (-)
ADI	air distribution index (-)
AQI	air quality index (-)
AT	air treatment
ATT	air turnover time (s)
BS	building simulations
BZ	breathing zone
C	concentration (ppm or µg/m3)
CF	cumulated frequency
CFD	computational fluid dynamics
CI	confinement index (-)
CP	corrective power
CRE	contaminant removal effectiveness (-)
CS	chamber studies
CTM	computational thermal manikin
ΔC	concentration asymmetry (µg/m3)
DFr	deposition fraction (-)
DR	draft rate (-)
ER	exposure reduction (-)
FS	field studies
HVAC	heating ventilation and air conditioning
IAQ	indoor air quality
IEQ	indoor environmental quality
IEA EBC	International Energy Agency's Energy in Buildings and Communities Programme
iF	intake fraction
KPI	key performance indicator
m	mass of pollutant (kg)
MAA	mean age of air (s)
N_{AQ}	air quality number (-)
N_{TC}	thermal comfort number (-)
OACE	occupied air change effectiveness (-)
OAS	outdoor air supply
$\dot{Q}$	mass flow rate (kg/s)
PAQ	perceived air quality
PECS	personalized environmental control systems
PEE	personal exposure effectiveness
PER	personal exposure reduction
PD	percentage of dissatisfied (%)
PM	particulate matter
PPD	percentage of people dissatisfied (%)
PV	personalized ventilation
RA	room air
t	time (s)
T	temperature (°C)
TAV	thermal acceptability vote
TCV	thermal comfort vote
TRL	technological readiness level
TSV	thermal sensation vote
u	velocity (m/s)
V	volume (m3)
$\dot{V}$	volumetric flow rate (m3/s)
VAS	visual analog scale
VE	ventilation effectiveness (-)

Greek symbols

ε	effectiveness
τ	mean age of air (s)
ρ	density (kg/m3)

Subscripts

a	air
AQ	air quality
i	reference point
m	modified
n	normalized
micro	microclimate
p	pollutant
TC	thermal comfort
v	ventilation

1. Introduction

Unlike conventional building systems that condition entire indoor spaces, Personalized Environmental Control Systems (PECS) deliver tailored conditions near occupants based on individual needs [1]. By enabling user individualized control over environmental parameters - such as temperature, airflow, lighting, and sometimes even acoustics PECS can enhance occupant comfort, productivity, and well-being while also reducing overall energy consumption by avoiding over-conditioning in unoccupied areas. Although PECS can address all comfort domains, research has primarily focused on thermal comfort and air quality to reduce HVAC energy use; this paper uses PECS to refer specifically to these two domains.

Despite their promising benefits, PECS are still rarely implemented in buildings. This limited adoption suggests a potential gap in technological readiness and the lack of guidelines for developing and testing the effectiveness of proposed systems. Indeed, any developing field needs standardized performance evaluation methods and metrics to differentiate approaches, systems, or products for their usefulness in achieving their goals. This is especially important when the field spans diverse contexts, as for the PECS case that operates under varied indoor conditions, must accounts for occupant acceptance, and address targeted energy performance. Performance evaluation methods for systems targeting individual environmental well-being through localized conditioning range from simulations, useful for exploring system potential during the design phase, to experiments, which validate expected outcomes, particularly in terms of occupants' responses.

Building energy simulations or building simulations (BS) has contributed to the design and operation of high-performance buildings, and the formulation of policies aimed at achieving energy and carbon emission goals [2], through supporting energy-efficient designs [3], operations [4], and retrofits [5]. BS uses models to represent a building's features, operations, controls, and systems. They calculate energy flows, airflows, consumption, thermal comfort, and other Indoor Environmental Quality (IEQ) metrics, capturing the dynamic interactions between occupants, building systems, HVAC, and environmental conditions. With technology advancements, BS have become a powerful tool used in practice for standardization [6] and legislation (EPBD [7]). Moreover, initiatives for validating BS [8] played a crucial role in guaranteeing software reliability and regulatory compliance (ASHRAE 140:2023 [9]). Originally, BS have been conceptualized for buildings integrating total volume systems [10] assuming a single node value for environmental parameters per zone (like those in EnergyPlus or TRNSYS), which may lack spatial detail. Often called building energy modelling (BEM), building energy simulation (BES) or dynamic thermal modelling (DTM), whole building simulations have been conceived primarily for energy predictions over a long period of time such as season or a year. They provide also thermal comfort and IAQ indications at zone level, and might include airflow networks to consider air flow from zone to zone. However, the spatial resolution achievable with such simulations is significantly less accurate than what CFD can provide, and hence unsutable for studying PECS local effects.

Computational Fluid Dynamics (CFD) simulations have emerged as a vital tool in assessing and optimizing the performance of HVAC [11]. CFD is a subset of BS, but it serves a specialized role within that broader domain and is therefore presented separately. CFD solves detailed fluid flow and heat transfer equations to analyse airflow, temperature and contaminant distribution in space and time [12]is used for a micro-environmental scale analyses of PECS, to which simpler models (e.g., zone-based airflow) are often insufficient. This granularity offers deeper insights than BS, helping designers optimize HVAC layouts, diffuser placement, occupant comfort and energy use [13]. As computing power advances, CFD is becoming increasingly accessible, supported by integrated platforms and user-friendly interfaces [14]. Furthermore, evolving efforts to validate CFD models against standardized experiments [15] have been essential in improving model reliability and fostering wider acceptance in practice and guidelines (ISO 7730 [16]).

Chamber studies (CS) serve as a fundamental experimental method for evaluating system performance and assessing IEQ under controlled, repeatable conditions [17]. These tests are conducted in specialized rooms where key environmental variables—such as air temperature, humidity, concentration—can be precisely regulated and monitored to simulate real-world scenarios. They provide reliable settings for validating models, testing new systems and studying occupant responses. CS also play a pivotal role in developing comfort standards, HVAC control strategies, and new technologies, contributing to the formulation of design guidelines and performance benchmarks in standards such as ASHRAE 55 [18] and ISO 7730 [16]. CS remain indispensable for bridging gaps between simulations and real-world application.

Field studies (FS) provide essential real-world insights into the performance of HVAC systems and IEQ, complementing CS and simulations [19]. Conducted in buildings under normal operating conditions, these studies evaluate thermal comfort, air quality, energy use, and occupant satisfaction across different seasons and usage patterns [20]. FS capture the complex and unpredictable interactions between buildings and occupants [21], uncovering gaps between design intent and real-world operation [22]. Field data also serve as critical evidence for updating building codes and developing comfort models such as the adaptive model in ASHRAE 55 [18] and EN 16,798–1 [23].

In adopting these methods for performance evaluation of PECS, challenges arise due to the absence of standardized methodologies making it difficult to draw meaningful comparisons or synthesize findings as also discussed in [24], with particular emphasis on the energy performance of PECS for heating, cooling, and ventilation. Moreover, there is difficulty categorizing the wide spectrum of available solutions. This questions the feasibility of applying a single, unified standard across all PECS types. Rather than aiming for a one-size-fits-all protocol, assessment procedures tailored to specific categories, guided by a structured classification framework could constitute a better approach, accelerating the market diffusion of PECS.

Previous literature reviews on PECS have primarily focused on the definition of technical design principles [25,26], typically targeting specific PECS types such as personalized ventilation [27–30] or thermal chairs [31], related control strategies [32,33], often linked to the development of Personal Comfort Models [27–29] or achievable benefits, particularly in terms of environmental comfort and energy savings [1,34–36]. The only review focusing on methods of evaluating PECS was a review of CFD methods for the evaluation of PECS in 2019 [37]. However, the scope was limited to personalized ventilation without a comprehensive review of the methods to assess comfort, IAQ and energy use and associated key performance indicators. Among existing PECS reviews, this is the first to offer a comprehensive three-layered categorization and a critical examination of both simulation and experimental methods for implementation and performance evaluation—covering thermal comfort, indoor air quality (IAQ), and energy use—while identifying emerging trends. Advantages and limitations are discussed to finally provide recommendations for structured PECS performance assessment and reporting. This includes identifying best practices to guide users in tailoring methodologies to maximize the accuracy and relevance of outcomes.

2. Review methodology

This review was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [38], designed to help reviewers enhance the quality of reporting in systematic reviews and meta-analyses. The statement features a checklist and a flow diagram delineating a standardized four-step process: Identification, Screening, Eligibility, and Inclusion, for identifying, assessing and including sources.

2.1. Literature search

An extensive literature search was conducted between September 2023 and January 2024 for papers published between 1990 and 2023, using Google Scholar, Web of Science, Science Direct, Pub Med, Scopus, and ResearchGate, and combinations of the following keywords describing three levels: (i) the general background environment: “built environment”, “indoor environment”, “occupant”, “human”, “user”, “system”, “HVAC”, (ii) the PECS environment: “personal”, “personalized”, “individual”, “micro”, “local”, “centric”, “portable”, and (iii) the different performance evaluation methods: “simulations”, “computational fluid dynamics”, “chamber studies”, “lab studies”, “field studies”, “experiment”. The searches were systematically conducted by combining the keywords and using the Boolean operators “AND” and “OR” to produce the most relevant studies. Moreover, search results were checked for review articles. Peer-reviewed papers published after January 2024 until 2025 were added manually at a later stage during the review process.

2.2. Selection criteria

The search resulted in an extensive number of potential publications. The selection is shown in Fig. 1. First, studies in non-English text or unavailable full text if any, duplicates, and studies with no PECS were excluded. To limit the scope of this review, PECS of interest were systems that could be integrated into the furniture or the building envelope under typical moderate conditions and designed for healthy individuals conducting typical indoor activities. Based on this, the following studies were excluded:

- wearables like active or passive textiles, protective equipment tested under extreme indoor or outdoor conditions (i.e., extreme heat, cold, fire).
- PECS designed for disabled individuals whose thermoregulation differs from able-bodied people.
- special environments requiring strict temperature and IAQ control (i.e., cleanrooms, operation facilities).

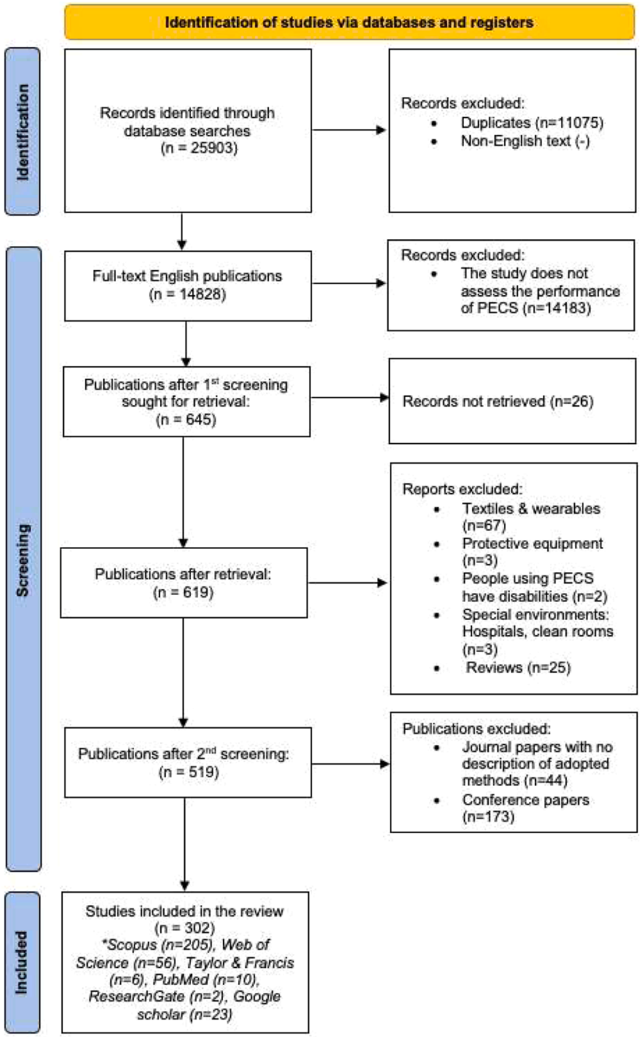


Fig. 1. Flow chart showing the search and selection process of publications.

Studies on the performance of PECS integrated in non-building environments, e.g., vehicular or aircraft cabins, were included to cover assessment solutions that may be adapted in buildings.

From the remaining publications’ pool, a quality assessment was conducted to eliminate peer-reviewed journal and conference papers whose methodology was not clearly presented (i.e., completely or partially missing methodology section focusing only on results of the work).

2.3. Study classification according to PECS evaluation methods

From the final pool of selected papers, studies were classified depending on the adopted evaluation method(s): a) Building Simulations (BS), b) Computational Fluid Dynamics (CFD), c) Chamber or Lab Studies (CS), and d) Field Studies (FS) and relevant methodological elements were extracted. If a study adopted more than one method, it was included in multiple categories. Within each method, two classes “main” and “supporting” were defined. A method is “main” if the study conclusions regarding thermal comfort and/or IAQ performance of PECS were reached using this method. A method was “supporting” if it indirectly assisted another main method in reaching its conclusions regarding PECS. Different methods can have different supporting roles. The purpose of this classification is to provide an overview of the current state of the art regarding existing simulation and experimental methods used to evaluate the performance of various types of PECS. The analysis focused on the specific characteristics of each method and differences among studies that assess PECS performance using the same approach are pointed out considering different purposes of reviewed studies.

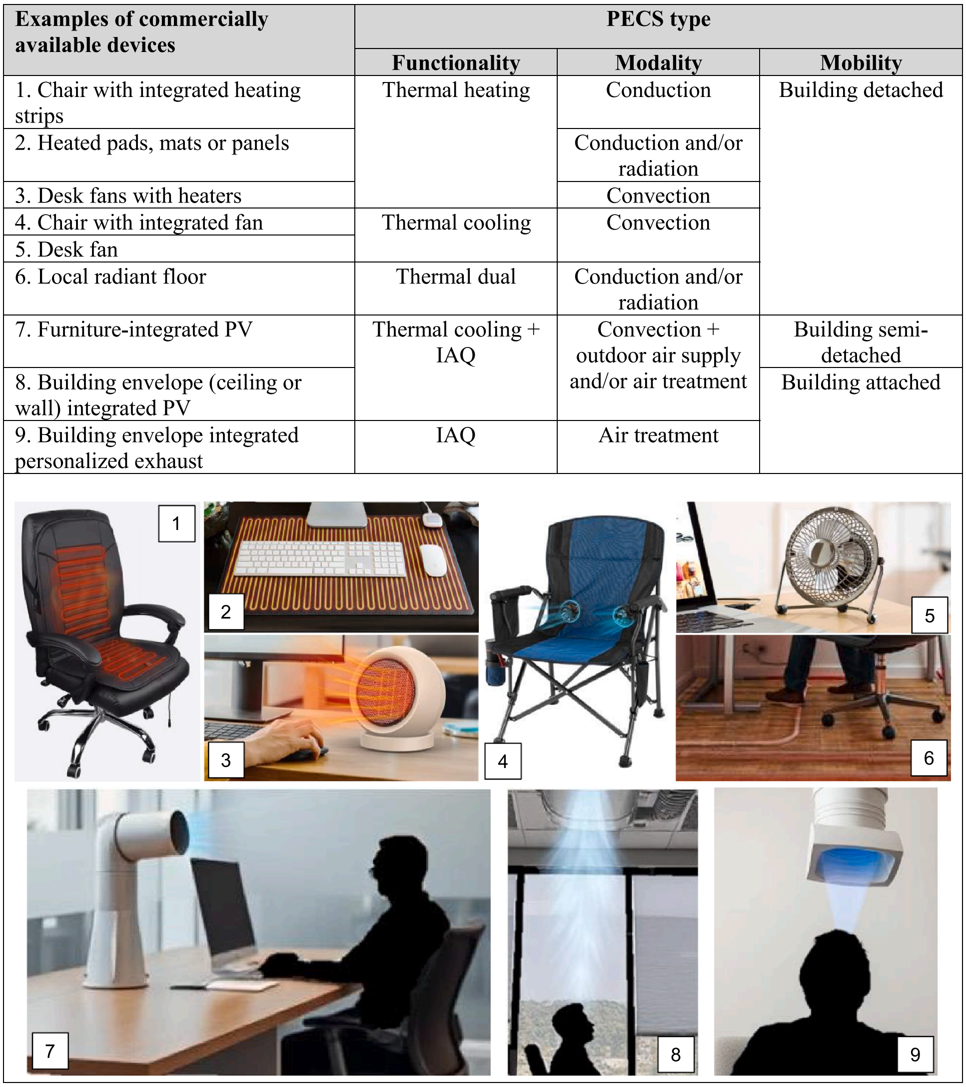
2.4. PECS classification according to their functionality, modality, and mobility

PECS can be classified in a variety of ways, including heat transfer modes or subjective responses [1]. In this review, PECS were classified into types depending on their functionality, modality, and mobility. Table 1 showcases a selection of common PECS devices in the literature, classified according to the above terminology.

- Functionality refers to IEQ domains manipulated by PECS and it recognizes three categories: thermal, IAQ and thermal+IAQ PECS. Thermal management refers to the ability of PECS to manage the body’s heat fluxes for: (i) thermal heating, (ii) thermal cooling, or (iii) dual (able to provide both).
- IAQ management refers to the ability of the PECS to manipulate occupants’ inhaled air quality by controlling the contaminants’ concentrations. It refers strictly to objective IAQ and not subjective perception.
- Modality refers to delivery mode. Thermal management can be delivered through different heat transfer modes: conduction, convection, radiation, evaporation. IAQ can be managed by diluting the concentration of contaminants in the inhaled air through outdoor air supply (OAS) or through inhaled air treatment (AT) (e.g., filtration, exhaust, ultraviolet germicidal irradiation).

Table 1
Examples and illustrations of common PECS devices and their associated types.

Examples of commercially available devices	PECS type		
	Functionality	Modality	Mobility
1. Chair with integrated heating strips	Thermal heating	Conduction	Building detached
2. Heated pads, mats or panels		Conduction and/or radiation	
3. Desk fans with heaters		Convection	
4. Chair with integrated fan	Thermal cooling	Convection	
5. Desk fan			
6. Local radiant floor	Thermal dual	Conduction and/or radiation	
7. Furniture-integrated PV	Thermal cooling + IAQ	Convection + outdoor air supply and/or air treatment	Building semi-detached
8. Building envelope (ceiling or wall) integrated PV			Building attached
9. Building envelope integrated personalized exhaust	IAQ	Air treatment	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- Mobility refers to positioning of PECS with respect to the building and its spatial degrees of freedom. Four categories were defined: (i) building detached, (ii) building semi-detached, (iii) building attached, and (iv) other (vehicles, aircrafts). Building detached PECS refer to devices that are completely independent from the building permanent infrastructure (envelope or background system). They are portable devices with full degrees of freedom and can be placed anywhere. They become operational by plugging them into a power source or can be battery-operated. Building semi-detached PECS are attached to the building's permanent infrastructure (permanent furniture, envelope, other systems) but allow for some degree of freedom within certain planes of motion. They cannot be easily moved around. Building attached PECS are stationary PECS fully attached to the building's infrastructure with little to no degree of freedom.

After classifying studies, different methodological elements were extracted. With BS and CFD, information regarding PECS integration into the computational domain, assumptions, boundary conditions, and extensiveness of experimental validation were extracted. With CS and FS, information regarding the protocol, measurement set-up, including designed exposure conditions with both humans and manikins, was extracted. For all methods, thermal comfort, IAQ and energy use assessment procedures and most adopted key performance indicators (KPIs) were extracted.

3. Results: PECS evaluation methods

3.1. Overview of selected studies

Fig. 2 shows the distribution of studies into each method further classified into main or supporting. CS was the most prevalent method in the literature to evaluate PECS, followed by CFD, BS, and FS. Most methods were used as “main” methods for PECS evaluation. 16.6 % of BS studies were supporting methods, used to assess the year-round energy consumption of PECS with other methods (namely FS). 4 % of CFD studies were supporting methods to inform PECS design for CS evaluation. 30 % of CS and 24 % of FS were used as supporting methods to validate CFD models or to inform boundary conditions of BS.

Fig. 3 showcases Sankey diagrams detailing the type of PECS investigated via simulations. Most of the thermal functions were either heating or cooling, with limited PECS offering both (dual). In terms of IAQ management, most PECS provided outdoor air treated e.g., with filters or ultraviolet germicidal irradiation (IAQ outdoor air supply (OAS) & air treatment (AT)). A small portion implemented a personalized exhaust instead of supplying outdoor air (IAQ AT). Notably, BS never addressed IAQ only PECS, focusing almost exclusively on thermal PECS. CFD studies showed the opposite trend, with just 23 % focusing solely on thermal aspects. An expected outcome considering the simulation capabilities of the two approaches.

Fig. 4 showcases Sankey diagrams detailing the types of PECS investigated via experiments. For both CS and FS, building detached PECS studies dominated, suggesting two different considerations about PECS technological development and implementation feasibility. Indeed, CS uses laboratory facilities not specifically designed for PECS investigation, requiring flexibility in the study setup. Temporary systems that are easy to install and remove are preferred, explaining the dominance of detached PECS due to their convenience in experimental setting. Conversely, FS are conducted in real buildings and building-attached PECS require integration into the building structure, either at the design stage or through major renovations. The small number of such cases suggests a low technological readiness level and limited commercial availability of the PECS building-attached solutions. Among building detached PECS, convection was the most common mode of heat transfer for cooling in both methods. In FS, convection was the only mode of heat transfer tested for cooling. On the contrary, PECS based on conduction and radiation or the combination of the two were most reported for heating in both methods. Building detached PECS capable of both heating and cooling were a minority and only tested in CS, suggesting that these are devices still in development and testing phase. Building semi-detached and attached PECS were mainly convective devices, both in CS and FS, as most of them were PV systems and ceiling mounted air terminal devices. For IAQ PECS, OAS was the most common. Studies explicitly mentioning AT of the outdoor air supply were scarce. The trend in IAQ management types was similar among CS and FS. Figs. A1 and A2 in the appendix show a chronological evolution and discussion of methods’ usage over the years for different types of PECS.

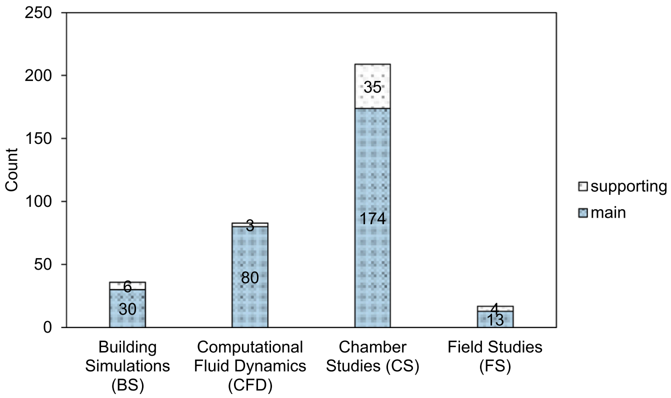


Fig. 2. Distribution of studies into main and supporting according to different evaluation methods.

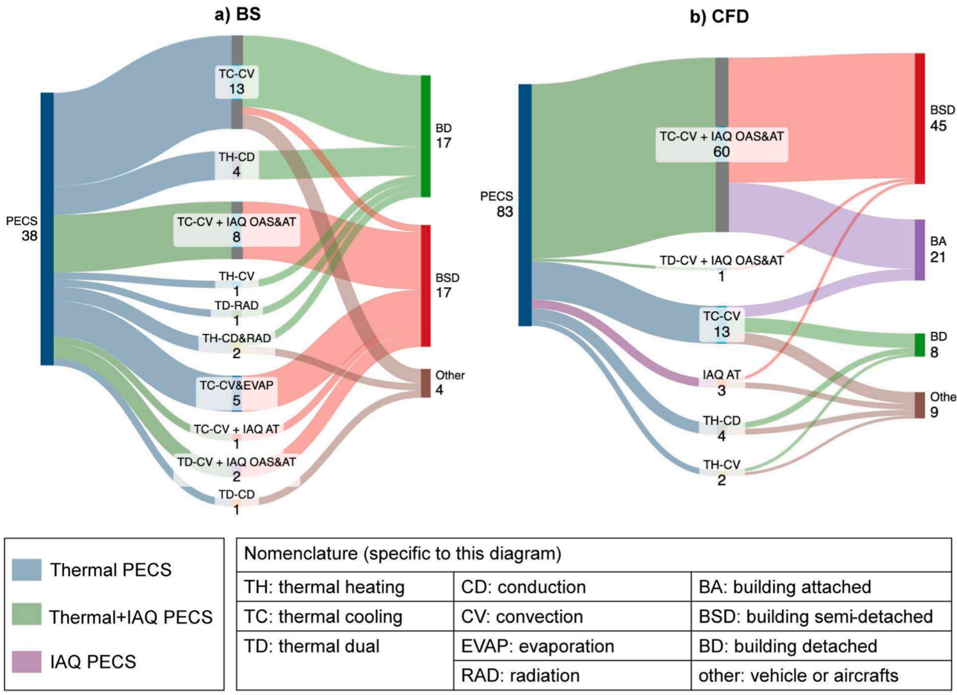
3.2. Building simulation studies

Out of 30 instances where BS was used as main method, 18 studies used only BS for the PECS evaluation, 5 studies used CS and FS to inform BS modeling inputs (i.e., occupancy patterns, usage patterns of PECS by occupants). 1 study additionally used CFD to gain more insight into the body segments of a 3D thermal manikin most affected by PECS. Out of 6 instances where BS was a supporting method, it was used to assess the PECS energy performance.

3.2.1. PECS modeling and integration in simulations

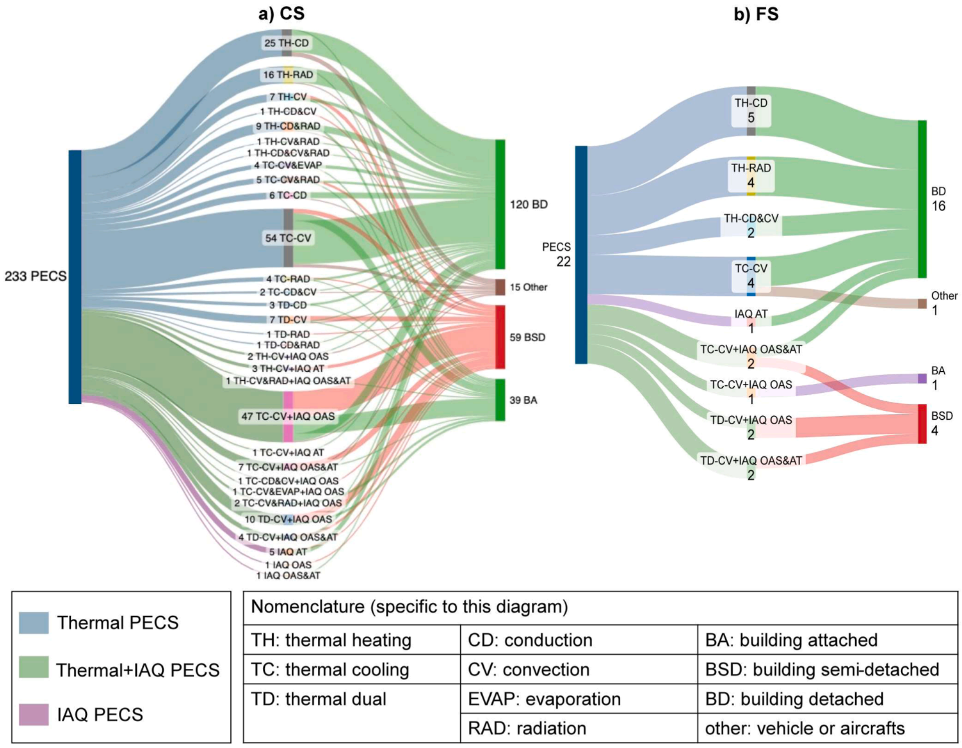
Three different approaches were identified to integrate PECS into BS: **direct, collaborative,** and **custom**. Fig. 5 illustrates the different types of BS tools used to simulate each type of PECS. “Own code” corresponds to custom approaches while the rest are commercial tools (e.g., Modelica, EnergyPlus) used in direct and collaborative methods. Table 2a gives an overview of the PECS integration methods in energy simulation studies and Table 2b shows the reviewed BS studies and their corresponding integration and assessment approaches:

- **Direct integration (6 studies)**, the PECS geometry and its related variables (e.g., usage and operation schedules, operating conditions such as surface temperature, input power, supply temperature or flow rates) are directly modelled into the tools’ computational domain. While this method should be the most efficient method as it allows the modeler to work within a single computational domain, its level of spatial granularity is limited. Moreover, the PECS time response is much smaller than the background system and this often cannot be captured using commercial tools. This often leads to assumptions such as ignoring the interaction between the PECS and the background or considering PECS supply conditions as the ones reaching the occupant without decay. This method was applied to building detached thermal conduction- based PECS [31,39] and to building semi-detached thermal (dual convection) + IAQ outdoor air supply (OAS) PECS [40]. Shahzad et al [31,39]. integrated multiple chairs into the office using IES-VE simulation tool. The integration was straightforward, requiring a single power input. IES-VE allowed for some spatial variation prediction of thermal fields, which the authors used to analyze the impact of PECS in their surroundings (exact locations unspecified). However, the robustness of these predictions were not validated. Lipczynska et al [40]. integrated personalized ventilation (PV) directly into IDA-ICE by modeling its own air handling unit. While current IDA-ICE versions allow predictions of spatial variations in the thermal fields like IES-VE, these features were available at the time of this publication and thus were not tested. PV interaction with the background was ignored as it could not be modeled as this level of resolution.
- **Collaborative approach (13 studies)**: Only the building thermal zones, associated internal gains, the background HVAC and energy systems are modeled in the simulation tool itself. The PECS geometry and related variables (e.g., usage and operation schedules, operating conditions such as surface temperature, input power, supply temperature or flow rates, rejected heat if applicable) are not directly integrated or modeled in the tool. However, its impact on occupants’ microenvironment (reducing or increasing temperatures, near-occupant velocities) is coupled externally to the BS tool as a boundary condition. Depending on the PECS type, its impact on the targeted human segment is either assumed, determined through measurements of environmental change (velocity or temperature), or continuously controlled to offset a thermal discomfort threshold under relaxed background conditions. Subsequently, the boundaries impacted by PECS and the background system are taken as input into



*diagrams refer to the number of PECS found in the reviewed studies

Fig. 3. Sankey diagram illustrating the different PECS types for a) BS, b) CFD methods.



*diagrams refer to the number of PECS found in the reviewed studies

Fig. 4. Sankey diagram illustrating the different PECS types for a) CS and b) FS methods.

a thermophysiological model to predict occupants' thermal response. This approach was used for thermal heating, cooling building detached PECS and thermal cooling + IAQ (OAS and air treatment (AT)) building semi-detached PECS [41]. Boudier et al [42]. integrated the software Esp-r with the "PhySCo" thermophysiological model [43–46] and the sensation and comfort models developed by Zhang et al [47,48]. Three types of PECS were simulated, namely a heating and cooling chair, desk fan, and a thermoelectric-movable wall. For example, the chair's seat temperature was adjusted by ±4 K for heating or cooling, based on measurements. The adjusted temperatures were included in each body part's equivalent temperature, serving as boundary conditions for

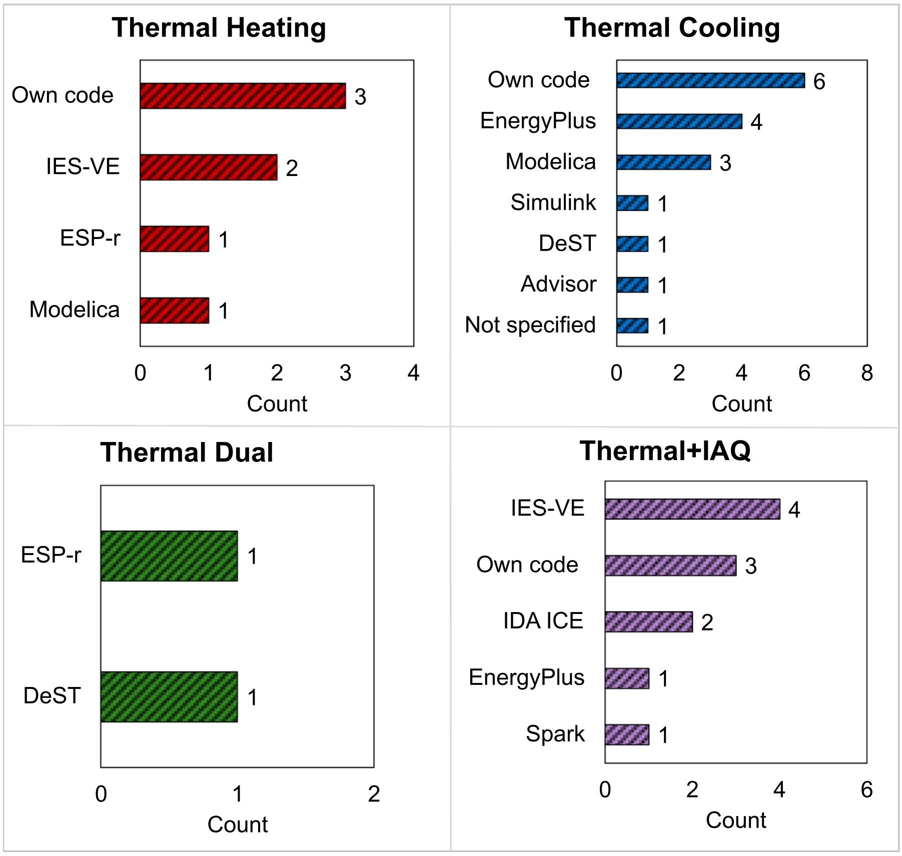


Fig. 5. BS tools used in the literature per PECS type.

Table 2a
Overview of PECS integration methods in BS.

Integration	Ease of application*	Use of commercial software	Potential for spatial and temporal granularity**	PECS coupling strategy	Advantages/Limitations
Direct	High	Yes	Low	Boundary within software	Convenient and straightforward. It allows for fast assessment with some loss in accuracy
Collaborative	Medium	Yes	Medium	External boundary assumed outside software	It requires coupling work, but still allows for fast and better assessments than direct methods
Custom	Low	No	High	Boundary within code	Flexible and most accurate among the three. It requires most work to setup

[*] Effort made by modeler to setup model *(High: Requires minimal work, Medium: Requires some work, Low: Requires a lot of work)*.

[**] Ability to capture spatial variations in indoor parameters due to PECS and their small response time compared to background system *(Low: limited potential, software dependent, Medium: some potential depending on PECS modeling related assumptions, High: allows for "CFD-like" granularity depending on level of model discretization and overall modeling related assumptions)*.

the PhySCo model. They excluded interactions between the PECS and the background. Another coupling method modeled PECS using a performance curve linking power use to increased thermal sensation. This was done in [49] to assess the performance of a building detached, thermal heating conduction PECS in EnergyPlus. PECS was assumed to compensate negative values of predicted mean vote (PMV). PECS energy use for the desired thermal sensation was converted to energy use per floor area based on occupancy, with heat output released into the zone.

- **Custom code (17 studies):** BS commercial tools as shown in Fig. 5 (i.e., IES-VE, IDA-ICE, Modelica) are not used. Authors develop their own code using their preferred programming language. A state space model of the building thermal zones is developed including the internal gains and dynamic effects (solar gains, weather) and the supply conditions of the background HVAC systems. The state space model includes additionally a nestled thermal zone for the PECS. The nestled zone can interact with the background state space model through solving the heat and mass transfer equations.

Custom codes are characterized by varying levels of modeling complexity and spatial granularity depending on the level to which the different state space models (background and PECS) are discretized. This makes them distinct from direct integration methods. Jain et al [50]. studied the performance of a building detached, thermal heating, convection PECS (i.e., SPOT). They developed a custom lightweight C/C++ open-source thermal simulator "ThermalSim". It includes a thermal model with two fully mixed regions with homogenous temperature —an occupied area with integrated PECS and an unoccupied area—separated by a thin imaginary air layer. Authors calculate room temperature due to the impact of the background HVAC, heat exchange with outside, and heating/cooling loads. The change in temperature due to coupling PECS+occupant is considered separately. The temperature in the occupied area is then calculated as the sum of the room temperature due to

Table 2b
Evaluation methods of PECS performance by different studies in the literature using BS.

Ref.	Device	Integration	Performance aspects, KPIs		
			Thermal comfort	IAQ	Energy
Thermal heating, building detached					
[31, 39]	thermal chair	direct	PMV-PPD[a]	-	heating load
[42]		collaborative	coupling of PhySCo thermo-physiological and Zhang's sensation/ comfort model		heating, cooling load, HVAC energy use
[69]			coupling of Zhang's thermo-physiological and sensation/ comfort model (9 pt scale)		operational energy use, primary energy use, environmental impact
[71]			via experiments		HVAC energy use[b] and operation duration
[72]		custom			HVAC energy use
[73]			heat transfer at body seat interface, energy flux required for thermal equilibrium		PECS energy use
[49]	foot heaters (mats, pads)	collaborative	PMV	-	thermal energy provided to space
[72]		custom	via experiments	-	HVAC energy use
[49]	heated desk	collaborative	PMV	-	thermal energy provided to space
[42]	thermo-electric movable wall	collaborative	coupling of PhySCo thermo-physiological and Zhang's sensation/ comfort model	-	heating, cooling load, HVAC energy use
[50]	convective heating device (desk)	custom	PMV	-	HVAC energy use
[74]	local radiant heater	custom	coupling of Tanabe thermo-physiological and Zhang's sensation/ comfort model (9 pt scale)	-	-
Thermal cooling, building detached					
[71]	desk fan	collaborative	Via experiments	-	HVAC energy use and operation duration
[69]			coupling of Zhang's thermo-physiological and sensation/ comfort model (9 pt scale)	-	operational energy use, primary energy use, environmental impact
[42]			coupling of PhySCo thermo-physiological and Zhang's sensation/ comfort model	-	heating, cooling load, HVAC energy use
[62]			adaptive comfort model	-	cooling load, HVAC energy use
[54]		custom	PMV	-	HVAC energy use
[52]				-	operational energy use
Thermal cooling, building semi-detached					
[63,38,39, 75]	fan with evaporative cooling	custom	coupling of AUB thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale)	-	HVAC energy use
Thermal cooling, other					
[76]	Ventilated seat	custom	coupling of Zhang's thermo-physiological and sensation/ comfort model (9 pt scale)	-	HVAC energy use, fuel consumption in vehicle
Thermal dual, building detached					
[55]	Localized radiant wall	custom	PMV-PPD	-	HVAC energy use (PECS only)
Thermal cooling/dual + IAQ (OAS & AT) building semi-detached					
[40]	PV	direct	PMV and RH levels	indirect	HVAC and operational energy use
[57]			PMV-PPD		HVAC energy use
[65]			other (CF or Degree.hours)		heating, cooling load
[66]			other (temperature fluctuation within acceptable comfort standards)		HVAC energy use
[67]		collaborative	via experiments		cooling load, HVAC energy use
[41]			coupling of AUB thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale)		HVAC energy use
[15]		custom	coupling of AUB thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale)	direct (ventilation effectiveness)	cooling capacity of PECS
[77]				-	HVAC energy use
[28]			other (regression 9 pt scale TCV)	indirect	HVAC energy use
[78]					cooling load
[64]			other (inhaled air temperature variation within acceptable comfort standards & RH)	Direct (CO_2 and water vapor removal rate)	HVAC energy use

[a] PMV range of −0.5 to 0.5 and three comfort categories (A, B and C) from ISO 7730 were used.
[b] includes PECS when simulated.

HVAC and the change in temperature in occupied area due to PECS. The temperature in unoccupied areas is calculated as sum of room temperature due to HVAC and heat exchange between unoccupied and occupied areas. The physics of the convective PECS jet (entrainment of background room air) were not modeled. The latter was considered in [51] to assess PV performance in a stratified environment. The authors developed their own MATLAB code specifying different heat/pollution sources. They discretized the space, plumes and PV jet into layers and interlayer heat and mass exchange was considered. The jet layers mixed with exhaled air at the breathing zone (BZ). The authors did not detail the building envelope and ignored outdoor weather fluctuations.

For all three integration methods, modeling assumptions, inputs and validation need to be discussed. Occupancy schedules were either assumed from standards or extracted from experiments or using machine learning. If collaborative or custom approaches were used, often uniform conditions of temperature and IAQ were considered in the background and only local PECS effects on occupants or in their micro-environment were modeled. If a direct integration was used, BS tools can consider heterogeneity to some level of accuracy.

When it comes to validating models, out of 30 studies, 16 studies do not validate or do not mention any validation. Remaining studies that mention it mostly validate their model for heating, cooling energy demand [31,39] or room temperature during heating or cooling seasons however, without PECS and only one [51] validated for the evaluation with height of temperature and/or IAQ with PECS at different operating conditions (jet frequency) in the background macroclimate and in the occupant's thermal plume which included the breathing zone. This was done only for a custom code approach where a finer granularity in PECS integration and its impact on the background was modeled. This allowed for more detailed spatial validation in different parts of the space influenced by PECS. Thus, the accuracy of direct, collaborative and custom codes having lower spatial resolutions and their assumptions regarding PECS still needs to be confirmed through detailed experimental validation to mitigate the risk of misleading conclusions regarding PECS performance.

3.2.2. Thermal comfort assessment

PMV-PPD: Shahzad et al [31,39]. assessed PMV and PPD indices from Fanger model near the heated chair. Two benchmark cases were used for comparison with the PECS. One case was at a standard heating setpoint of 22 °C without PECS, the other was at reduced setpoint of 20 °C with PECS. Jain et al [50]. calculated the PMV in the occupied zone and evaluated the percentage of time it fell outside the comfort range. Xu et al [52]. calculated the standard effective temperature (SET) using Gagge et al's two-node model [53]. To recalculate SET, elevated air speed was replaced with still air at 0.2 m/s, while indoor air and radiant temperatures were adjusted to reflect the cooling effect. Using these adjusted temperatures, PMV was calculated with a simplified linearized model. Other studies using PMV-PPD are [40,54,55–57]. With PMV-PPD, calculation and inputs are often not explicitly given, limiting reproducibility.

Coupling models with thermo-physiological and sensation/comfort models predicting the thermal response of occupants due to PECS usage. The latter is taken as input to calculate local and/or overall sensation and comfort. This was a common approach (Table 2). Thermo-physiological models used by order of frequency are the AUB model [58,59], Zhang's model [33], and Tanabe (JOS)'s models [60,61] and the sensation and comfort models are always Zhang's models on a 9 pt scale (also known as the UCB model [35]). The UCB sensation model ranges from −4 (very cold) to +4 (very warm) and the comfort model ranges from −4 (very uncomfortable) to +4 (very comfortable). The coupling procedure was well laid out in literature (e.g [51]).,

Adaptive comfort model: In Castro et al [62], thermal comfort was assessed using ASHRAE 55′s adaptive comfort model. The comfort threshold was extended to 30 °C with personal fans, providing local cooling as a corrective measure. To quantify thermal comfort, the study utilized both percentage of acceptable comfort hours and probability of overheating, defined as hours exceeding 1 °C above the adaptive comfort zone. The comfort model inputs include adaptive comfort limits based on each city's outdoor conditions and indoor operative temperatures at varying setpoints (24 °C-30 °C).

Other methods: In [63], thermal comfort was assessed by developing and experimentally validating a multivariable regression model that correlates thermal comfort with occupant facial temperature and its rate of change and indoor conditions. The adopted thermal comfort range, based on Zhang's comfort scale, targets values between 0–1, enabling the controller to maintain thermal comfort with minimal occupant intervention. Harrouz et al [64]. used primary air temperature (targeted at 24 °C for optimal comfort) and velocity, with these factors dynamically adjusted to maintain consistent cooling in the BZ. In [65], thermal comfort was evaluated using Cumulated Frequency (CF), representing the degree-hours of discomfort when indoor temperatures exceeded a reference value (28 °C for classical ventilation, 30 °C for PV).

Fig. A3 in the appendix illustrates KPIs and metrics used to assess thermal comfort for PECS in BS.

3.2.3. IAQ assessment

Concerning IAQ assessment, two distinct groups of papers were recognized depending on the implemented approach linked to specific and different scopes. The following two classes were defined:

- C1: studies adopting an indirect assessment approach that does not evaluate any effect of PECS usage on the occupants or the environment but monitors the suitability of PECS supply conditions (ventilation rate). In [65,41,66] and [67], IAQ was indirectly evaluated by PV system's provision of 100 % OAS directly to occupants, effectively reducing reliance on recirculated air and limiting potential exposure to indoor pollutants. Sekhar & Zheng [57] outlined methods to ensure high IAQ using a dedicated outdoor air system with PV. It supplied 15 L/s.person of fresh air, exceeding ASHRAE 62.1:2022 [68] and Singaporean standards, with MERV >6 filters. Dehumidification maintained indoor RH between 55 and 65 %, suitable for hot and humid climates. The PECS conditioned air was delivered directly to occupant BZs at velocities >0.3 m/s, effectively managing thermal plumes and particle dispersion.
- C2: studies adopting a direct assessment approach that solves for mass balance of species and analyzes their concentrations in relevant locations (i.e., occupants' breathing level) with/without PECS. It was done twice using custom codes. Al Assaad et al [51]. emitted pollutants from the carpet (toluene). Ventilation effectiveness index was calculated in the BZ (see formulation in Table A1). In [64], IAQ was assessed by focusing on CO2 and humidity control, using a sorption-based mechanism in the PV device. The device leverages an amine-functionalized adsorbent to capture CO2, maintaining concentrations below 400 ppm, and controls RH between 40–60 %. KPIs for IAQ included CO2 concentration, RH stability, and purge-to-supply air flow rates to maintain these levels.

3.2.4. Energy performance assessment

Improvement in energy performance due to PECS was assessed through calculation of either: (i) heating/cooling load, (ii) HVAC energy use (including PECS), (iii) thermal energy, (iv) operational energy use, (v) primary energy use, (vi) PECS cooling or heating capacity, (vii) PECS energy use and their relative change. In vehicles, reduction in fuel usage was assessed. These quantities are calculated for a benchmark without PECS at typical comfort setpoint and/or at a setpoint that provided the same comfort level as with the case with PECS, and for a case with PECS where the background system was either downsized or background setpoints were relaxed. Subsequently, reduction in energy use due to PECS was quantified. Table 2b (and Fig. A5) show the evaluated quantities in literature. Notably, Landuyt et al [69]. conducted a life cycle assessment (LCA) based on the ReCiPe 2016 method [70] using the software SimaPro 9. The environmental impact of materials and operational energy use was expressed in a single score (environmental points). However, material impact of HVAC system and PECS was not included in the calculation. In some studies (e.g [50,52]).. energy consumption was used in the objective function to control PECS.

3.3. Computational fluid dynamics studies

Out of 83 studies, CFD was used 80 times as main and 3 times as supporting. When CFD was main, 57 studies used CS, and 5 studies used FS as experimental support. 1 study used BS as an assistive method to assess PECS energy performance, and 18 studies use no other methods. 2 CFD studies assisted a FS and assisted a CS. When assisting FS, CFD was used to inform PECS design and gain understanding of the airflow phenomena to estimate airflow velocity as an input for PECS thermal comfort assessment. When assisting CS, CFD was used to evaluate the impact of PECS on the thermal field around the occupant. When CFD was supporting, models were not validated.

3.3.1. PECS modeling and integration in simulations

PECS is directly integrated into the computational domain by including the simplified geometry of the terminal device and assigning adequate boundary conditions that reflect its modality. The mobility type of PECS is not modeled. Fig. 6 shows the software used per PECS type. ANSYS Fluent [79] remains one of the most used commercial tools.

Thermal conduction-based PECS are assigned a constant surface temperature, or constant heat flux obtained from experimental measurements [31,80]. In cases with radiation-based thermal PECS, additional radiative properties (emissivity) are assigned (e.g [81])., For convection-based thermal PECS, supply velocity and temperature are assigned based on experimental measurements (e.g [82])., For thermal+IAQ PECS (PV), an inlet pollutant concentration is also assigned. In most studies, for species and particles, concentrations are assigned to zero to denote clean filtered air. For ductless personalized ventilation (PV) [83–85], or assistive devices (desk fans, chair fans) [86–88], that redirect room air, additional modeling considerations are needed and are usually well-described.

Indoor flow field involves complex physics due to the background HVAC system, PECS, occupants that generate thermal plumes, breathing function, and other internal gains. Therefore, a high-quality mesh is critical for accurately analyzing performance of PECS ensuring key flow characteristics at such scales are accurately captured. This includes gradients next to boundaries (human body) needed for thermal comfort analysis and contaminant transport for IAQ analysis. The choice of mesh depends on the geometry and is not directly dependent on PECS type. Table A3 details different mesh types in the literature. To compensate for higher numerical diffusion associated with unstructured meshes, local mesh refinements were often adopted. This includes boundary-proportional face sizing of 5 mm – 4 cm and refining cells in the microenvironment encompassing occupant and PECS to 1–2 cm. To solve for the thermal boundary layer near surfaces (e.g., occupants), inflation layers are created near boundaries where cells transition in size while progressing towards the core flow. These layers are such that the dimensionless wall distance $y+$ of the first grid point was approximately 1 (enhanced wall treatment). Specifying accurate wall boundary conditions is one of the most important foundations of an accurate CFD model as it impacts near-wall shear stress and heat/mass transfer due to PECS. 43 % of studies adopt such treatments while the rest do not detail if they were carried out. In some cases, it can be seen via study figures that the mesh was refined but no details in the text were given for reproducibility.

A computational thermal manikin (CTM) is an essential element of any PECS CFD simulation. A CTM with a realistic human body geometry ensures precise prediction of thermal plumes due to metabolic activity (plume velocity, thickness). This in turn determines the performance of any PECS type and design considerations. In case of convective-based PECS, their performance is dependent on their ability to penetrate the CTM's plume to increase heat losses and/or deliver clean air to the breathing zone (BZ). An inaccurate plume prediction due to an unrealistic CTM can affect sizing choice of PECS fan unit. Many studies (e.g [89,90])., have investigated the effect of simplification of CTM shapes (rectangular vs. detailed human geometry) and its subsequent effect on temperature and contaminants' distribution favoring more detailed CTMs. Table A4 shows different levels of detail in modeling CTMs in CFD studies on PECS.

The occupants' breathing was only adopted for studies that tackle IAQ. 32 out of 63 thermal+IAQ studies do not consider breathing, assuming rapid dissipation of exhaled air. The rest considers breathing from nose or mouth following sinusoidal 3 s inhalation/exhalation patterns with/without pause at rates of 6–8.4 l/min. Russo et al [91]. compared these different patterns and the case of no breathing and found similar results. They recommended using a constant inhalation as it does not increase simulation complexity. For the CTM's boundary conditions, either constant temperature or heat flux was adopted [92, 93]. Emissivity was not always specified unless radiative-based PECS

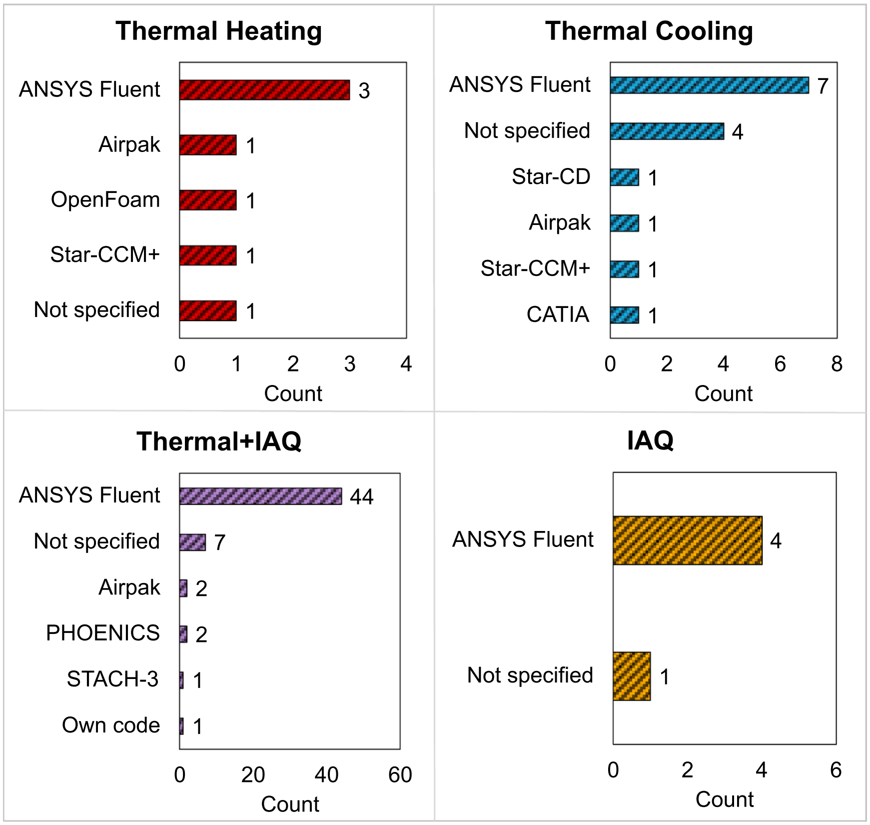


Fig. 6. Classification of CFD tools used in the literature per PECS type.

were used [94].

Careful selection of turbulence models is key, as it determines the resolution scale of the flow field [95]. In literature, Reynolds Average Navier Stokes (RANS) models are the only ones used balancing between computational efficiency and accuracy. The *Re*-Normalization Group (RNG) k-ε model was most common (30 %) followed by realizable k-ε model (18 %), standard k-ε model (10 %), shear stress transport (SST) k-ω model (6 %), Reynolds Stress Model (RSM) (3 %) used in conjunction with particles' Lagrangian modeling and zero-equation model (1 %). 15 % of studies do not report their model or report it partially (19 %) (e.g., k-ε model).

Of 81 main studies, 62 are validated with their own experimental data from climatic chamber or field experiments. 12 validate from published experimental data in literature and 7 studies do not mention validation. When validated, the validation is focused on the microclimate, next to the PECS's zone of influence for one or two conditions. In the case of thermal PECS, validation is focused on selected points around the occupant that are directly influenced by the PECS. In the case of thermal+IAQ PECS (personalized ventilation), the validation is focused on the evaluation of the air temperature, velocity and pollutants' concentrations along the issued jet starting from the supply reaching the occupant's breathing zone. In some studies, validation of indoor environmental parameters in the background is considered. This is the case where single or multiple PECS can have influence especially on IAQ (i.e., transport of contaminants). However, no studies fully validate the impact of PECS on the direct occupant microclimate, macroclimate directly influenced by PECS and the background HVAC system, macroclimate mainly influenced by the background HVAC systems. Such an integrated validation would be beneficial to improve the reliability of CFD-based PECS studies.

3.3.2. *Thermal comfort assessment*

Different methods varying in complexity were adopted and shown in Table 3. They were not particularly motivated by PECS type. The coupling of physiological models (Zhang [47], Radtherm software including the Fiala model [96], AUB [58,59]) and Zhang's thermal sensation and comfort models [35] with CFD models was most common for all PECS types. The coupling was often clearly laid out in the studies. The second approach was to use psychological rational models such as PMV/PPD, SET and ET at segmental level, where studies do not detail all necessary inputs to calculate them. Few studies on convective-based PECS additionally assess draft rate (DR), turbulence and airflow fluctuation frequencies. All CFD studies utilize temperature and velocity contours to further support their conclusions (Fig. A3 for all KPIs and metrics).

3.3.3. *IAQ assessment*

Studies were classified depending on their scope into 3 main categories built upon those already recognized in BS studies (studies can belong to multiple categories):

- **C1:** Studies assessing IAQ indirectly via air renewal metrics.
- **C2:** Studies assessing IAQ performance with respect to gaseous or particulate non-infectious pollutants originating from building elements (e.g., carpet) or occupants themselves (PV and non-PV users). In C1, tracer gas used is CO2 (exhalation), SF6 (body emissions, outdoor pollutant) and non-infectious particles or tracer gas (N2O) from furniture.
- **C3:** Studies assessing the ability of PECS in protecting occupants from cross contamination due to exposure to infectious aerosols (or "airborne particles", "particulate matter", "droplet nuclei"). In C2, a susceptible CTM was always determined occupied by 2 or more people and is exhaling infectious PM2.5, PM10.

Table 3
Thermal comfort assessment approaches adopted in the literature for different PECS types.

Assessment approach	Modality + Mobility
(a) thermal heating (7)	
Coupling of Fiala's physiological model to CFD model. Thermal comfort was evaluated through fluctuations in segmental skin temperatures and heat losses. Thermal sensation was evaluated using ASRHAE 7-point scale **(2)**	Convective vehicles [97] Conduction vehicles [98]
Segmental SET, local thermal sensation model **(1)**	Conduction vehicles [99]
Empirical thermal comfort model based on equivalent temperature, output is mean thermal vote (MTV) on a 7-point scale (cold to hot) **(1)**	Conduction building detached [82]
Temperature and velocity contours in CTM midplanes **(all)**	All
(b) thermal cooling (15)	
1. Coupling of AUB Thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale) **(2)** 2. Not assessed **(2)** 3. PMV or ΔPMV of target person **(2)** 4. Non-dimensional temperature variations in occupied zone **(1)** 5. Draft discomfort rate (DR) at face (20 %) **(1)** 6. Local operative temperature and velocity in occupied zone fell within acceptable conditions for thermal comfort according to ASHRAE's standard 55 **(1)** 7. Velocity and turbulence uniformity, temperature evenness around human body[a] **(1)**	Convective building detached 1 [86,87]. 2 [100,101]. Convective building attached or semi-detached 3 [102] 3 + 4 [103] 5 [104] 6 [105] Convective vehicles 7 [106] Radiative building attached 3 [94]
Coupling of Radtherm Thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale)[b] **(1)**	Convective vehicles [107]
Temperature and velocity contours in CTM mid-planes **(all)**	All
Local Equivalent temperature (ET) **(3)**	Convective vehicles [107–109]
(c) thermal + IAQ (cooling, OAS+AT) (61): convective building semi-detached or attached (personalized ventilators)	
Not assessed **(23)** (e.g [84,93,110–121].,	
ET (segmental) and PMV/PPD[c] **(12)** ([122,56,123,83,88,124–128])	
Coupling of AUB or Zhang's Thermo-physiological and Zhang's sensation/ comfort model: overall thermal sensation and comfort (9 pt scale) **(13)** (e.g [84,101, 129–131]).,	
DR and air velocity fluctuation frequencies (0.2–0.6 Hz) **(6)** [56,92,123,132–134]	
Air temperature and velocity **(6)**: gradients of facial skin temperature of the CTM [135], air temperature distribution and speed around CTM (e.g [136–138]).,	
Head-foot temperature differences, EN ISO 7730 **(2)** (e.g [92,133]).,	
Thermal comfort zone given by Nilsson and Holmér [139] with ET indicates a thermal comfort evaluation for each segment **(1)** [122]	
Average air distribution temperature in occupied zone **(1)** [134]	
Effective heat removal index defined by Awbi et al. [11] as ratio of the exhaust temperature over room mean radiant temperature[d] **(1)** [140]	
Temperature and velocity contours in CTM mid-planes **(all)**	
(d) IAQ PECS (AT, Building semi-detached)	
PMV/PPD[c,d] **(1)** [141]	

[a] accompanied by subjective thermal sensation/comfort assessment on a 6 pt scale and sweat evaluation on a 4 pt scale.

[b] results were benchmarked to those from actual human subject test.

[c] PMV range of −0.5 to 0.5 and three comfort categories (A, B and C) from ISO 7730 were used.

[d] values were not associated with a specific threshold and comfort state.

Fig. 7 shows the distribution of PECS types across categories, while Fig. 8 presents IAQ KPIs (Table A1) and their frequency by category and PECS type. The metrics are assessed often at occupants' BZ defined as a small air volume in front of the CTM's nose.

For thermal PECS, four studies examined detached convective devices assisting HVAC systems by directing clean air to the BZ before it mixed with polluted air ([86,87,100,101]. They belonged to C1. The study in [100] belonged additionally to C2 since pollution was considered from an infected manikin exhaling infectious particles and CO_2. For thermal+IAQ PECS, most studies (21) belonged to C1, followed by C2

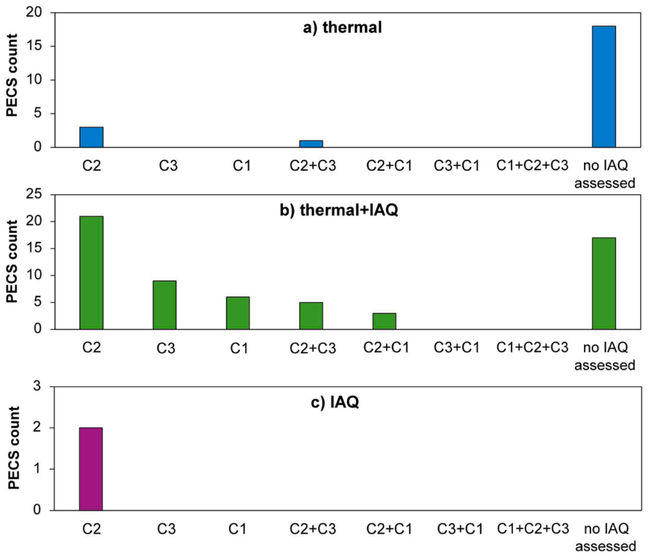


Fig. 7. Distribution of IAQ assessment per study category.

(9), C3 (6). Combinations of categories were less occurring with 5 studies combining C1 and C2, and 3 studies combining C1 and C3.

Multiple studies misused KPIs adopting the KPI's terminology but different formulation making it harder to compare and communicate PECS performance across studies ([85] [92,115,138,141]). The misuse of KPIs happened in two instances. In C1, [92,115,138,141] looked at the normalized concentration C_n in the BZ with respect to the exhaust. The C_n index stems from the inverse of the ventilation effectiveness index $1/\ \varepsilon_j$ or *CRE* used by Alsaad et al [85]. with $C_{p,\ PECS} = 0$. However, in [115,138], it was also referred to as ventilation effectiveness when it is the inverse of it. Using C_n correctly means the inhaled air quality improves with decreasing C_n due to PECS and a misuse of it means worsening inhaled air quality with decreasing C_n. This can lead to false interpretations of PECS performance. The second instance was also when using the ventilation effectiveness index (Table A1). This index was first defined by Russo et al [142]. under the name "Air quality index" or *AQI*. A similar approach was used in Alsaad et al [85]. when assessing the performance of a ductless PV. This KPI benchmarks the inhaled air quality with respect to the exhaust (polluted) and supply (clean) concentration resulting in a number between 0 and 1 with higher values signifying better inhaled air quality. Ventilation effectiveness index ε_j (%) was used under a different formulation. This formulation is also known as the contaminant removal effectiveness (*CRE*) index [143]. This KPI is similar to the *AQI* but is formulated differently resulting in a KPI with no upper limit. Good performance is considered if the index far exceeds 1 ($C_{BZ}>>C_{exhaust}$). This can be confusing when interpreting the results of certain studies.

In addition, there was no clear link between KPI choice and PECS type or study scope, and KPIs were often used without justification, making it hard to identify the most suitable ones. Thus, it would be beneficial in future research to have a standardized KPI framework to assess the IAQ performance of certain PECS.

In the reviewed literature, there was no consensus on the definition of the BZ. Some studies tend to mention that the inhaled air quality was assessed at the BZ without specifying its location (e.g [57,83,84,114, 144]). Others (e.g [111]). consider the BZ as a horizontal air layer at breathing height ranging from 0.9 m to 1.2 m or specify the breathing height at 1.3 m for a seated person [92,141] and 1.6 m for a standing person [115].

Some studies are more specific and (e.g [117,129]., and other similar papers from the same research institution) consider the BZ as a sphere having a radius of 1 cm located at 2.5 cm away from the manikin's nose or a single point at breathing height (1.03 m) [116]or a virtual box (30×30×30 cm) in front of the mouth [132], a point at a distance of 10 mm or 25 mm from the nose [145]. The latter more precise definitions could be inspired by Brohus and Nielsen [146]who concluded that inhalation zone is approximately a half spherical space centered at the tip of the nose.

In an experimental study with human subjects, Pantelic et al [147]. revisited the concept of the BZ due to varying definitions present in the literature as seen above and tried to re-define it by sampling the CO_2 concentrations at different points in front of the subjects' noses (below and above nostrils). The entrainment of exhaled breath into the sampled air caused inconsistency in concentration measurement at some locations above and below the nostrils. They found that sampling 0.5 cm from the tip of the nose had the most consistent measurements and was selected as the optimal sampling location. This was in agreement with the definition of Brohus and Nielsen [146].

Given the fact that this has been proven by experimental studies both on human subjects [147] and thermal manikins [146], and keeping in line with the definition provided by ASHRAE standard 62.1:2022 [68], it is recommended to define the BZ as a sampling volume at short distance (e.g., 0.5 cm) from the region from which a person would be inhaling from (nose, mouth). It is equally important that authors provide this definition in their work, explain their motivation for using it, and, if applicable, clarify any reasons for deviating from it.

Most used KPIs in CFD methods are the intake fraction (iF) and AQI. Few C2/C3 studies examine PECS impact on the background environment or other occupants, which can lead to a positive bias in IAQ performance results and overlook key design factors such as layout, occupant density, and partitions. Examples of studies considering impact of PECS on the background and discuss its potential design implications are [100,118,148]. Another often-overlooked aspect in C2 studies is surface deposition of infectious particles on furniture or clothing, which can be a significant infection pathway. Refs [88,149, 150] are examples of studies quantifying the deposition fraction (*DFr*) and discuss its implication on PECS design.

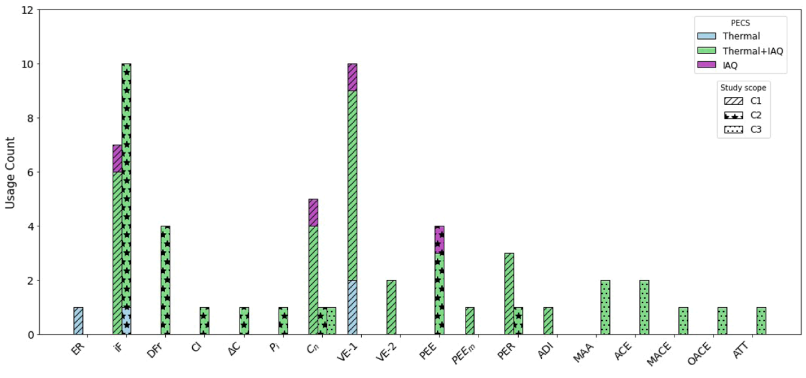


Fig. 8. Usage count of KPIs used in CFD studies per PECS type and study scope (C1, C2, C3).

C2/C3 studies evaluate IAQ via contours, streamlines and vectors of velocity distribution, species or particles concentrations in manikins' midplanes. C1 studies look at velocity distribution. 17 studies (e.g [93, 113,119,124,125,128,135,136,151–153])., assessed performance of PV, focusing on thermal comfort improvements but do not assess IAQ or assess it in other published work.

3.3.4. Energy performance assessment

Out of 84 studies, only 18 assess energy performance using outputs from simulations. The energy assessment is not done in the CFD tool, but a separate calculation or 'rough check'. The assessment was focused on calculating the load reduction under steady state outdoor conditions (i.e., weather) and internal gains. While some studies consider partial loads and include measured values of envelope surface temperature, the calculation does not include the full background HVAC system with all AHU components and in case of PV, besides the fan, PECS related AHU components were ignored. For thermal, thermal+IAQ and IAQ PECS, 5, 13 and 1 studies assessed energy performance respectively. Sekhar and Zheng [57] combined CFD and BS to assess energy performance. This allowed to consider outdoor weather dynamics and dynamic cooling loads due to variable occupancy and equipment schedules. The energy performance was assessed for the standalone background system and PV system with chilled beam under similar comfort range. The results were expressed in terms of monthly and annual energy use for different cooling loads.

3.4. Chamber studies

174 reviewed studies used CS for evaluating performance of PECS. Of these, 75 % implemented exclusively CS, while 34 studies used CS as supporting, primarily for validating simulation studies, especially CFD models, or for informing simulation studies regarding PECS settings required for providing comfortable conditions [52]. Ten studies using CS as main method for investigating PECS performance, included additional supporting methods to scale up the tested solution and demonstrate its energy savings potential when implemented at a larger scale, at the building level [154,155].

3.4.1. Experimental design

Laboratory studies enable controlled observation of occupant responses to PECS under tailored conditions aligned with specific research goals. Prior reviews gave an overview of global experimental facilities for IEQ research, noting varying designs based on the comfort domain studied [156,157]. PECS assessment requires control over both background and micro-environments around participants. Facility characteristics and participant type vary with available resources and research goals, influencing experimental procedures and test condition design.

Facilities characteristics. CS reviewed include both controlled and semi-controlled environments. Most (112 studies) were conducted in fully controlled climate chambers—independent from the hosting institute—where key parameters can be precisely regulated within defined margins [158,159]. This setup helps minimize response bias caused by environmental fluctuations. A smaller number of CS (33) were conducted in semi-controlled environments—typically dedicated rooms within research institutes offering some environmental control, though with less precision than fully controlled chambers [160]. Reduced control accuracy is partly balanced by greater environmental realism, which helps mitigate the Hawthorne effect—where participants alter their behavior simply because they know they're being observed [161]. Overall, CS lacks the realism of FS, but often interior arrangements are designed to mimic specific settings. Most reviewed studies tested office-like or classroom environments, with participants engaged in desk-based activities, while others included waiting rooms [162–164], bedrooms [165,166], and car or airplane cabins [167–170]. The size of the experimental environment significantly influences PECS integration studies and occupant response assessments. Smaller chambers accelerate thermal equilibrium but may lack realism, while larger spaces offer more realistic conditions and enable zone-based control analysis, though they require greater effort to maintain uniformity. Reviewed studies used facilities ranging from 13 m^3 to 240 m^3, with 24 % not reporting dimensions. Notably, 66 % of CS supporting other methods employed chambers under 20 m^2, often substituting manikins for human participants [145,171,172]. Larger spaces accommodated more participants per session—a key factor for examining how individual PECS choices affect others in shared environments. Notably, 44 % of studies involved multiple occupants, an uncommon feature in IEQ lab research. Participant numbers ranged from 2 (most frequent, cited in 33 studies) to 40 (in a simulated aircraft cabin using manikins [168]). In some studies, measures were taken to prevent participant interaction, limiting the potential of multi-occupancy setups to enhance experimental design by observing diverse responses to identical environmental conditions. Other studies recognized a further role to multi-occupancy. Li et al [168]. observed interactions between gasper jets and the main ventilation over a large velocity range, in an aircraft cabin. Li et al [173]. used feedback messaging to nudge an energy-conservative use of PECS taking advantage of social norms and competitions among peers. Others investigated PECS potential in reducing cross-contamination in multi-occupied configurations with breathing manikins and tracer gas [164,174,175], further accounting for the disturbance of a walking person [176].

Experiment participants: Of the reviewed studies, 98 involved real subjects, 52 used manikins, 12 included both, and 12 used neither. The latter focused on mapping PECS-generated microenvironments and monitoring energy consumption, with 4 employing CS as supporting method for CFD analysis [64,136,177,178]. When both humans and manikins were used in PECS assessments, they typically participated in separate sessions. Human subject sample sizes ranged from 4 [52] to 126 participants [179] with an average of 28 per study. Most studies (51) balanced gender distribution, while 13 did not specify it. While most focused on young adults, some evaluated PECS efficacy across various age groups, including children, adults, and elderly [160,166,180,181]. In [182], the sample was primarily composed of young adults (24 out of 36 participants), with smaller groups of children (11.7 ± 1.2 years) and elderly adults (58.5 ± 4.7 years), each represented by only six participants. This uneven distribution emphasized the response of young adults while offering limited insights into the other age groups. In contrast, Lan et al [160]. employed a more balanced sampling approach, with a total of 36 gender-balanced participants evenly distributed across three predefined age categories: children (6–14 years), young and middle-aged adults (20–55 years), and elderly adults (60+ years), with 12 participants in each group. This structure allowed for a more consistent comparison across age groups in evaluating the impact of a bedside PV system on sleep quality. The study by Risetto et al [181].adopted a two-group classification, focusing on "Younger" adults aged 18–34 years (mean 29 ± 6.45, 16 participants) and "Older" adults aged 50–70 years (mean 65 ± 4.04, 25 participants). The three studies adopted different approaches to defining participant age groups, highlighting a lack of standardization and reflecting the common practice of tailoring sampling strategies to the available resources of each research group. When manikins were used to mimic occupants, varying levels of detail were employed. The simplest configurations included heated cylinders, boxes, or basic dummies without heating. These representations, which approximate the footprint of a sitting or standing person, fail to realistically capture the human body's thermal plume. This solution is suitable for introducing heat load or acting as an airflow obstacle in the experiment. Simple dummies, while resembling body shape, provide realistic representation of occupant exposure but lack thermoregulatory mechanisms, serving merely as placeholders for microenvironment characterization. Heated dummies improve occupant representation accuracy, offering insights into how the human body's thermal plume interacts with the convective boundary layer, influencing performance of both thermal and IAQ focused PECS [183]. However, this solution typically uses a single heat source, which does not accurately represent key physiological responses, such as skin temperature variation or sweating. To address this, multi-segment hygro-thermal manikins were introduced, originally designed to assess clothing thermal and water vapor resistance, but now also useful for PECS performance evaluation through objective physiological indicators. Additionally, breathing functions were usually simulated with artificial lungs or inhalation circuit, as detailed in the IAQ-assessment section.

Experimental conditions: CS tested between 1 and 58 combinations of background and micro-environments. A unique combination of background and PECS settings was used in 36 studies (21 % of CS), with over a third (14) using CS to validate CFD models. Other examples include studies on non-building environments (e.g., car or aircraft cabins), first-use tests of new PECS [184], or research focused on developing individual PECS components [185]. The highest number of tested conditions in a single experimental campaign was reported in Shinoda et al [159], a comprehensive assessment of a multifunctional PECS targeting both thermal and IAQ in the microenvironment. To assess PECS performance objectively, a composite factorial design was used, covering three main scenarios (cooling, heating, and ventilation) with varying background temperatures and PECS settings, totaling 176 conditions. Each condition was replicated in a laboratory setting and evaluated with thermal manikins, with 30-minute observations per session after steady-state conditions were reached. The maximum number of conditions tested by participants in a single campaign was 54, with each condition tested for 3.5 min, resulting in a total session duration of 200 min [186]. Although the study included the highest number of cases, it was designed to minimize participant fatigue, with single-condition exposure being the shortest among reviewed papers. In contrast, the longest exposure lasted 480 min, as reported in five studies, three of which assessed PECS impact on sleep quality [160,166,187], with participants typically experiencing two conditions (with/without PECS) except in [166] with no reference scenario. The remaining two papers [158,188] described the same setup, where participants performed desk-based tasks while exposed to transient background environment with air temperature changing by 1.5 °C/hour, from 17 °C to 25 °C, between 9:30 and 17:30. Given the session's extended duration, scheduled breaks for meals, exercises, and rest were included. As with other CS, participants completed the protocol with/without PECS, a key design feature for evaluating performance. However, 39 % of reviewed CS did not report a reference scenario, a figure slightly reduced to 37 % in studies where CS was the main method. Although less common, another recognizable pattern in CS design involves granting users control over PECS operation, which was observed in 24 % of studies. The motivations for this approach varied and included identifying optimal settings or preferred designs to enhance user comfort under different background conditions [189,190], as well as developing behavioral models of PECS usage [71].

3.4.2. Thermal comfort assessment

Of the 174 reviewed CS, 170 focused on PECS for thermal management. The experimental setups covered a wide range of thermal environments, with most frequently tested conditions between 18 °C and 30 °C. Relative humidity was typically between 30 %–70 %, and air velocity ranged from below 0.1 m/s to 6 m/s. A total of 106 studies evaluated PECS under cooling conditions, 39 under heating, and 25 examined both. Most studies (127) tested steady-state conditions, while only 43 assessed PECS under dynamic or combined conditions. Dynamic conditions can be applied to either background or micro-environment, depending on the research objective. Changing background conditions during sessions allows observation of participants' responses, including PECS use patterns [146,178,191]. Generating fluctuations in thermal exposure with PECS help evaluate its potential in creating alliesthesia, a conceptual framework explaining pleasant sensations from temporary or spatially limited exposure to environmental stimuli that oppose the individual's internal state, i.e., in the thermal domain, a cool stimulus may be perceived as pleasant when the body is above thermal neutrality [192,193]. It may happen that both background and local thermal environments change over the experimental session as in [194]. They observed occupants' willingness to modify the background environment of a shared space with or without local heating or cooling devices. While participants controlled PECS settings, they could not adjust the background environment directly but could request thermostat adjustments every five minutes, which were implemented by researchers. Of the reviewed studies, 71 reported control types used, which included user control (participant-adjusted settings), non-user control (settings adjusted by researchers or automatically), and combined.

Out of 98 CS involving human subjects, 41 included pre-trial phase where participants were instructed to prepare by ensuring sufficient sleep, avoiding alcohol, caffeine, intensive physical activities, smoking, and drug use, and adhering to clothing requirements. Most studies with a pre-trial phase also included an acclimation period. Reported by 78 studies, it averaged 26 min, with extremes ranging from 10 [167,195,196] up to 80 min [166]. 42 studies acclimatized participants within the same experimental environment as the official test, while 25 conducted acclimations in separate locations, three reported both as double-step procedure [72,197,198] and the remaining did not specify. Out of 98 studies, only 11 did not collect subjective thermal environment assessments via surveys, while 33 gathered at least one physiological signal, including skin (31) and core (4) temperature, heart rate or variability (10), blood pressure (5), and metabolic rate (5). The collection of physiological data was more common in dynamic exposure experiments, with skin temperature monitored in 26 % of dynamic exposures compared to 17 % in steady-state conditions. The number of skin temperature measurement points ranged from 1 to 26, with 7 or 8 sites being most common. While consistent measurement locations were not identified across the same thermal modalities (cooling or heating), most studies used portable dataloggers or wearable systems to reduce monitoring invasiveness. Some even opted for remote monitoring via infrared cameras [199].

Participants' thermal experience was mainly assessed through questionnaires, providing subjective insights into different thermal dimensions, mainly thermal sensation and thermal comfort. Thermal sensation votes (TSV) are used to express the intensity and direction of a perceived thermal stimulus ranging from cold to warm and presenting the neutral state in the middle. TSV is commonly collected through the 7-point ASHRAE scale (-3 cold to $+3$ hot), though some studies applied extended 9-point scales or continuous visual analog scales (VAS). One detailed study used a 9-point scale to capture both overall and local sensations across body parts. Thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment and its assessment through thermal comfort votes (TCV) varied in scale, including 4-point, 5-point, 7-point, and 9-point formats, often addressing both overall and localized comfort. As additional thermal dimensions, comfort preference was also explored using categorical and continuous scales. Most studies (95 %) reported activity types, primarily sedentary, while 38 % did not report clothing insulation and 63 % omitted participants' metabolic rate.

Manikin-based evaluations were conducted in 60 studies, with 39 also addressing PECS IAQ management. Multi-segmented heated manikins, used in 35 experiments, had between 16–34 segments. Breathing functions were introduced in 11 studies, while 15 used commercial thermal manikins with breathing capabilities but didn't employ them. Three studies utilized sweating manikins to simulate latent heat exchange. Conceição et al [172]. described the hygro-thermal manikin developed at the University of Algarve, which consists of eight hygroscopic sections: head, trunk, upper limbs, thighs, and legs. These manikins were configured to represent various activity levels through heat flux values and dressed in different clothing ensembles. The reviewed studies reported heat flux values ranged from 22.6 W/m^2 to 95 W/m^2 [124,200,201], corresponding to typical sedentary office activities. Clothing levels of manikins varied widely, from nude to summer and winter clothing ensembles. In some studies, heat flux was not directly measured; instead, manikin surface temperatures were controlled. These, along with background environmental conditions, allowed for thermal comfort quantification using indices like Manikin-Based Equivalent Temperature (MBET), Standard Effective Temperature (SET*), and Effective Temperature [176,202–204], thermal comfort models, e.g., Zhang's model [205], PMV/PPD [88,124,200,206] or direct surface temperature analyses [122,207]. Environmental parameters were consistently recorded during experiments, including air temperature (with accuracy between ±0.1 °C and ±0.5 °C), air velocity (±0.01–0.04 m/s), RH (±1 %–5 %), mean radiant temperature, and operative temperature. Additional data collected included surface temperatures (e.g., walls, seats, ceiling panels) and turbulence intensity, measured at multiple heights (0.1 m, 0.6 m, and 1.1 m) to capture vertical gradients. While local environment characterization received greater attention, the background was often assumed as preset conditions. Fig. A4 shows the thermal comfort KPIs, and metrics used in CS. Table A5 lists KPIs and metrics used only once.

3.4.3. IAQ assessment

79 CS addressed IAQ, with most evaluating it alongside thermal environment analysis. Only 4 studies focused exclusively on IAQ, all investigating PV systems [151,165,195,208], or assistive devices (local exhaust) [209]. Experimental procedures and environmental boundaries closely mirrored those in the previous section, with 14 studies specifically detailing contaminant concentration control strategies to create varied IAQ scenarios. These strategies are primarily relied on dilution of tracer gas – CO_2 [51,64,86], N_2O [159], SF_6 [176,210], particulates [88], directly injected into the chamber to emulate typical indoor pollution. 4 studies, all from the same research group, dating before 2012, created highly polluted scenarios by introducing an old carpet into the experiment. The carpet was hung on racks and concealed behind a partition to keep it out of participants' view [190,195,211,212]. Participant selection often excluded smokers to minimize perceptual bias. Manikins, typically the same models used in thermal assessments, were utilized in 43 studies. In 21 of these, they were equipped with artificial lungs, simulating human breathing as done in CFD. The study scopes aligned with those introduced in Section 3.3.3 (**C1, C2, C3**). Two new human-centered scopes emerged—both uniquely accessible through experimental studies and specifically via surveys: (**C4**) perceived air quality, and (**C5**) health impacts, particularly sick building syndrome (SBS) symptoms (see KPIs Fig. A4).

3.4.4. Energy performance assessment

Only 39 studies specifically addressed this. Metrics typically adopted can be broadly categorized into: energy related, e.g energy consumptions [72,99,192,213–216]., energy savings, or heating/cooling capacity; power related, referring to PECS power and peak power throughout use [72,99,159,192,213–216]; and performance related, indirect metrics including energy efficiency rate (%) or COP computed from directly measured variables such as the heat removed from the targeted manikin when included in the experimental design. Performance metrics include, among others, heat removal efficiency, which evaluates how effectively heat is extracted from a space or directly a body part [217,218], or, when PECS operation is dominated by convection, the convective heat transfer coefficient is used as a performance proxy [185]. A few studies also isolate and report energy consumption of specific PECS components, such as cooling coils [219], offering further granularity in system evaluation. Finally, CS participants were almost never informed about energy fluxes during experiments. Few exceptions allowed participants access to information such as current setting level of the PECS device [219] or their current level of energy consumption compared to others with the aim of nudging energy-conservative behaviors [173] (see KPIs Fig. A5).

3.5. Field studies

Out of 17 studies, 13 used FS as the main method and 4 as supporting. Despite FS being the main method, 4 papers also included CFD and 3 included BS, meaning only 7 studies used FS exclusively. Of 4 studies where FS was supporting, 2 combined it with one other method, while the other 2 combined it with two additional methods. Zhang et al [71]. applied FS to collect data to model occupant behavior into BS but also conducted CS to understand the PECS performance and energy use. Bauman et al [220]. also applied FS to understand occupant behavior and additionally ran CS to assess PECS performance and control capability. In both cases, occupant behavior is intended to estimate energy consumption in real-use scenarios. Wan et al [106]. also added CS to assess energy consumption but used CFD to comprehend in detail the effect of PECS. These studies complemented FS, which focused on occupants' thermal perception, by assessing energy, air distribution, and thermal comfort performance through integration of the three methods. Finally, Kong et al [122]. did a more simplified study, without human subjects, using FS to validate CFD by measuring simulated room during PECS operation. FS studies are applied to collect real life information on occupant behavior, perceived effect or distribution of an effect in a space occupied daily by people.

3.5.1. Experimental design and PECS integration

Table 4 shows different PECS types and associated devices investigated in FS. There are more studies focusing on heating PECS of different kinds with heating chairs being the most studied PECS in FS. Although 3 references relate to the same experimental campaign and chair [31,39], there were 3 types of chairs tested (2 of them provide heating and cooling) while radiant panels and heating desk include only 2 products each.

Offices are the most common typology (14 studies). One study was in a vehicle, another in a residential building (portable air cleaner), and one in a market (Huotong). All specified offices were either shared or open plan, with only one study not specifying office type [222], and 1 includes both open plan and private offices [223]. Studies have been carried out in US (5), China (5), Singapore (1), Canada (1), Austria (1), UK (1) and 1 did not indicate location. Participants in office FS ranged from 5 to 73, with an average of 30. Studies were typically conducted in spaces between 10.5 m^2 and 204.2 m^2, with three examining multiple stories but limiting PECS implementation to specific areas. Most studies (14) compared conditions or occupant perceptions with and without PECS. Among the 3 studies that did not collect data on a reference condition, 3 simulated the reference case to estimate energy consumption [71,224] or predicted thermal sensation without PECS based on PMV model [227]. Some studies delt with refurbishment, collecting data before and after the system's permanent installation [151,222]. Although Peschiera and James [151] collected a single response before and after, waiting 3 days after installation for occupant adaptation; Menzies et al [222]. collected 1 week of data before and 2 weeks after. In other cases, with detached systems, researchers were able to promote long-term installation, reducing the reference to 1 response [223] or to 2 weeks [225], while the period of exposure to PECS was more than 2 months. However, some studies applied very short exposure periods, for

Table 4
Types of PECS investigated in FS.

Functionality	PECS device	
IAQ	portable air cleaner [221] personal exhaust [122]	
thermal+IAQ	ceiling PVs [151,222] furniture PV [128,220]	
thermal	cooling	heating
	chair [71,223,224]	chair [31,39,223,225]
	desk fan [71]	Heating desk [224,226]
	vehicle PV [106]	Foot warmer [225]
		Warm barrel (huotong) [227]
		Radiant panel [151,228]

1 h [80] for one day, 1 h for 7 days [226] with pre-exposure condition assessed instantaneously before or 10 min before, respectively. The other 2 studies had 1day exposure for reference period and 1 day per test scenario [128,221].

All studies except 3 included questionnaires to assess occupants' perception of achieved environmental conditions. Among those 3 studies, 2 focused on IAQ, focusing on pollution concentration in the room [221] or using a thermal manikin to validate CFD thermal conditions and air flow around a user [122], and the third one focusing on occupant behavior [71]. Apart from studies using a single pre- and post-questionnaire, others administered questionnaires 2, 3, or 9 times a day. Two studies used 3 per day, while the others used fewer. Most studies used digital questionnaires (via email, apps, or online platforms), with only one study using printed versions. Response rates, when reported, ranged from 100 % to 61 %.

Longer exposure periods help participants acclimate to PECS and minimize environmental condition variations between pre- and post-testing. An alternative approach is simultaneous data collection, where different participant groups are exposed to either PECS or no PECS within the same building to reduce potential differences. This approach was less common among studies, applied only in 2 studies [220,228]. Although it could reduce the total experiment period, if the groups are small, personal preference variations could affect the results. Additionally, a habituation period is suggested before starting data collection for exposure period in both cases, to ensure participants get used to the equipment [223]. In general, long exposures have benefits for the study but are challenging due to time and financial constraints. As the space is regularly used, the chances of layout, occupants and infrastructure change increase over time, creating new confounding effects [222]. Questionnaires repetition should also be restricted not to overburden participants, which can be achieved with automated strategies [229].

3.5.2. Thermal comfort assessment

To assess thermal comfort, the main collected variables are described in Table 5. The most used KPIs are 7-point TSV and 7-point TCV. Air movement sensation and comfort, as well as humidity perception, are only used in one study on a PV system. PMV is used mainly to compare the votes with predicted results (see KPIs in Fig. A4)

Additional measurements are taken from the environment, for example to calculate PMV or to assess indoor environmental conditions during the FS. Inlet and outlet temperatures were also used by Zhang et al [225]. to estimate HVAC energy consumption. Table 6 shows all studies (15) include indoor dry bulb temperature and most (11) also include RH. There is variation in the number of measurement points across studies. In 7 studies, each workstation was assessed, while others evaluated 1 (2 studies), 2 (2 studies), 3 (1 study), 4 (2 studies), and 9 (1 study) points to represent the study space.

Table 5
KPIs used in FS to assess thermal comfort.

KPI	scale (references)
thermal sensation	7-point[80,128,224,226–228]
	9-point [225]
thermal comfort	7-point [106,128,224,226,228]
thermal preference	3-point [224,226]
	7-point [227]
thermal satisfaction	7-point [80]
satisfaction with the PECS	7-point [80]
thermal acceptability	7-point [31,224]
	6-point [225,226,228]
local TSV	7-point [31,226,228]
	9-point [225]
local TC	7-point [106]
air movement sensation	5-point [128]
air movement comfort	5-point [128]
humidity sensation	7-point [128]
PMV	7-point [80,128,226,227]

Table 6
Measurements applied in FS.

Measured variable	Refs.
dry bulb temperature (°C)	[71,106,122,128,151,220–228]
RH (%)	[71,128,220–224,226–228]
air speed (m/s)	[71,106,122,220,222,226,227]
globe temperature (°C)	[71,220,221,223,224,226,227]
radiant mean temperature (°C)	
outdoor air temperature (°C)	[224]
outdoor RH (%)	[224]
inlet/outlet temperature (°C)	[225]
radiant asymmetry	[71,220]

3.5.3. IAQ assessment

Taheri et al [128]. assessed IAQ subjectively in terms of IAQ acceptability on a 5-point scale from very stale to very fresh. As Huotong uses charcoal for heating, CO at BZ was measured and CO_2 concentration was also measured at 0.6 m height [227]. Peschiera and James [151] also assessed IAQ satisfaction through questionnaires and measured CO_2 at BZ. 2 other studies focused on health KPIs. Tran et al [221]. measured $PM_{2.5}$ and PM_{10} and, based on results, calculated Excess Life-time Cancer Risk (ELCR) and Risk Quotient (RQ). While Menzies et al [222]. measured total volatile organic compounds, nitrogen oxide (NO), NO_2, formaldehyde, total airborne dust, fungal spores, and colony-forming units (CFUs) outdoors and at 4 – 6 locations on each floor. The authors also distributed questionnaires to assess air quality and SBS symptoms, i.e., occurrence of headache, fatigue, and difficulty concentrating, occurrence of irritation of eyes, nose, throat, and skin, and musculoskeletal and respiratory symptoms. The measured variables can all be classified in scope **C2**. Additionally, two human-centered scopes introduced in CS can be identified, i.e., **C4** [128], and **C5** (ELCR and RA in [222]) (see KPIs Fig. A4).

3.5.4. Energy performance assessment

This was included in 5 studies [71,220,221,224,225] indicating PECS power supply and energy consumption and/or calculated energy savings compared to a scenario without PECS (with conventional heating and cooling systems). Therefore, the main KPI used to assess energy performance in FS is percentual energy savings. Tran et al [221]. included the most extensive energy information, including also use duration, operation cost, and predicted operation cost in 70 years (see KPIs Fig. A5).

4. Discussion: advantages & limitations of PECS evaluation methods

Simulations provide key advantages over experimental methods for modeling and optimizing PECS, allowing rapid evaluation without the time, resources, or installation constraints. BS of PECS allow simultaneous evaluation of energy performance, CO_2 emissions, and occupant comfort under varying conditions, enabling efficient, scalable studies and optimization of heating, cooling, ventilation, and power consumption. CFD enables detailed analysis and visualization of flow fields influenced by PECS, helping optimize their design, operation, and impact on occupant comfort. Simulations' cost-effectiveness and technological advancements enable rapid prototyping and iterative development, potentially speeding up PECS market adoption.

There remain challenges with simulations arising from method limitations. Many BS tools are unable to directly model a nested PECS zone within larger space volumes, which gave way to collaborative and custom methods. Furthermore, almost all integration methods do not consider the full impact of PECS on the space. While CFD avoids these issues, it requires careful setup (mesh, airflow modeling, CTM, boundary conditions) for reliable results. The steep learning curve and high computational costs limit long-term simulations, often leading to rough energy performance checks. Both BS and CFD models couple with thermoregulation and comfort models to assess comfort improvements. While the first approach might be the best available to date for capturing segmental and transient comfort, it does not fully account for inter- and intra-individual variations in PECS operation.

Realistic observations of human responses can only be gathered through experimental methods once ethical, or privacy concerns are addressed. Overall, CS is the most widely used for assessing PECS performance, likely due to its applicability across all stages of development, from conceptualization to testing. Depending on the Technological Readiness Level (TRL), CS can focus on evaluating device performance, testing component effectiveness, assessing PECS impact on the environment under different scenarios, or studying specific components' effects on various occupant responses, especially physiological ones. Achieving controlled conditions needed for CS is resource-intensive, requiring dedicated facilities and advanced monitoring equipment. Testing numerous configurations also demands complex experimental design and significant effort in recruiting and testing sufficient participant sample. Experimental sessions must also be carefully designed to avoid participant fatigue or boredom, which could compromise response accuracy. Furthermore, laboratory environments may limit the ecological validity of findings due to a lack of realism. FS are preferable for capturing a broader range of real-world conditions and authentic user behavior. Long-term FS are particularly valuable, as they allow researchers to account for variations across seasons, times of day, and changing occupancy patterns. However, FS requires PECS technology to be at high TRL, and careful planning is necessary to minimize disruptions to occupants' primary activities. This involves designing an appropriate feedback frequency and developing non-intrusive monitoring setups for detailed spatial mapping and physiological or behavioral data collection.

Both simulation and experimental approaches share common limitations, particularly in method implementation and reporting. Most reviewed studies fail to justify method or KPI choices (some even misuse KPIs) and lack key method-specific details, such as model setup and monitoring setup, limiting reproducibility and transparency. This emphasizes the need to have standardized methodologies and a universal KPI framework to accurately evaluate and express different PECS performance aspects. This issue extends to model validation, which is almost absent in BS for PECS-integrated spaces. In CFD, validation is emphasized but often limited to areas directly affected by PECS, neglecting broader spatial interactions. Finally, when using simulation tools, most users do not integrate stochastic occupancy profiles (usage of PECS and other equipment, presence) when it is possible to do so. These issues may stem from resource limitations and lack of open data, which could explain the skepticism around simulation tools and their lower usage compared to CS. Fig. 9 suggests a conceptual framework characterizing simulation and experimental methods for PECS performance assessment by temporal and spatial coverage capabilities and required implementation resources, as derived from literature and the intrinsic potential of each method.

5. Conclusion - recommendations and future research

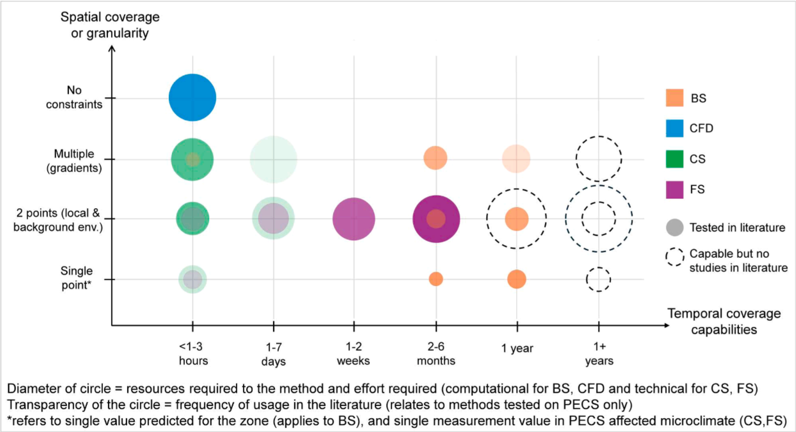
Based on the review, a set of best practice recommendations was developed to help researchers improve the reporting quality of their methods and results. They are presented by order of importance:

Simulation methods (BS, CFD):

1. Validate models with and without PECS, covering all relevant microclimate and macroclimate locations. Validation should include thermal, airflow, and species concentrations. Acknowledge validation limitations in BS.
2. Clarify limitations associated with PECS modeling, assumptions, and its implications on performance.
3. When assessing human thermal comfort with PECS by coupling with thermoregulation and comfort models, clearly report the coupling procedure and required inputs. Account for inter-individual differences in the inputs.
4. Provide a comprehensive description when integrating different PECS types into BS and CFD tools (e.g., PECS integration, mesh, CTM, boundary conditions, airflow models) to enhance model reproducibility and propagation.

Experimental methods (CS, FS):

1. Explore PECS performance under dynamic conditions (CS) and long-term campaigns (FS). Include proper acclimation time in CS for consistent initial conditions, and adaptation period in FS for occupant adjustment to PECS. Longer FS may be beneficial as new behaviors take time to become habits.
2. Introduce uncertainty analysis to improve confidence in accuracy and results comparability.
3. Consider underrepresented populations (children or elderly) and evaluate PECS implementation in shared spaces accounting for occupants' response to mutual affection. Among the various types of responses, behavioral responses require further investigation to ensure PECS effectiveness, particularly in understanding usage patterns and their interaction with background system settings.
4. Provide a comprehensive description of experimental protocol, including hypothesis definition, sample size, test conditions, session design accounting for participant fatigue (CS) and annoyance (FS),



Diameter of circle = resources required to the method and effort required (computational for BS, CFD and technical for CS, FS)
Transparency of the circle = frequency of usage in the literature (relates to methods tested on PECS only)
*refers to single value predicted for the zone (applies to BS), and single measurement value in PECS affected microclimate (CS,FS)

Fig. 9. Conceptual framework for organizing simulation and experimental methods.

and monitoring setup to characterize both background and local environments.

All:

1. Assess PECS' IAQ performance, for different pollution sources and multiple study scopes.
2. Consider the impact of PECS on background and other occupants' microclimate, as it can influence design and reduce positive bias in reporting PECS performance.
3. Justify the choice of approach and KPI when assessing PECS' thermal comfort and IAQ performance, considering a reference scenario and the conditions created by PECS, its required inputs, and acknowledging any limitations.

Given the strengths and limitations of each method, this review recommends combining simulations and experiments for a more comprehensive PECS performance assessment. Fig. 10 presents a multi-method PECS evaluation framework which points out specific outcomes of each approach and how these are used throughout the design and testing phases of both PECS device and system integration deployment. Simulation-based approaches are particularly valuable during the design of PECS or building system infrastructures. They support the exploration of multiple solutions and the definition of the optimal one in terms of both PECS components design or integration strategy between PECS and background systems. In contrast, experimental approaches, whether involving recruited volunteers or actual case studies occupants, are essential for validating simulation outcomes regarding energy savings and improvements in indoor environmental quality, as they enable the direct collection of human responses including perceptual and behavioral ones that push for personalized control and dedicated PECS interface design. Some studies in the literature (e.g [31,39])., already use such combinations to assess PECS performance.

Assuming a project that covers all the stages of PECS design and test, a multi-method sequential process can be suggested as simplified in the following:

1. Use BS tools for initial assessment of PECS' performance and potential energy savings. BS can help identify the building zones where PECS integration would be most effective in achieving both energy efficiency and IEQ targets, as well as determine the most suitable type of PECS for each context. This can be used to inform an initial PECS design
2. Use CFD models to gain deeper and visual understanding into PECS heat and mass transfer mechanisms to further refine design (supply conditions, design of outlet device, PECS' positioning, space layout).
3. Test PECS with real users in CS. Note subjective human response, user-PECS interaction and inter-individual differences. This can be used to further refine and individualize design (PECS' control, user interface or dedicated algorithm for control automation)
4. Move to long-term PECS' evaluation in FS. This can result in small tweaks to design and operation based on occupants' feedback in terms of PECS use patterns or reported user experiences. Collected data on user behavior profiles and interaction with the PECS can be used as input to BS tools to re-quantify possible energy savings and compare differences with the initial check.

Additionally, future research is still needed to improve the efficiency of existing methods:

- Open data and real case repositories on occupant behavior and interaction with PECS. These can be used as inputs into building simulation tools (e.g., Modelica, IDA ICE, custom codes) to improve the accuracy of PECS simulation outcomes.
- Detailed LCC/LCA studies in BS for both new constructions and retrofits integrating PECS
- Unified KPI evaluation framework enabling comparisons among studies and future meta-analyses to quantify the benefits of PECS for human health and wellbeing, e.g., 7-point thermal sensation scale from ASHRAE 55, and standardized reporting. To achieve such a unified approach, common benchmarking reference case studies (simulation/experimental round robins with PECS-specific surveys) should be developed to test and report KPIs, enabling direct comparison across studies. Moreover, open-access repositories for simulation models, measured data, and KPI results should be

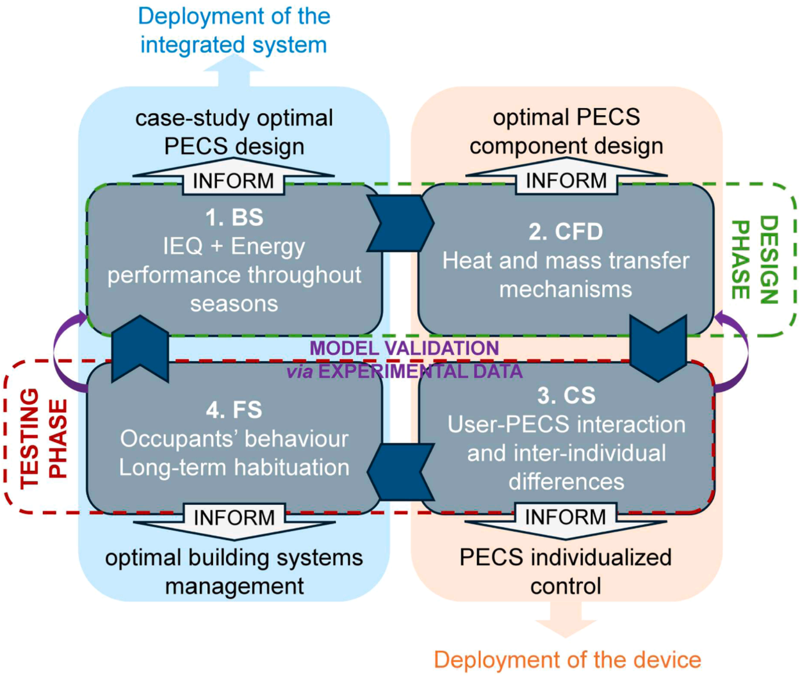


Fig. 10. Multi-method PECS evaluation framework.

promoted to ensure transparency and reproducibility. This is a planned future activity within the framework of IEA EBC Annex 87 where existing and new benchmark case studies of spaces equipped with different types of PECS will be collected from participants that have long-standing expertise in studying PECS. These benchmark case studies will report on a measured and computed set of consensus-selected KPIs that facilitate cross-study comparison in addition to establishing standardized reporting guidelines.

According to a suggested scoring grid in Table A2 based on ease of calculation, interpretation, spatial granularity, relevance to human comfort/health, and benchmarkability with respect to recognized reference values, the best ranking KPIs were the exposure reduction (ER), normalized concentration, ventilation effectiveness and personal exposure effectiveness. These KPIs are similar in their definition, ease of calculation, interpretability and suitability in assessing PECS IAQ performance. Moreover, one can easily calculate one from the other as shown in Eq. (1):

$$1 - PEE = \frac{\varepsilon_{j.noPECS}}{\varepsilon_{j.PECS}} \tag{1}$$

Out of all three, the personal exposure effectiveness would be the most suitable as it integrates the reference case with no PECS directly in its formulation. Their only disadvantage is that they only quantify the relative improvement due to PECS and thus lack benchmark or threshold values which limits inter-study comparability. Other KPIs that take care of this issue are the intake fraction or the Wells-Riley infection risk where benchmark values can be determined in addition to relative improvement with respect to reference cases. However, calculating them is more time consuming making them more suitable for simulations hence their slightly lower scores. Consequently, a combination of both KPIs is recommended.

The measurements provided in the benchmark tests can be used to validate and calibrate both energy and CFD models. Personalized ventilation systems have been extensively studied and validated using CFD tools. However, there exists only one open-access benchmark test for a computer-mounted personalized ventilation system published in [230]. More tests are needed for different air terminal devices in multi-occupied spaces for different pollution sources, under different background HVAC systems and including more measurement locations. Similar tests are also for thermal PECS (thermal chair, local radiant systems) and combinations of different types of PECS as none exist yet (Table 1).

- Multi-method, multi-domain adaptable tiered framework of PECS performance evaluation to ensure methodological consistency and reproducibility. This could accelerate acceptance of PECS in building codes and certification schemes (Fig. 10)

This review gave a comprehensive overview of simulation and experimental methods used to evaluate PECS performance, usage trends, benefits and limitations. The main limitation is its exclusion of wearable PECS and its focus on typical environmental conditions, potentially restricting generalizability of findings. Future systematic reviews should encompass wearables and wider range of environments to ensure more comprehensiveness.

CRediT authorship contribution statement

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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

Fig. A1 shows the chronological evolution of simulations studies on PECS. There was an overall increase in the number of PECS studied with BS and CFD from 2010 onwards. None of the selected studies investigated an IAQ-only PECS through BS. This is likely due to the common assumption of uniform zonal conditions in BS, which makes it difficult to evaluate the IAQ. Building detached, thermal PECS were most commonly studied with BS from 2017 and peaking in 2022. Owing to its capability to provide a detailed evaluation of the temperature and flow field in the micro-environment, CFD studies were conducted more often than BS studies. Building attached or semi-detached PECS serving both thermal and IAQ functions were commonly studied throughout the years. The majority of the studies were based on ceiling mounted or desk mounted personalized ventilation (PV) systems, both of which supplied conditioned outdoor air.

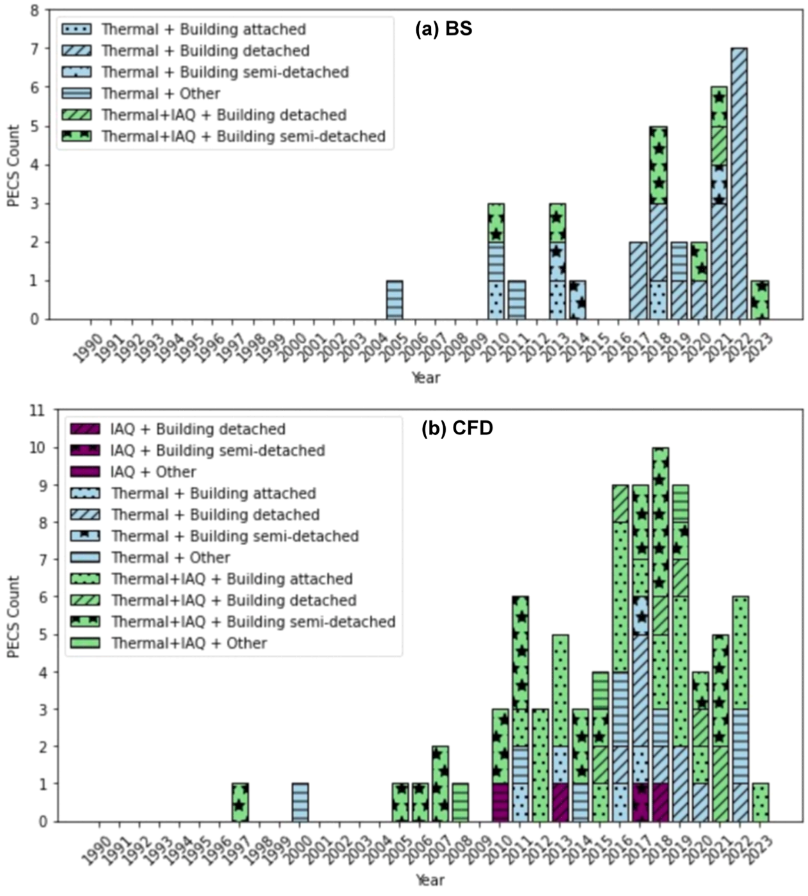

Fig. A1. Illustration of the chronological evolution of PECS’ simulation studies (BS, CFD).

Fig. A2 shows the chronological evolution of studies on PECS in chambers and in the field. Similarly to the BS studies, an increase in the number of CS was observed around 2010, with an increasingly larger share of building detached, thermal PECS from 2016. Despite earlier studies dating back to 1993, occurrences of FS were generally lower compared to the other methods. More recent studies occurred from 2015 and the majority of them were building detached, thermal-only PECS due to their ease of installation.

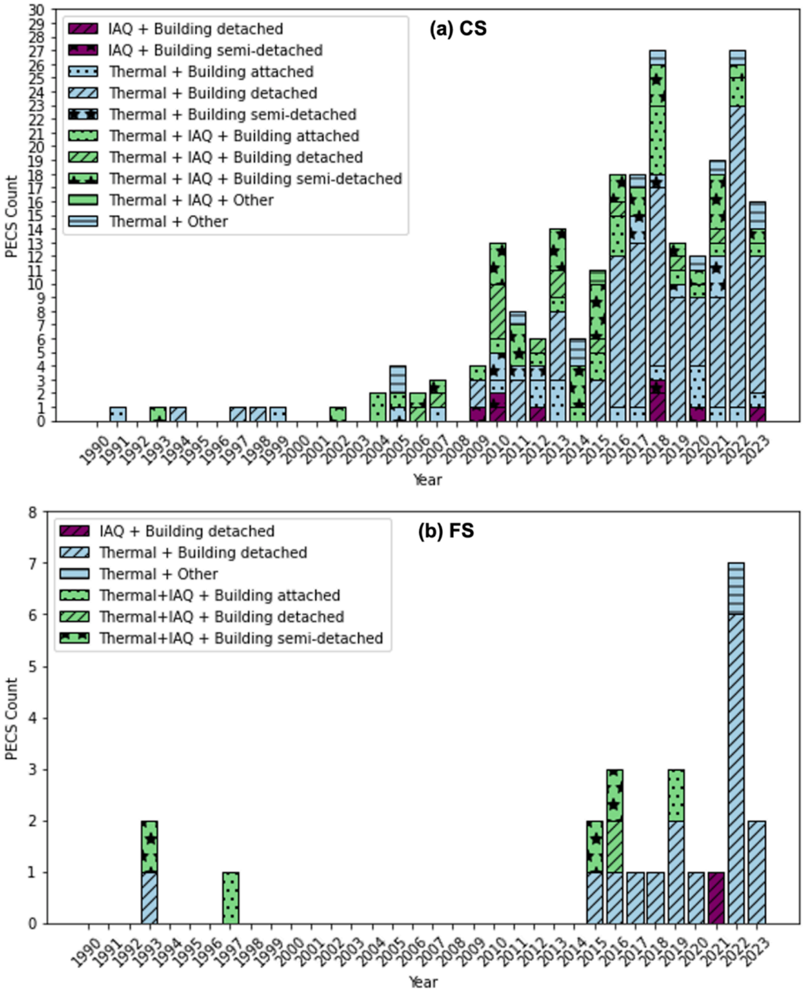

Fig. A2. Illustration of the chronological evolution of PECS' experimental studies (CS, FS).

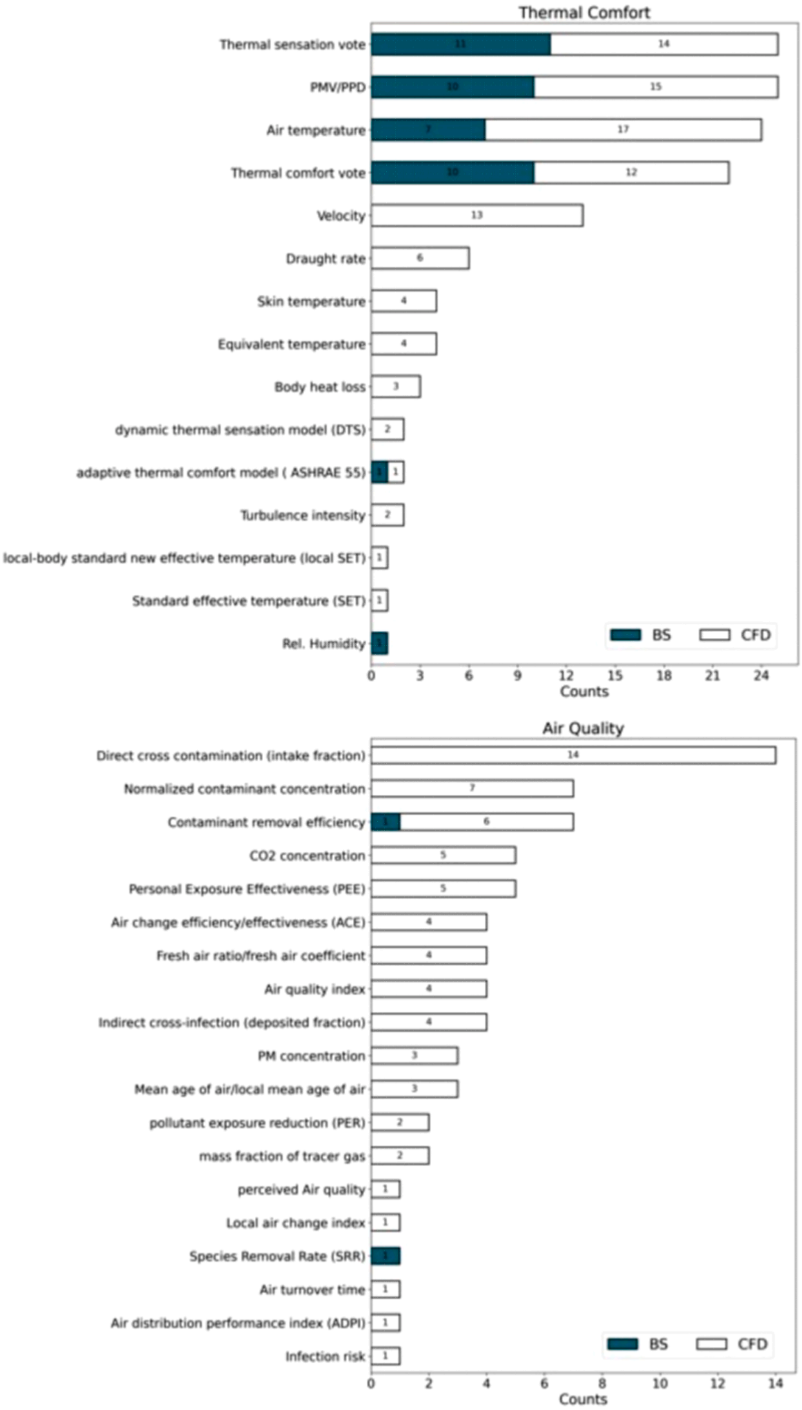

Fig. A3. Illustration of KPIs and metrics used to evaluate thermal comfort, IAQ of PECS in BS and CFD studies.

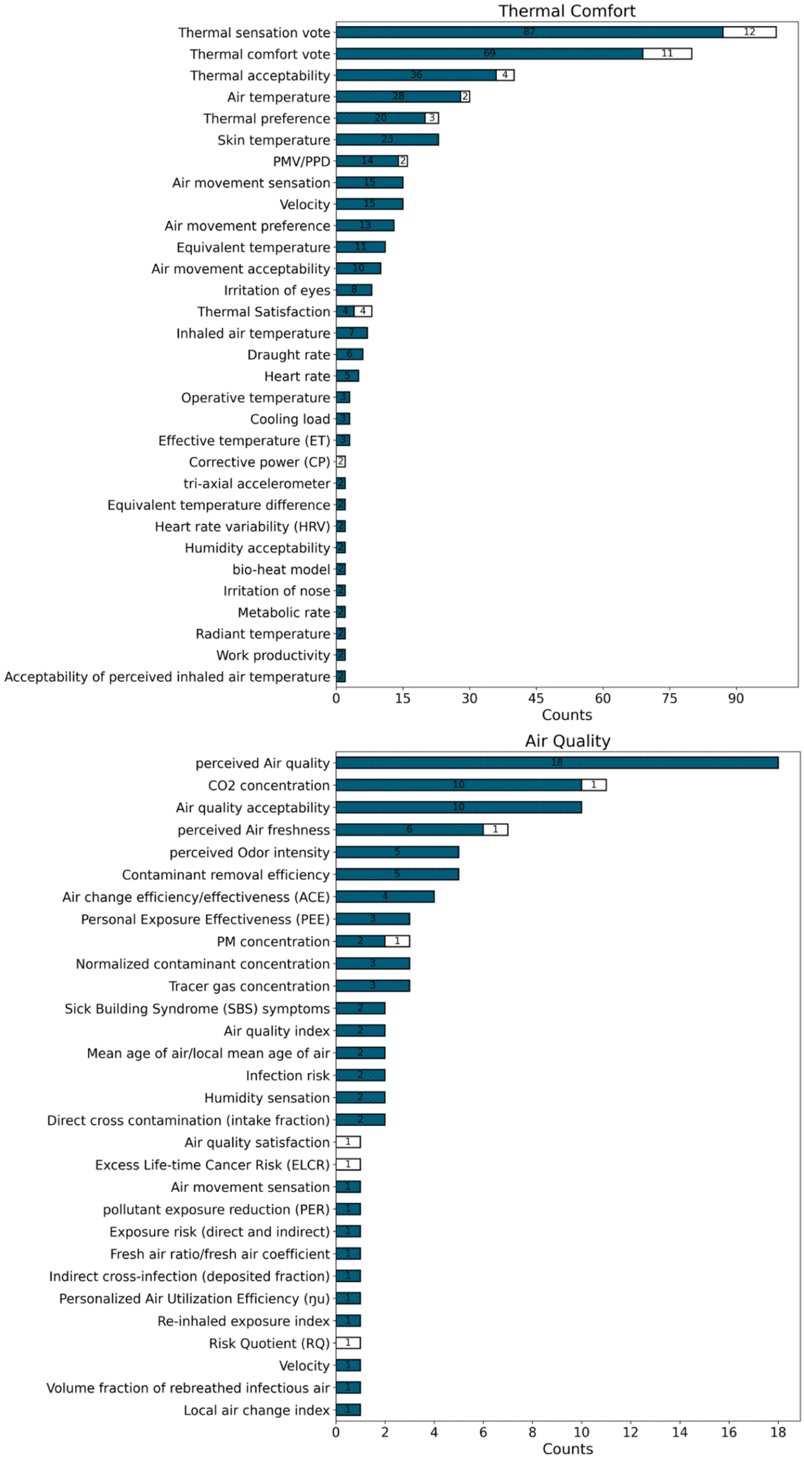

Fig. A4. Illustration of KPIs and metrics used to evaluate thermal comfort and IAQ performance of PECS in CS and FS.

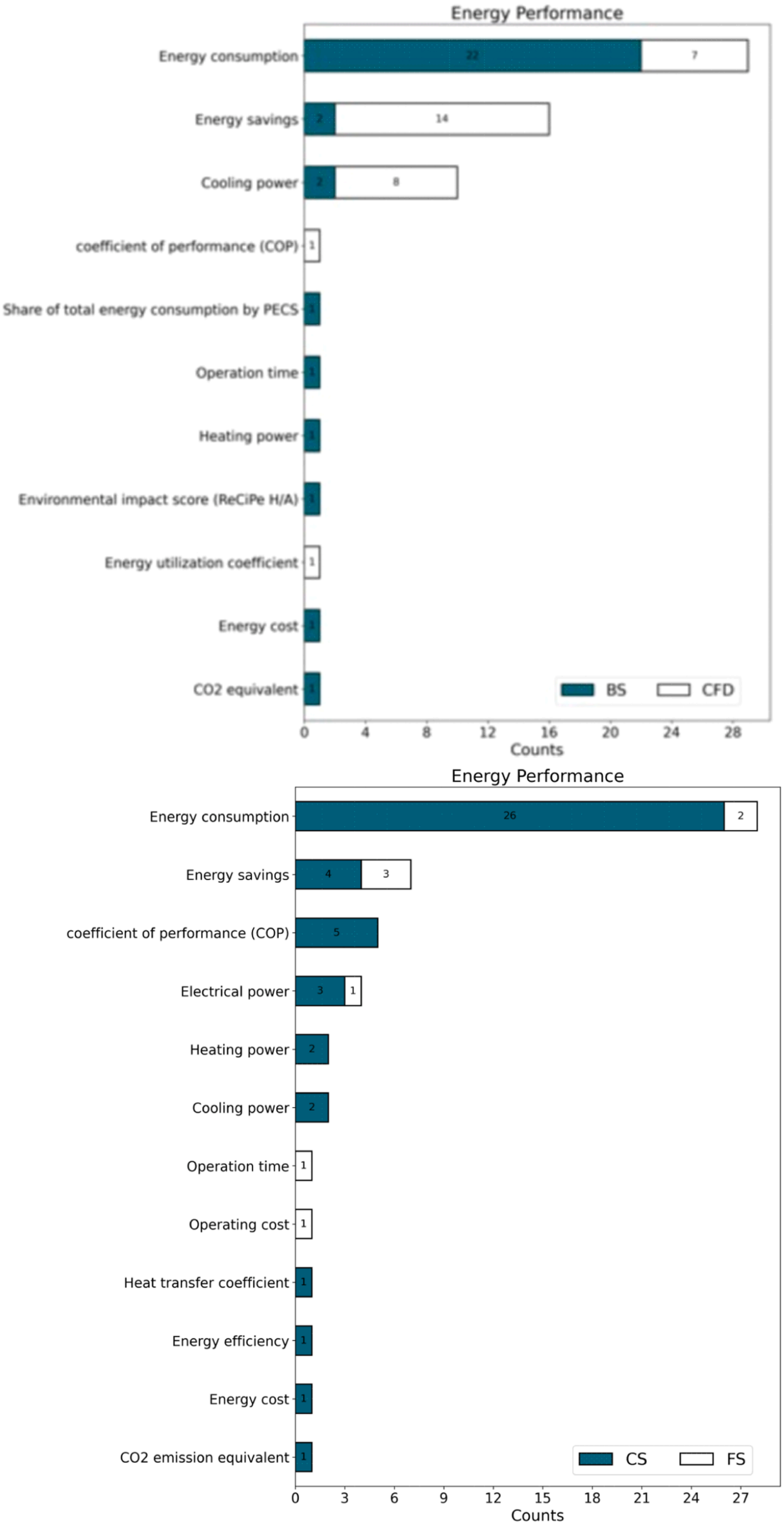

Fig. A5. Illustration of KPIs and metrics used to assess energy performance of PECS in BS, CFD, CS and FS.

Table A1
KPIs used for PECS IAQ assessment, their formulation, and their alternative terminologies used in the literature.

KPI	Formulation	Interpretation
Exposure reduction (*ER*)	$ER = \frac{C_{p,i(No\ PECS)} - C_{p,i(PECS)}}{C_{p,i(No\ PECS)}}$ (1)	0 (worst) – 1 (best): Relative reduction of the concentration of pollutants at a reference point (e.g., breathing zone) due to the use of PECS in comparison to a reference case with no PECS.
Intake fraction (*iF*)	$iF = \frac{m_{inhaled}}{m_{released}} = \frac{\int_t^{t_{exposure}} \dot{V}_{inhaled} C_{p,BZ} dt}{Emission\ rate_p\ \Delta t}$ (2)	0 (best) – 1 (worst): mass of pollutants inhaled by occupants over the initial mass released. It considers the inhalation rate of occupants and exposure time but requires precise knowledge of pollution emission rates over time. Ideal for controlled experiments or simulations but not PECS deployment in the field
Deposited fraction (*DFr*)	$DFr = \frac{N_{particles\ deposited\ on\ surface}}{N_{particles\ released}}$ (3)	0 (best) – 1 (worst): ratio of number of particles deposited on surfaces close to occupant over number of particles released. It requires precise knowledge of the latter
Confinement index (*CI*)	$CI = \frac{N_{particles\ confined\ in\ the\ microclimate}}{N_{particles\ released}}$ (4)	0 (worst) – 1 (best): ratio of number of particles confined in the microclimate over number of particles released. It requires precise knowledge of the latter. It indicates the efficiency of the system in containing the spread of particles in the space
Concentration asymmetry (ΔC)	$\Delta C_{< 1.8m} = \lvert C_{front} - C_{back} \rvert$ (5)	Difference in volume-averaged concentrations between front and back of the occupant in the occupied zone in the space. Lower values indicate the mixing effect created by the system (good) and higher values indicate the sharp gradients created by the system (bad)
Well-Riley infection risk (P_i)	$P_i = 1 - e^{-C_{p,BZ} \dot{V}_{breathing} t}$ (6)	Probability of infection due to exposure to a certain pollutant concentration at a certain time. It considers the inhalation rate of occupants and exposure time.
Normalized concentration (C_n)	$C_n = \frac{C_{p,i}}{C_{p,exhaust}}$ (7)	0 (best) – 1 (worst): ratio of pollutant concentration at a reference point *i* over exhaust concentrations. Equal to $1/\varepsilon_j$ for $C_{p,PECS\ supply} = 0$.
Ventilation effectiveness (ε_V %, ε_j %, *VE*)	$\varepsilon_V = \frac{C_{p,exhaust} - C_{p,i}}{C_{p,exhaust} - C_{p,supply}}$ (8) (also known as air quality index AQI)	0 (worst) – 1 (best): Benchmarks concentration of pollutants at a reference point due to the use of PECS with concentration at the exhaust (most polluted) and supply (cleanest)
	$\varepsilon_j = \frac{C_{p,exhaust} - C_{p,supply}}{C_{p,i} - C_{p,supply}}$ (9) (also known as contaminant removal effectiveness CRE)	>1 with no upper limit: Benchmarks concentration of pollutants at a reference point due to the use of PECS with concentration at the exhaust (most polluted) and supply (cleanest)
Personal exposure effectiveness (*PEE* %, ε_p %)	$PEE = \frac{C_{p,inhaled\ no\ PECS} - C_{p,inhaled\ with\ PECS}}{C_{p,inhaled\ no\ PECS} - C_{p,PECS\ supply}}$ (10)	0 (worst) – 1 (best): Relative reduction of the concentration of pollutants at a reference point due to the use of PECS in comparison to a reference case with no PECS. Refers to the % of PECS supplied air in the inhaled air. Equal to the *ER* with $C_{p,PECS\ supply} = 0$
(modified) Personal exposure effectiveness (PEE_m %, $\varepsilon_{p,m}$ %)	$PEE_m = \frac{\%\ RA_{exhaust} - \%\ RA_{i(PECS)}}{\%\ RA_{exhaust} - \%\ RA_{PECS}}$ (11)	0 (worst) – 1 (best): Relative reduction of the % of return air at a reference point due to the use of PECS in comparison to a reference case with no PECS.
Pollutant exposure reduction (*PER*)	$PER = 1 - \frac{C_{p,inhaled}}{C_{p,ambient}}$ (12)	0 (worst) – 1 (best): Benchmarks concentration of pollutants at a reference point due to the use of PECS with ambient concentration (average in the room).
Air distribution index (*ADI*)[*]	$ADI = \sqrt{N_{TC} \times N_{AQ}}$ (13) $N_{TC} = \frac{T_{a,exhaust} - T_i}{T_{a,body} - T_i} \times \frac{1}{PPD}$ $N_{AQ} = \frac{\varepsilon_j}{PD}$	0 (worst) with no upper threshold: Square root of the multiplication of the thermal comfort and IAQ numbers that are ratio of objective to subjective measures of comfort. Higher values indicate better overall indoor environmental quality.
Mean age of air (local): *MAA*, τ in seconds	$\frac{\partial(\rho\tau)}{\partial t} + \frac{\partial(\rho u_j \tau)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_i \frac{\partial \tau}{\partial x_j}\right) + \rho$ (14) $\tau = 0\ at\ supply\ and\ \frac{\partial \tau}{\partial t} = 0\ at\ exhaust$	Indicates the average time that air particles have spent inside a space since entering. Low values indicate that clean air is reaching the space quickly while higher values indicate stagnation
Air change effectiveness/efficiency (*ACE*) (-)	$ACE = \frac{\tau_{exhaust}}{\tau_i}$ (15)	Ratio of the mean age of air at the exhaust to that at a reference point. It helps evaluate how quickly air at a particular point is being removed compared to the average age of air being exhausted from the space. <1 (good): air at point *i* is removed faster than average, >1 (bad): slower than average
Mean Air change effectiveness/ efficiency (*MACE*) (-)	$ACE = \frac{\tau_{exhaust}}{2.\tau_i}$ (16)	Similar to ACE. A bit stricter as it compared to half the exhaust air age. <1 (good), >1 (bad)
Occupied air change effectiveness/ efficiency (*OACE*) (-)	$OACE = \frac{\tau_{micro}}{2.\tau_i}$ (17)	Benchmarks the mean age of air at a reference point to that of a polluted reference point in the occupied zone. <1 (good), >1 (bad)
Air turnover time (*ATT*) in minutes	$ATT = \frac{V_{room}}{\dot{Q}_{supply}}$ (18)	Ratio of the room volume to the supply flow rate to room. Represents the time required to completely replace the air in a space once through ventilation. It's a basic indicator of how frequently the air volume is renewed and is closely related to air change rate (ACH). Shorter ATT = faster air renewal, Longer ATT = slower replacement

[*] Combined IEQ index.

Table A2
Scoring grid of KPIs used for PECS IAQ assessment.

KPI	Ease of calculation via simulations or measurements[a]	Benchmarkability with respect to threshold guideline values[b]	Relevance to human health/ comfort[c]	Suitability for PECS (spatial granularity)[d]	Interpretability[e]	Score (out of 12)[f]
Exposure reduction (*ER*)	×××	×	××	××	××	10
Intake fraction (*iF*)	×	××	××	××	××	9
Deposited fraction (*DFr*)	×	×	×	××	×	6
Confinement index (*CI*)	××	×	×	×	××	7
Concentration asymmetry (ΔC)	××	×	×	××	×	7
Well-Riley infection risk (P_i)	×	××	××	××	××	9
Normalized concentration (C_n)	×××	×	××	××	××	10
Ventilation effectiveness (ε_V %, ε_j %, *VE*)	×××	×	××	××	××	10

(*continued on next page*)

Table A2 (*continued*)

KPI	Ease of calculation via simulations or measurements[a]	Benchmarkability with respect to threshold guideline values[b]	Relevance to human health/ comfort[c]	Suitability for PECS (spatial granularity)[d]	Interpretability[e]	Score (out of 12)[f]
Personal exposure effectiveness (*PEE* %, ε_p %)	×××	×	××	××	××	10
(modified) Personal exposure effectiveness (PEE_m %, $\varepsilon_{p,m}$ %)	××	×	×	××	××	8
Pollutant exposure reduction (*PER*)	×××	×	××	××	×	9
Air distribution index (*ADI*)*	×	×	××	××	×	7
Mean age of air (local): *MAA*, τ in seconds	×	×	×	××	××	7
Air change effectiveness/ efficiency (*ACE*) (-)	×	×	×	××	××	7
Mean Air change effectiveness/efficiency (*MACE*) (-)	×	×	×	××	××	7
Occupied air change effectiveness/efficiency (*OACE*) (-)	×	×	×	××	××	7
Air turnover time (*ATT*) in minutes	×××	×	×	×	×	7

[a] ×: difficult to calculate both via simulations and experiments, requiring several steps; ××: difficult to calculate either via simulations or experiments; ×××: straightforward to calculate in both simulations and experiments.

[b] ×: cannot be benchmarked; ××: can be benchmarked.

[c] ×: weak link to human direct or indirect objective exposures; ××: strong link to direct or indirect objective exposures; ×××: strong link to direct or indirect objective exposures and subjective experience.

[d] ×: non suitable; ××: suitable.

[e] ×: easy to interpret results; ××: difficulty in interpreting results.

[f] < 3: KPI is not relevant and difficult to calculate; 3–6: Mediocre KPI, needs fundamental improvement to reflect PECS performance; 7–9: Good KPI, needs improvement in certain aspects to reflect PECS performance; 10–12: Strong KPI of PECS performance. Needs minor improvement.

Table A3
Adopted mesh types and mesh metrics in PECS CFD studies.

Mesh type	Description	(%) of studies[*]
Hexahedral structured	High accuracy but may be challenging for complex curved geometries	14 %
Tetrahedral/polyhedral unstructured	Less accurate than hexahedral meshes due to their higher numerical diffusion, tetrahedral and polyhedral elements can easily conform to irregular and curved surfaces (furniture, human body)	43 %
Hybrid	Combination of the two above: Unstructured grids in the microenvironment containing the occupants and the PECS and a structured mesh in the rest of the space	8 %
Skewness	measure of how distorted a mesh element is compared to an ideal shape, $0.5 <$ target value < 0.9 for tetrahedral/ polyhedral meshes and < 0.2 for structured meshes	Only 26 % report 1 or 2 of these metrics
Aspect ratio	ratio of the longest to the shortest edge of a mesh element, Values of 10–50 near boundary layer cells is preferred and lower than 5 in the background space. This highlights the importance of inflation layers near boundary layer cells.	
Orthogonality	measures of how close an element's angles are to the ideal: 90° for hexahedral meshes, 60° for tetrahedral. Acceptable target values range from 0.5 to 0.85.	
Grid growth rate	measures how quickly cell sizes grow. A target value < 1.2 denotes a smooth transition.	
Mesh sensitivity analysis	ensures quality of simulation outputs (independent of the mesh) by sequential refinements until a 5 % maximum relative error is reached	40 %

[*] 35 % of studies do not detail their adopted mesh.

Table A4
Adopted CTMs in PECS CFD studies.

CTM type	Description	(%) of studies
realistic	replica of the curved human body geometry obtained from 3D scanning or online libraries. Already in use from the early 2000s	54 %
simplified	simplified cylindrical geometry ignoring complex curved features of the body	21 %
rectangular	segments are rectangular boxes. still looks like a human. Some studies are even recent dating back from 2019 to 2023 and do not make clear the choice of this simplification	15 %
single segment	rectangular or cylindrical box, adopted by studies dating back to 2008, 2014. Studies do not make clear the choice of this simplification	10 %

Table A5
List of CS thermal comfort KPIs used only once.

thermal comfort KPIs
cochlear temperature
thermal discomfort (DISC) / Gagge's DISC
user interactions with PECS: number of interactions
user interactions with PECS: level of selected airspeed
SBS symptoms: headache
SBS symptoms: difficulty in thinking
SBS symptoms: tiredness
UC Berkeley Comfort Model
quasi-steady state model
turbulence intensity
body surface temperature
electroencephalogram (EEG)
photoplethysmography (PPG)
clothing insulation
blood flow
sleep quality
inhaled air temperature sensation
irritation of throat
irritation of face
irritation of head
air movement comfort
core temperature
irritation of lips
air movement expectation
skin wetness sensation
rate of perceived exertion (RPE)
body heat loss
heat removal effectiveness
corrective power (CP)
acceptable temperature threshold
body cooling effect
heating load
humidity sensation
standard effective temperature (SET)

Data availability

Data will be made available on request.

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