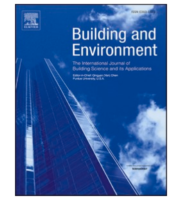
A framework for assessing the energy performance of Personalized Environmental Control Systems (PECS) for heating, cooling and ventilation

Building and Environment 265 (2024) 111925

Contents lists available at ScienceDirect

# Building and Environment

journal homepage: www.elsevier.com/locate/buildenv




# A framework for assessing the energy performance of Personalized Environmental Control Systems (PECS) for heating, cooling and ventilation

Marco Perino, Matteo Bilardo *, Enrico Fabrizio

*TEBE Research Group, Department of Energy (DENERG), Politecnico di Torino, Corso Duca Degli Abruzzi 24, 10129, Torino, Italy*

A R T I C L E I N F O

*Keywords:*
Thermal comfort
Personalized environmental comfort system
PECS energy efficiency
Personalized comfort efficiency
Thermal comfort energy assessment

A B S T R A C T

This study presents a methodological framework for assessing the energy performance of Personal Environmental Control Systems (PECS), aiming to address the existing gaps in standardized evaluation approaches. Initially, a systematic approach to delineate the distinct spatial control volumes associated with PECS is presented, facilitating the classification and comparison of various system types. Utilizing this framework, the study introduces definitions for energy efficiency and effectiveness specific to PECS, providing a procedure for the experimental assessment of the quantities related to these definitions. To validate the proposed framework, the method was applied to an illustrative case study involving two PECS under varying operational conditions – heating and cooling. The experimental results provide insights into the energy performance of the evaluated PECS, highlighting the framework's applicability and effectiveness in assessing their energy efficiency. The study underscores the importance of systematically evaluating PECS energy performance, offering a robust methodology that can guide future research and development efforts in this domain.

| | |
|---|---|
| **Acronyms** | |
| CP | Corrective Power |
| CPE | Corrective Power Efficiency |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IEA | International Energy Agency |
| PCD | Personal Comfort Devices |
| PCS | Personal Comfort Systems |
| PECS | Personalized Environmental Control Systems |
| PTMS | Personal Thermal Management System |
| PV | Personalized Ventilation Systems |
| RES | Renewable Energy Sources |
| TAC(S) | Task Ambient Conditioning System |
| **Symbols** | |
| $\Phi_{PECS}$ | PECS power, [W] |
| $\eta_{PECS}$ | PECS efficiency [−] |
| $\omega_{PECS}$ | PECS ventilation effectiveness [−] |
| $\Delta L$ | Thermal load, [W] |
| $\Delta L^*$ | Ideal supplementary power, [W] |
| C | Convective rate, [W] |
| $C_k$ | Conduction rate, [W] |
| $C_o$ | Background pollutant concentration, [μg/m$^3$], [ppm] |
| $C_{res}$ | Pollutant concentration in air flow, [μg/m$^3$], [ppm] |
| $C_{ve}$ | Sensible heat losses through respiration, [W] |
| $D^*$ | Inhaled pollutant dose - ideal, [μg/m$^3$], [ppm] |
| $D_{PECS}$ | Inhaled pollutant dose - actual with PECS, [μg/m$^3$], [ppm] |
| $E_{sk}$ | Latent heat losses through the skin, [W] |
| $E_d$ | Heat losses through skin transpiration (vapour diffusion), [W] |
| $E_{sw}$ | Heat losses through sweating, [W] |

(*continued on next column*)

(*continued*)

| | |
|---|---|
| $E_{ve}$ | Latent heat losses through respiration, [W]. |
| I | Clothing insulation, [m$^2$K/W], [clo] |
| M | Metabolic rate, [W], [met] |
| P | Thermal power, [W] |
| $R_{res}$ | Sensible and latent heat losses due to respiration, [W] |
| R | Radiative rate, [W] |
| RH | Relative humidity, [%] |
| T | Temperature, [°C], [K] |
| TCC | Temperature Correction Capacity, [K] |
| TCCE | Temperature Correction Capacity Efficiency, [W/K] |
| v | Velocity, [m/s] |
| $\dot{V}$ | Air flow rate, [m$^3$/s] |
| W | Output mechanical power, [W] |
| **Subscript/Superscript** | |
| * | Comfort condition achieved ($\Delta L = 0$) |
| a | Ambient |
| b | Background environment |
| cl | Clothes |
| eq | Equivalent |
| exh | Exhaust |
| Me | Micro-environment |
| mr | Mean radiant |
| o | Outdoor |
| PECS | Personalized Environmental Control Systems |
| res | Respiration |
| Set-point | Set point conditions |
| sk | Skin |

* Corresponding author.
*E-mail address:* matteo.bilardo@polito.it (M. Bilardo).

https://doi.org/10.1016/j.buildenv.2024.111925
Received 17 April 2024; Received in revised form 23 July 2024; Accepted 5 August 2024
Available online 6 August 2024

## 1. Introduction

Energy consumption is a crucial factor in achieving optimal indoor environments. The growing demand for comfortable indoor spaces, driven by both the residential and commercial sectors, has led to a significant increase in the deployment of air conditioning systems worldwide. The International Energy Agency (IEA) has reported that the energy consumption for space cooling is the fastest growing use of energy in buildings, and will more than triple by 2050 if current trends persist [1]. This surge in energy demand not only poses significant challenges for sustainable energy management but also exacerbates environmental concerns, including greenhouse gas emissions.

The efficient control of indoor comfort is intricately linked to air conditioning consumption, which accounts for a considerable portion of building energy use. Studies indicate that heating, ventilation, and air conditioning (HVAC) systems can contribute to as much as 38 % of worldwide energy consumption, both in residential (38 %) and commercial/industry (47 %) sectors [2]. Consequently, there is an immediate requirement to develop and implement strategies that enhance energy efficiency without compromising occupant comfort.

The indoor environmental control in air-conditioned buildings is typically achieved using centralized mechanical HVAC systems. For decades the ideal solution was considered that of "perfect mixing". This involved the goal of the system being to provide a set of indoor conditions as uniform as possible (air temperature, relative humidity, pollutant concentration) [3]. Most HVAC systems continue to be designed and constructed based on this principle. Nevertheless, it has been recognized that conditioning the entire enclosed space within a building is often unnecessary and constitutes an inefficient use of resources. In reality, only a fraction of the total room volume is occupied by individuals and, consequently, requires conditioning.

In response to these considerations, "Displacement Ventilation" systems were conceptualized. Initially implemented in industrial settings, specifically within the welding industry and shipyards in Scandinavia and Germany towards the end of the 1970s, these systems have since gained popularity in civil buildings as well [4,5]. The possibility of providing the required thermal comfort conditions and IAQ just in the occupied zone – if the system is properly designed and controlled – allows to achieve better indoor environmental conditions with reduced energy consumption. Nevertheless, even if displacement systems may represent a first step toward a more efficient air conditioning, the underlying idea is still that of controlling the entire room and operate the HVAC system under spatially uniform conditioning. At best, this approach results in two distinct zones, each with uniform indoor conditions, rather than directly meet to the occupants' needs.

Consequently, the traditional approach to the air conditioning results in pronounced energy consumption [6–9] and leads to energy waste due to the stringent control of non-occupied spaces [10]. In addition, it struggles to achieve complete occupant satisfaction (reaching only 80 % at best [11,12]) and cannot effectively prevent occupants from indoor air pollutants and possible cross-contamination [13–16].

In order to overcome these problems, new systems were recently developed and proposed, considering individual differences and preferences [13,17–21]. They have been variously referred to as: "Task Ambient Conditioning System" (TAC), "Personal Comfort Devices" (PCD), "Personal Comfort Systems" (PCS), "Personalized Ventilation Systems" (PV), "Personal Thermal Management System" (PTMS) and, more recently, "Personalized Environmental Control Systems" (PECS). Sometimes the name varies according to the different provided functions (e.g. cooling/heating/ventilation) [10], other times the same name/acronym classifies appliances that cover transversal and wider fields [22]. What characterizes and unifies all these systems is the central idea of directly targeting the environmental control of the "personal space" instead of the entire built volume, in contrast to conventional heating, ventilation, and air conditioning (HVAC) systems.

In essence, the new axiom on which PECS rely on is: "*making people comfortable not rooms*". This concept is illustrated in the diagrams presented in Fig. 1. In a typical mixed ventilation system (A), control over air temperature, relative humidity, and pollutant concentration is maintained without significant variations in the space domain. However, the adoption of displacement ventilation systems (B) enables the establishment of a vertical gradient in air temperature, pollutants, and other factors, potentially leading to reduced energy consumption, particularly in spaces with considerable height. In contrast, the concept of PECS systems (C) provides a localized micro-environment where the control of the climate is "reinforced", thus enabling a "loose" control of the climate in all other areas of the enclosure (which may be considered the background environment). Although the theoretical aspects of this process are relatively straightforward, in practice there is a need to first define the micro-environment and its boundary, and then to make the two environments significantly different and to thermally control them for a given period of time.

The implementation of a non-uniform conditioning system, which combines local intensified and customizable conditioning of the micro-environment around each user [10] with a conventional (centralized) HVAC system as a background control, has the potential to enhance thermal satisfaction and inhaled air quality among occupants, while simultaneously reducing energy consumption [23–26]. In recent times, there has been a notable increase in the interest of researchers and industries in PECS. This is evidenced by the growing literature on the potential advantages of PECS, including improved indoor environmental quality, occupants' satisfaction, and reduced energy demand. The number of review papers published in recent years on the topic of personalized and local control of the indoor environment is a witness to this trend (see e.g. Refs. [10,21,22,24,27,28]). Nevertheless, despite the considerable body of literature and research activity that has been conducted in this field, a comprehensive and coherent understanding of the topic, a widely accepted definition of PECS, and a standardized classification of technologies is still lacking. Moreover, a number of research questions are still open and needs to be properly addressed as underlined in Refs. [8,20]. For this purpose, in 2021 an IEA project started (IEA EBC – Annex 87 – Energy and Indoor Environmental Quality Performance of Personalized Environmental Control Systems [29]) with the objective of establishing design criteria and operation guidelines for PECS and of quantifying the benefits regarding health, comfort and energy performance. This includes also control concepts and guidelines for operating PECS in spaces with general ambient systems for heating, cooling, ventilation, and lighting. Within Annex 87 the following general and unifying definition of PECS was proposed: "*A Personalized Environmental Control System (PECS) is a system that can provide individually controlled thermal, air quality, acoustic or luminous environments in the immediate surroundings of an occupant, without affecting directly the entire space and other occupants' environment*", which comprises all the previous classifications. In fact, it includes TACS, PV, PCS, PDS and PTMS, each of which can be seen as specific taxonomy of a common family, targeting either specific functions (e.g. ventilation, heating, cooling, etc.) or "personal spaces" having different sizes (more or less close to the human body).

The identification and classification of "personal spaces", sometimes referred to as "micro-environments", "local-environments", or "comfort bubbles", remain somewhat ambiguous and undefined to date. This ambiguity arises from a confluence of terms and definitions derived from various literature sources. A systematic and standardized definition of the spatial domains within which PECS exert their localized influence, as opposed to the broader control provided by conventional HVAC systems, is still lacking. Furthermore, the majority of studies to date have concentrated on the thermal comfort and air quality aspects of PECS, with less focus on the potential for energy savings [22]. However,

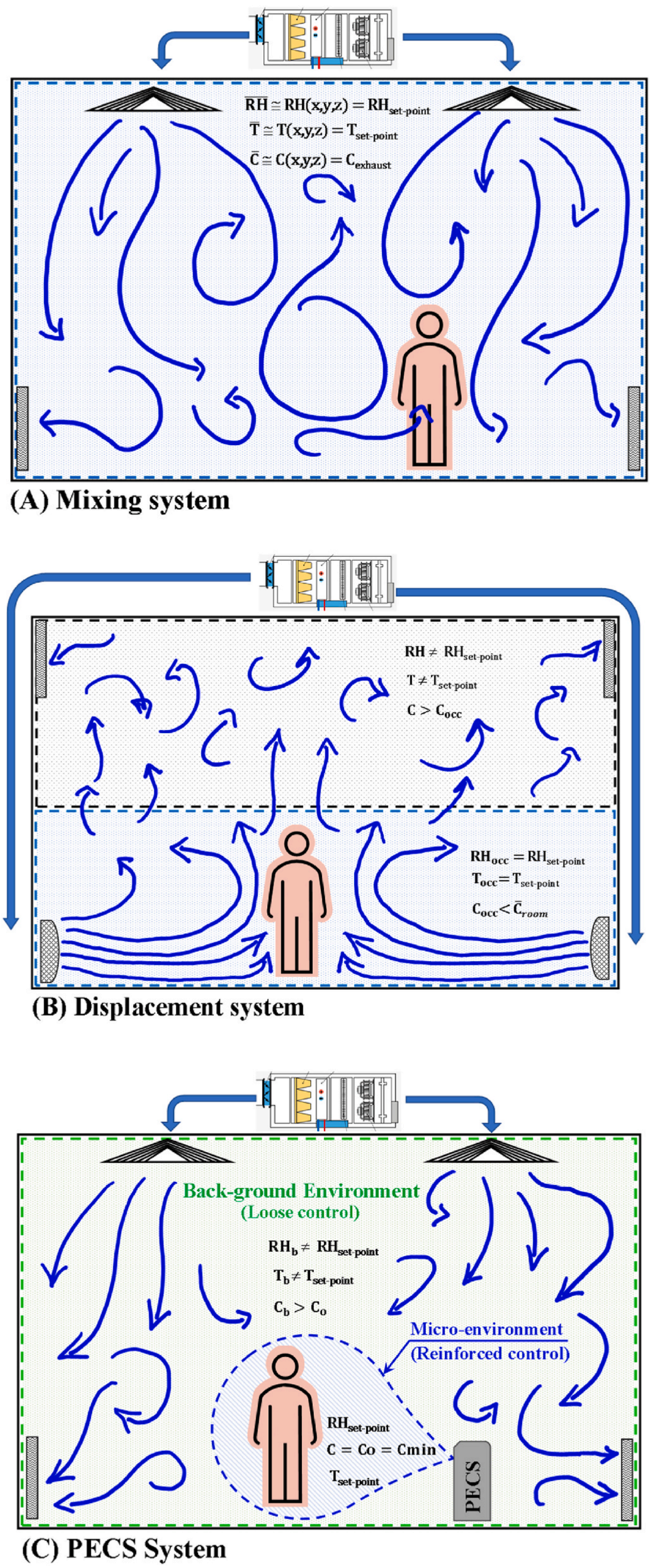



**Fig. 1.** The evolution of the concept: from the uniform conditioning of the built environment to the local intensified and customizable conditioning of the micro-environment around the human body. A – Mixing systems, B – Displacement systems, C – PECS systems.

there is evidence that the adoption of PECS can result in significant savings on the energy used by HVAC systems [10,17,21,22,30–32]. A recent literature review has identified several key areas for further research on PECS [20]. The main subjects that are worth of attention include:

- Studying the energy savings achievable with PECS. This is a key factor and, currently, it is challenging to make direct comparisons between their efficiencies.
- The scaling and comparison of the performance of various PCS devices with a comparable reference holds great potential for future research.
- Adopting a consistent framework among researchers to evaluate both direct and indirect costs would be highly beneficial (which must include a rational methodology to assess/estimate the operational energy).
- The subject of the energy savings and of reducing the installed capacity remains insufficiently explored and merits in-depth investigation.

In light of this context, the objectives of the present study are:

1. To propose an integrated and systematic approach for identifying and defining the spatial domains that characterize indoor environmental control when employing PECS.
2. To formulate and recommend a methodological framework for evaluating the energy performance of PECS devices (e.g. appliances, for the purposes of "product marking" and performance ranking). This includes assessing the potential energy savings achievable when PECS are integrated with and complemented by conventional HVAC systems (e.g. the air conditioning energy use savings during the building operation).

The study will primarily focus on PECS designed for heating and cooling, with an emphasis on their energy implications while leaving aside comfort-related qualities, which have already been extensively researched. Additionally, some of the proposed concepts may also be applicable to Personalized Ventilation (PV) systems.

## 2. Review on energy related aspects of PECS

The conceptualization of PECS initially centred on enhancing comfort conditions, air quality, and user satisfaction. More recently, they have also been acknowledged as effective measures for reducing the risk of cross-infection and cross-contamination [33–35]. Consequently, the adoption and utilization of PECS have not traditionally been motivated by energy demand reduction goals [22]. However, the recent momentum towards energy transition and decarbonization, driven by the policies of the European Union and numerous other countries [36–38], presents both significant challenges and promising opportunities for innovative technologies. Within this context, PECS could potentially play a non-secondary role, particularly concerning energy consumption in air conditioning. There are two main reasons that support this projection.

First, in the future energy scenarios the electrification of heating and cooling in buildings is considered as a key factor for reducing the emissions of the built environment, as evidenced by strategies like "*Sector Coupling and Energy System Integration*" [32]. Hypothetically, if all existing fossil-fuelled heat generation technologies in EU countries were instantaneously replaced with electrical systems, emissions from the combined heat and power sectors could be reduced by approximately 16 %. In this picture, the demand for electric heating/cooling would account for roughly 26 % of total electricity demand, translating to an additional 526 TWh on top of the EU's final electricity consumption of 2910 TWh [39]. The majority of available PECS, whether experimental prototypes or commercially available appliances, primarily utilize electricity as main energy vector and optimally aligning with this electrification scenario.

However, to achieve the desired levels of electrification through extensive penetration of renewable energy sources (RES) while ensuring the safe and efficient management of the electric grid – thus avoiding energy shortages or curtailments – it is imperative to significantly enhance the energy flexibility of end-use applications. This forms the second domain where PECS could potentially make a substantial impact. According to the Demand Response Research Center at Berkeley Lab, demand flexibility can enhance electricity affordability by enabling consumers to reduce consumption during peak pricing periods, enhance grid reliability by lowering demand during high-stress intervals, and support the transition to a cleaner electric grid by aligning consumption with renewable supply [40]. Traditionally, demand flexibility has been conceptualized as the ability of loads to adjust their consumption patterns over various time intervals, commonly referred to as "*Time Demand Flexibility*". However, the incorporation of PECS introduces a novel dimension to this concept, giving rise to what can be termed as "*Space Demand Flexibility*", thereby adding a new layer of value to the definition.

A PECS is in fact a device purposely developed to provide the desired environmental conditions only when and where they are required, without affecting in a significant way the entire conditioned environment. Compared to HVAC systems, PECS consume much less heating or cooling energy (the power consumption of personal comfort devices is typically less than 1500 W [22]) and they can be easily and flexibly switched on/off on demand. Finally, even if the framework is fragmented and non-conclusive, various studies pointed out that PECS may also offer possibilities for improving the energy efficiency of final uses [32], if they are applied and controlled properly [27]. For example, a study of Lund Madsen and Saxhof [17], dating back to the 1979, highlighted that a setpoint decrease of 1 °C in a room temperature (heating mode), backed using a heated seat for comfort purposes, would correspond to an energy saving of about 10 %. This position was lately confirmed by Zhang et al. [24]. Various other studies have shown consistent opportunities of energy savings if PECS of different type are adopted for heating, cooling, or ventilation purposes. Table 1 resumes some of the outcomes on the energy savings achievable with PECS. A more ample and comprehensive overview and analysis of energy data for PECS is available in Refs. [10,22].

Although the insights shown in Table 1 provide promising perspectives for the adoption of PECS in enhancing energy efficiency and facilitating energy transition, it is important to acknowledge that the current understanding remains fragmented, lacks complete generalizability and definitive conclusions.

First, a significant portion of the existing studies have been conducted in Asia, potentially introducing biases related to outdoor climate conditions, building construction technologies, and the national energy infrastructure of the countries where the buildings are located [47].

Second, as highlighted in various papers (see e.g. Refs. [31,32,43,44]), the achievable energy savings strongly depends on several factors (e.g. fan power, reference conditions, building type/age, occupancy profiles, control strategy, …) that can be selectively chosen for the analysis. Depending on the choice, the results may vary significantly and if the PECS are not designed and operated correctly, there could be an increased energy use instead of the intended energy saving [22,31]. Moreover, the figures related to the energy saving performance of PECS depend largely on the climatic conditions, HVAC reference configuration assumed for the comparison, cultural and individual differences which were inherent to the original test conditions [48].

Finally, each study is usually aimed at analysing a single type of PECS and it is difficult to derive a direct comparison between the efficiencies of different appliances.

Concerning the relation with the users, it is worth mentioning that the space flexibility does not only provide promising opportunities for the energy saving (thanks to the reduced requirements in the background environment), but also offer the possibility to adjust the micro-environment conditions to the personal preferences. This feature has two prominent consequences. The first one is related to the improvement of the perceived quality of the indoor environment and the occupant's satisfaction [21]. The second one, instead, is directly linked to the energy demand. In fact, the possibility offered to each person to change the working conditions of the PECS introduces a stochastic variability of the actual energy demand during the building operations, whose magnitude may vary even if the boundary conditions are kept fixed. It will be therefore, necessary to include in any procedure developed for assessing the energy savings achievable through PECS, the effect of the user's behaviour and to account for a statistical variability of the preferred thermal comfort conditions within the micro-environment.

To date, a coherent, generalisable, and widely shared framework for consistently evaluating, scaling, and comparing the performance of various PCS devices is still lacking and holds a prospect for future research. Additionally, the topic of reduced installed capacity is yet to be researched in depth [22].

In summary, PECS have the potential to effectively support the implementation of emerging and future energy policies by.

- introducing a "*Space Demand Flexibility*", beside the "*Time Demand Flexibility*",
- improving the energy efficiency of the air conditioning in the built environment [32],
- increasing the electrification rate of final uses, thus providing additional means for realizing the "*Energy Sector Integration*" [32].

However, to make these theoretical expectations to happen in practice there is still the need to address the issues that have been previously highlighted.

## 3. Definition of the PECS space domains

As previously noted, there is currently a lack of a standardized "language" or universally accepted scheme delineating the distinct spatial domains over which the various entities (the general/background HVAC system, PECS, and human body) exert their influence and exchange mass and energy fluxes.

This section will present a schematization of the rationale behind the PECS, based on the numerous concepts and ideas that have been adopted in the past and layered over time in an unsystematic manner.

When considering the aspects of energy and mass flow rates associated with PECS, three thermodynamic systems can be identified, each of one being characterized by a clearly identifiable space domain (or control volume), as schematized in Fig. 2.

- *The human body*. This is the subject towards which all the actions are (or should be) aimed at, and on which the design of the indoor environmental control should be focused. The first and ultimate goal of the air conditioning is to enhance comfort and well-being of people, rather than attempting to modify the thermo-hygrometric conditions throughout the entire confined space.
- *The micro-environment*. This is the space in proximity of the occupant. It is the local volume that surrounds the human body and is significantly influenced by the PECS (heating / cooling / ventilation). It is not possible to provide a unique and unambiguous indication on how to directly and simply identify the size and shape of this volume, since it strictly depends on the type of PECS that is used.
  A general rule that can be proposed to define the size and location of the micro-environment is based on the physics of the fluid dynamic phenomena. Adopting a methodology analogous to the one that is

**Table 1**
Possible energy savings achievable with PECS as reported in various literature sources.

| Function performed | Type | Outcome | Ref. |
|---|---|---|---|
| Heating | 14 different configurations were considered. | An energy-saving potential of up to 34 % for the HVAC system during the winter period is revealed. This occurs when the heating set point is lowered by 3.5 °C (from 21.5 to 18 °C) and personalized heating is used to back up general HVAC. | [30] |
| Ventilation | Personalized Ventilation system | The use of a secondary PV system in conjunction with a primary air-conditioning can reduce energy consumption by 15–30 %. | [41] |
| Cooling, heating, ventilation | Various (review study) | The energy savings potential of different personalized conditioning systems was in the range of 4–60 %, since thermal comfort can be maintained at ambient temperatures that are 4–5 K higher as well as lower than the temperatures recommended by current standards. | [21] |
| Cooling | Fans (e.g. means for elevating the local air speed at the occupant location) | Cooling energy savings in the range of 17–48 % have been obtained in the case of increased room temperature and elevated velocity. The reduction of the maximum cooling power due to the increase of air movement is in the range 8–22 %. The required power input of the fan revealed to be a critical factor. Traditional systems, such as ceiling, standing, tower and desk fans may not be applied to save energy (under the assumptions made in this study) | [31] |
| Cooling | Fans | Elevating the set-point temperature from 23 °C without fans to 26 °C with fans was estimated to achieve annual energy savings of 44 kWh/m$^2$. Occupants with fans use less air-conditioning when the outdoor climate is the same. Using fans could save more than 40 % of energy. | [42] |
| Cooling | Fans | When the outdoor temperature is 25–35 °C, the AC-use rate is reduced by more than 15 %, which indicates that at least 15 % of cooling energy can be saved in Mixed Mode buildings. | [27] |
| Cooling | Portable PC systems that use Phase Change Materials (PCMs) for heat rejection | A comparison between old and new offices indicates a higher CO2 emissions savings from the deployment of PECS in the old offices. Savings vary from about 0.4 % to 3.5 % for the PECs deployment. In terms of the CO2 emissions reduction the offices are not the best-case studies. For midrise apartments the savings for the extended set-point is up to 21.8 % for the old midrise apartment buildings, while this saving is up to 16.5 % for the new midrise apartment buildings. The corresponding CO2 emissions reduction varies from 0.3 % to 9.4 % and 0.5 % and 7.8 % for old and new midrise apartments, respectively. | [32] |
| Cooling | Evaporative cooler combined with chilled ceiling | Energy savings calculated in percentage compared to the reference case (chilled ceiling and displacement ventilation system alone) were between 5.8 % and 17.5 %. | [43] |
| Cooling with ventilation | Personalized ventilation (PV) | Two reference conditions were simulated. They differed on the occupancy profiles and are based on the mixing ventilation. Reduction of the energy need depends on the reference condition assumed for the analysis and varied from 1 % to 36 % in one case and from 25 to 52 % in the other. | [44] |
| Cooling with ventilation | Desk mounted/Floor mounted supply system | Total predicted energy savings 21 % (office building). Predicted energy saving potential in a new construction office bld. 4 kWh/(ft$^2$Year); peak demand saving potential 1 W/ft$^2$. | [45] |
| Ventilation | Personalized ventilation (PV) | The energy consumption with personalized ventilation may increase substantially (in the range: 61–268 %) compared to mixing ventilation alone if energy-saving strategies are not applied. The most effective way of saving energy with personalized ventilation is to extend the upper room operative temperature limit (saving up to 60 % compared to the reference case). | [46] |

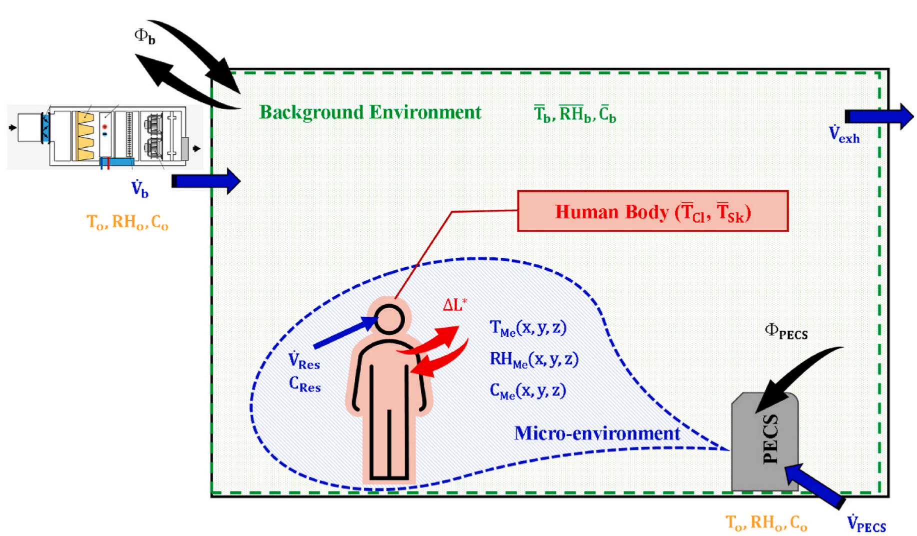



**Fig. 2.** Scheme of the thermodynamic systems and of the control volumes involved with PECS, together with the relevant quantities that govern the mass and energy flows exchanges.

used to determine the thickness of the boundary layer, we propose to identify the micro-environment as the volume within a built space where the environmental physical quantities (temperature, relative humidity, air velocity, pollutants concentration, …) are significantly[1] influenced by the direct action of the PECS.
- *The background environment*. This is the remaining volume (e.g. the complementary volume) of the room/space/enclosure, once the micro-environment is "removed"/excluded. It is usually air conditioned by means of a "general" and traditional HVAC system, which focuses its actions in this wider zone located all around the micro-environment. In general, the environmental physical quantities (temperature, relative humidity, air velocity, pollutants concentration) are relatively uniform inside the background environment and their control is less stringent than that of the micro-environment.

The identification of these three distinct control volumes also facilitates the classification of various PECS types proposed in prior studies, aligning them with their respective objectives.

For instance, TACS, PCS and PV, as introduced in Ref. [8], are primarily designed to target the micro-environment, although there are variations in the expected size of this volume. TACS are more inclined to establish larger micro-environments, whereas PCS and PV aim to minimize its size, approaching closer to the human body. Conversely, Personal Thermal Management Systems (PTMS) overcome the creation of a micro-environment and are designed to deliver the required energy and mass flow rates directly in proximity to the human body. In Fig. 2, the relevant mass (air, water vapour, pollutants), energy flow rates and physical parameters that affect the three identified thermodynamic space domains are shown.

Regardless from the adopted type of appliance, the working principles of an air conditioning system based on PECS is built on relaxing the temperature, relative humidity, and pollutants concentration requirements in the background environment, while intensifying the environmental control only inside the micro-environment [49] or – even better – at the human skin/body level. Consequently, it is possible to decrease the supply airflow rates and to extend the setpoints in a significant portion of the room volume, thereby reducing the air temperature below 20 °C in the heating season and increasing the air temperature above 26 °C in the cooling season (20 °C and 26 °C derive from comfort quality category 2 of EN 15251 [50]). This possibility is contingent upon the assumption that the occupants will be spending the majority of their time at their individual workstations (i.e., within the micro-environment) and will only intermittently occupy the background environment (during which some worsening of the comfort and IAQ conditions is acceptable [24,51]).

Furthermore, it is essential to recognize that these three control volumes represent distinct thermodynamic systems. In the context of building physics, they may be identified as three distinct thermal zones, characterized by varying environmental conditions and thermal loads [52]. As non-isolated thermodynamic systems, they are free to dynamically exchange mass (moist and dry air) and energy in accordance with the fundamental principles of thermodynamics. However, the rates of exchange in terms of mass and energy will depend on multiple factors, including ventilation strategies, air conditioning terminals used, set points and control rules. Therefore, mass and energy balances should be studied on a case-by-case basis, possibly with the support of specific experimental campaigns or computational fluid dynamics (CFD) modelling tools.

[1] For example, when their value differs more than the 20–25 % (or any other generally accepted percentage) compared to the value they assume in the – almost uniform – background environment.

## 4. Methodology

When characterizing the energy performance of a PECS, two main qualities need to be evaluated.

- the energy efficiency of the PECS itself, that allows to identify and classify the device for the sake of product certification.
- the effects of PECS on the overall space/building (HVAC system) energy use, that is, the expected energy savings.

Even though these two aspects are tightly related, their assessment requires different and specific methodologies. The first one is relevant for the design and development of PECS, the second involves the operation of the buildings.

The efficiency of PECS is, for a large extent, independent of the personal preferences and it is more closely connected to the thermo-fluid dynamics phenomena that govern the heat and mass exchange between the micro-environment and the human body. Moreover, if the main goal is that of classification/rating/ranking, the analysis must be done in steady-state conditions and with fixed and reference boundary conditions.

Conversely, if the objective is to assess the potential for energy savings associated with the utilization of PECS, the analysis must be conducted over a substantial period of time (a season or, ideally, an entire year). It must also consider non-steady conditions and, finally, must account for the variability of personal preferences, which will determine/create different conditions within each of the micro-environments present in the room.

In this paper, attention will be focused on the PECS energy efficiency, for which a methodological approach and examples of application will be introduced and discussed in more detail. As far as the energy savings potential are concerned, they will be dealt in a general way and more investigations may follow in future studies in order to generalize the results.

The most substantial contribution to this topic was done so far by Zhang et al. [24]. These researchers introduced and defined the concept of "Corrective Power" for PECS. However, this quantity is not actually a "power", but has the dimension of a temperature. It is defined as "*the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use*". Although the study provides interesting information about the effects of PECS, it does not consider any energy-related concept. Furthermore, this KPI does not derive from the application of the energy conservation law (its unit of measure being K or °C).

The next section presents the framework for obtaining an estimate of the energy efficiency of a PECS. It is based on the assessment of the thermodynamic systems introduced in section 3 and consists of the theoretical derivation of the energy efficiency from the body heat balance, followed by a procedure for measuring the quantities that can be used to derive the energy efficiency.

### 4.1. Definition and rationale of the PECS energy efficiency

In order to develop a rigorous rationale for the definition and the assessment of the energy efficiency of PECS a procedure based on the first principle of thermodynamic will be used. Moving the attention from the built environment volume, as it is the case with traditional HVAC systems, to the human body, as with PECS, determines a deep change in the way heat fluxes are managed and defined. When traditional HVAC systems are adopted the concepts of "cooling load" and "heating load" come into play, because the system is removing and/or supplying a heat flux from/to the environment.

Referring to Fig. 2, the HVAC system must, in general, exchange that precise total heat flux, $\Phi_b$ (sensible and latent; positive or negative), needed to meet the overall instantaneous room losses/gains and to keep the indoor air temperature and relative humidity at the desired set-point. However, when the focus is shifted on the occupant the heat flux is always dissipated (e.g. transferred from the body to the room). In fact, the human body works as a heat engine, where the metabolic rate M is the input energy and W is the output mechanical power. Therefore, based on the first and second principles of thermodynamics, the difference (M − W) must be compulsorily released to the environment. In steady homeothermic conditions it holds to Equation (1):

$$(M - W) = (C + R + C_k + R_{res} + E_{sk}) \tag{1}$$

Where.

- $C, R, C_k$ represent the dry heat power dissipated by the humane body through convection, radiation and conduction respectively,
- $R_{res} = C_{ve} + E_{ve}$ is the sensible and latent heat losses due to respiration,
- $E_{sk} = E_d + E_{sw}$ is the latent heat losses through the skin (sweating and water vapour diffusion).

Equation (1) is not necessarily compatible with thermal comfort. In extreme cases, it may even lead to conditions that are not compatible with life. In order to introduce the concept of comfort conditions, it is possible to utilize the concept of the heat load on the thermoregulatory system. This heat flux is defined by the Fanger theory [53,54] as ΔL and is evaluated using Equation (2) (see Fig. 3 for the scheme of the energy fluxes exchanged by the human body):

$$\Delta L = (M - W) - \left(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*\right) \tag{2}$$

In Equation (2) the quantities with the superscript "*" are evaluated in comfort conditions, and when $\Delta L = 0$ the comfort conditions are achieved.

The term $(C + R + C_k + R_{res} + E_{sk})$ in Equation (1) represents what the human body must dissipate in the actual condition (real energy balance equation). The term $(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*)$ in Equation (2) is the heat flux that the same person would dissipate in the same environment if it were in comfort conditions (energy balance equation for a subject in comfort conditions).

In case of conventional HVAC systems, the condition $\Delta L = 0$ (subject in thermal comfort) is achieved by controlling and adjusting the room environmental parameters (air temperature and velocity, relative humidity, radiant temperature, etc.) and thus by modulating the term $\left(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*\right)$. In other words, the task of the air conditioning system is that of suitably modifying the room environmental conditions and, consequently, to indirectly tune the dry (convective, conductive, radiative) and latent (sweating, transpiration, respiration, …) energy exchanges between the human body and the surrounding environment.

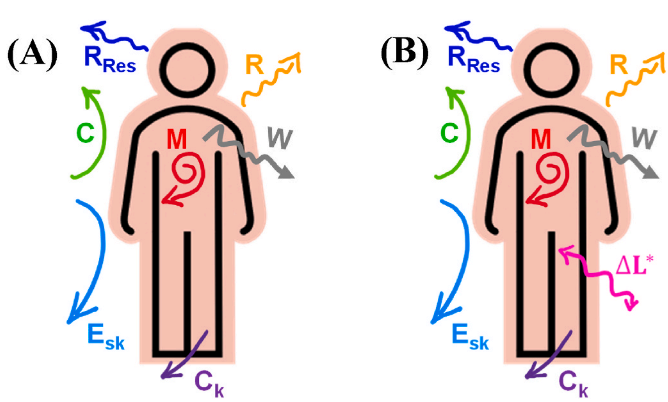



**Fig. 3.** Scheme of the energy fluxes exchanged by the human body. (A) in case of conventional HVAC systems (or free running buildings) and (B) in case of PECS.

In contrast, the use of PECS (eventually coupled with a conventional HVAC system for a loose control of the background environment) allows the relation that provides the heat load on the thermoregulatory system to be modified in accordance with Equation (3):

$$\Delta L = \left[(M - W) - \left(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*\right)\right] + \Delta L^* \tag{3}$$

In this case the term (M − W) is generally not balanced by the term $\left(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*\right)$ and the condition $\Delta L = 0$ is only reached thanks to the supplementary power $\Delta L^*$ provided by the PECS. Depending on the sign of the difference $\left[(M - W) - \left(C^* + R^* + C_k^* + R_{res}^* + E_{sk}^*\right)\right]$, the value of $\Delta L^*$ may be positive or negative (e.g. provided or removed).

In an ideal world, comfort and healthy conditions could be provided directly and only at the level of the occupant, without affecting the remaining part of the room. This is approximated in real life by means of PTMS and wearable PECS. Thus the $\Delta L^*$ can be considered as the "ideal" supplementary power.

However, in typical real operating conditions the heat flux $\Delta L^*$ is exchanged between the human body and the micro-environment, not directly with the PECS.

PECS is solely responsible for regulating the thermohygrometric conditions of the micro-environment, and thus indirectly modulating the $\Delta L^*$. This process necessitates a greater power compared to ideal PECS, which we will define and refer to as $\Phi_{PECS}$.

An equivalent logical approach may also be followed for the personalized ventilation systems (PV). In this case the aim of the PECS is to deliver at the breathing zone a flow rate of clean and fresh air. In an ideal system, the fresh air flow rate at the mouth/nose of the occupant would be precisely equal to the required inhaled respiratory air flow rate $\dot{V}_{res}$, with the minimum possible concentration of pollutants, namely, the background concentration in the outdoor air ($C_o$ in Fig. 2). Thus, the theoretical (minimum) inhaled dose $D^*$ of pollutant can be expressed by Equation (4):

$$D^* = \dot{V}_{res} \cdot C_o \cdot \Delta\tau \tag{4}$$

In practice the PECS delivers an air flow rate $\dot{V}_{PECS}$ characterized by a pollutant concentration equal to $C_{res}$ (see Fig. 2) and the actual inhaled dose of pollutant $D_{PECS}$ is represented by Equation (5):

$$D_{PECS} = \dot{V}_{PECS} \cdot C_{res} \cdot \Delta\tau \tag{5}$$

Therefore, the ideal benchmark for a PECS may be set once the heat flux $\Delta L^*$, and/or the inhaled dose $D^*$, are assessed and it becomes straightforward to define a PECS energy efficiency for heating and cooling following Equation (6):

$$\eta_{PECS} = \frac{\Delta L^*}{\Phi_{PECS}} \tag{6}$$

And similarly, a PECS ventilation effectiveness by means of Equation (7):

$$\omega_{PECS} = \frac{D^*}{D_{PECS}} = \frac{\dot{V}_{res} \cdot C_o}{\dot{V}_{PECS} \cdot C_{res}} \tag{7}$$

The efficiency and effectiveness defined by Equations (6) and (7) may be used to analyse the quality of various PECS and to easy compare their energy performance. These quantities may also be adopted by researchers and designers to evaluate in a rational and quantitative way the impact of products development and appliance modification (a procedure that, as underlined by Verhaart et al. [30] is still missing). Finally, they provide a measure of how much the real appliances are getting closer to the best ideal performance. All the quantities that appear in Equations (6) and (7) can be either assessed by means of numerical simulations and/or measurements. In this paper an example of application is given that makes use exclusively of laboratory tests (Section 4.2). Numerical methods also have promising potentialities for developing the proposed method and they are indeed worth of future studies. For the sake of clarity, Table 2 is intended to provide a summary of the innovative quantities introduced in this paper. These quantities, together with the thermophysical variables of classical comfort theory, are necessary to describe the impact of PECS on the air-conditioned environment. For a comprehensive overview of the variables discussed in this paper, please refer to the section on nomenclature.

### 4.2. *Procedure for the experimental assessment of the $\eta_{PECS}$ and practical implications*

In this paragraph some insights will be given in relation to $\eta_{PECS}$ for heating/cooling appliances. It is worth mentioning that the ideal supplementary power, $\Delta L^*$, is the heat flux that must be exchanged with the subject to assure proper comfort conditions and to balance Equation (3) with $\Delta L = 0$. Indeed, this quantity is in practice affected by the personal preferences of the thermohygrometric environment. Therefore, to determine its actual value during the all-day life operation it is necessary to conduct a series of measurements on the human body, using a number of appropriate sensors, while the subject declares to be in a state of comfort. Nevertheless, while such an approach may be useful for assessing a specific and contextualised situation, it would only be applicable to that particular individual and, therefore, would not be generalisable.

For these reasons such method is not coherent with the aim of ranking the performance of appliances and for the sake of comparison (inter comparison between different devices or before/after a technological development of the same appliance).

To this end a universal and reference procedure that provides unique and unambiguous results must be conceived and adopted. Two ways are possible to achieve this goal. One makes use of comfort models and design nominal data (e.g. nameplate data of the devices), the other is based on laboratory experiments.

In either case, however, a rather conventional choice is needed. In fact, it is necessary to establish if the subject is in comfort or not and, consequently, a comfort model must be mandatorily assumed.

There is a variety of comfort models, with different degree of complexity and detail [55], especially using PECS and when the environment is not uniform [56].

In this paper, in order to guarantee the generalizability of the application, the Fanger model was adopted [11,53,57] to determine the supplementary power, $\Delta L^*$. It is based on the simplifying hypotheses of uniform and steady state conditions over the subject and does not consider that more pleasant sensations and better thermal satisfaction of the person may be obtained by a local heating or cooling of certain part of the human body [58]. However, it has the advantage of being well know, tested, robust and easier to apply/understand. Furthermore, recent studies have found that the PMV concept provides frequently more reliable results compared to more sophisticated and dedicated comfort models (even though these lasts would be, in theory, more suitable for PECS) [59,60].

The identification of the optimal and most appropriate comfort model is of significant importance and should be the subject of future research.

Anyhow, the proposed procedure and the concept of $\eta_{PECS}$ are still valid and applicable even if a different comfort model would be adopted. This choice would simply change the way $\Delta L^*$ is quantified.

Once the ideal supplementary power $\Delta L^*$ and $\Phi_{PECS}$ are assessed, the values of the PECS energy efficiency may be calculated by means of Equation (6).

An alternative (and in principle more accurate) way of assessing $\eta_{PECS}$ is to directly and simultaneously measure both $\Delta L^*$ and $\Phi_{PECS}$. This procedure may make use of a thermal manikin and a thermostatic chamber. The majority of the studies done so far and dealing with comfort conditions achievable with PECS were conducted on thermal manikins in controlled conditions [20].

### 4.3. *Identification of the micro-environment of PECS*

Coherently with the definition given in Section 3, the micro-environment is identified as that portion of the built space where the environmental physical quantities are significantly influenced by the direct action of the PECS. In order to rationally quantify what a “significant influence” means, a procedure similar to that adopted for determining the thickness of the boundary layers in fluid flow analysis (for velocity and/or temperature) is proposed.

Limit values for the relevant parameters must be preliminarily chosen to establish if the fluid and/or local climate has to be considered as “perturbed” or not by the PECS. For example, in case of convective PECS limit values for the air speed and air temperature must be fixed: $v_\infty$ and $T_\infty$. In case of radiative PECS, the mean radiant temperature could be used: $T_{mr,\infty}$. If for a generic point within the room volume, P(x,y,z), it results $v(x,y,z) \geq v_\infty$ or $T(x,y,z) \geq T_\infty$ or $T_{mr}(x,y,z) \geq T_{mr,\infty}$ (or $T(x,y,z) \leq T_\infty$ or $T_{mr}(x,y,z) \leq T_{mr,\infty}$ in cooling mode) then the PECS is substantially modifying the local climate conditions and the point P belongs to the micro-environment, else it belongs to the background environment.

By measuring the air speed and the temperature over a grid of points that covers a sufficient portion of an open space domain (without obstacles and confinement walls) around the PECS, it is possible to determine the temperature and air velocity fields. Once these fields are known, by plotting the iso-surfaces at $v_\infty$ and $T_\infty$ the control surface of the micro-environment is defined (which coincide with the iso-surfaces at $v_\infty$ and $T_\infty$). For a heating or active cooling PECS two different micro-environments can be eventually identified, one for the air speed and one for the air temperature.

An understanding of the shape and dimensions of the micro-environment is beneficial from a design perspective. Indeed, it provides direct information on how to correctly position and orient the PECS within the room, thereby optimizing personal comfort at the workplace or the designated location of occupants. This can be considered analogous to the knowledge of air jet characteristics for the accurate design and placement of supply air grilles in rooms (see e.g. Ref. [61] chapter 20 space air diffusion).

**Table 2**
A summary of the novel variables introduced by the methodological framework for PECS energy performance evaluation.

| Symbol | Description | Unit |
|---|---|---|
| $\Delta L^*$ | Ideal supplementary power provided by PECS to reach comfort condition | [W] |
| $\Phi_{PECS}$ | Real thermal power delivered by PECS | [W] |
| $D^*$ | Minimum theoretical inhaled pollutant dose to satisfy ventilation requirements | [μg/m$^3$] or [ppm] |
| $D_{PECS}$ | Real pollutant dose inhaled with PECS | [μg/m$^3$] or [ppm] |
| $\eta_{PECS}$ | PECS energy efficiency | [−] |
| $\omega_{PECS}$ | PECS ventilation effectiveness | [−] |

## 5. Results

### 5.1. Supplementary power chart

In the present paper, the values of the supplementary power $\Delta L^*$ were assessed and subsequently reported in a chart. This was achieved through a parametric analysis, which involved solving the energy Equation (3) with $\Delta L = 0$. A set off different scenarios for the background environment were considered. The terms $C^*, R^*, C_k^*, R_{res}^*, E_{sk}^*$ were calculated adopting the equations provided by ASHRAE Std. 55 and EN-ISO 7730 [11,57]. The air temperature, relative humidity, air speed, radiant temperature and thermal resistance of the clothing were varied in the ranges shown in Table 3. The amplitude of variation of these parameters was chosen accordingly to the findings of [22], where it was highlighted that most of the studies done so far on PECS spanned from a minimum ambient temperature of about 8 °C (heating PECS) to a maximum of about 34 °C (cooling PECS). Moreover, the following hypotheses were done:

- sitting person doing office activity (M = 1.2 Met). Negligible mechanical work (W = 0),
- The value of the mean radiant temperature was assumed to be:
  - o $T_{mr} = (T_a - 0.2)$ °C if $T_a \leq 20$ °C (e.g. heating season),
  - o $T_{mr} = T_a$ if 20 °C < $T_a \leq 26$ °C (e.g. mid-season. Balanced heating/cooling or neutrality),
  - o $T_{mr} = (T_a + 0.2)$ °C if $T_a > 26$ °C (e.g. cooling season)
- The value of the clothing thermal insulation was assumed to be:
  - o $I_{cl} = 1$ if $T_a \leq 23$ °C,
  - o $I_{cl} = 0.7$ if $T_a > 23$ °C.

The results are presented in Fig. 4 and refer to a subject with an average skin surface area (e.g. 1.80 $m^2$).

It is worth noting how in a perfectly ideal condition the use of PECS would allow to reach a comfort condition for the "average" occupant[2] by just employing a thermal power lower than 150 W/person. This is a value far smaller than the typical heating/cooling loads exchanged by traditional HVAC systems (such values being, for a generic office space, roughly around 1200–1500 W/person for heating and around 500–700 W/person for cooling, if a standard occupant density of 5 persons per 100 $m^2$ is assumed [12]).

The power $\Phi_{PECS}$ can be either directly obtained from the nominal data of the appliance (nameplate data) or, for a more accurate estimate, directly measured during the operation of the appliance under real conditions and in a set-up that assure comfort conditions for the occupant.

### 5.2. Example of application on two commercial PECS

In order to provide a practical demonstration of the proposed procedure a case study is here presented.

Two commercially available Bladeless Fan Heater/Coolers were tested in the laboratory (in the following indicated as PECS "A" and "B"); they are representative of a family of PECSs, whose market penetration is becoming significant.

PECS "A" is characterized by a nominal air flow rate of about 450 $m^3$/h (at maximum fan speed) and by two levels of heating power (generated by an electrical resistance): $P_{max} = 1400$ W, $P_{min} = 1000$ W. The power absorbed by the fan is about 50 W.

PECS "B" is characterized by a nominal air flow rate of about 360 $m^3$/h (at maximum fan speed) and by a maximum heating power (generated by an electrical resistance) of $P_{max} = 1500$ W (that can be modulated). The power absorbed by the fan is about 40 W.

The experimental campaign was performed for two different operating modes: cooling mode (actually, isothermal conditions; the device just modifies the air velocity field over the body of the person and thus cools the occupant) and heating mode (the device modifies both the air velocity and temperature fields).

In a first phase the two PECS were tested in a large space to determine shape and size of the micro-environment and other features of the air jets in unconfined conditions. Subsequently, the appliances were located inside a typical single office room (of 18 $m^2$ for the heating mode and 12 $m^2$ for the cooling mode) in order to develop objective and subjective comfort analyses and to assess the ideal supplementary power, $\Delta L^*$.

The two analysed PECS are exerting their action mainly by means of convection, therefore the relevant climatic parameters for defining the micro-environment are the air speed and temperature, for which the following limit values were chosen.

- $v_\infty = 0.40$ m/s
- $T_\infty = 22$ °C.

Various tests were done before adopting the air speed limit, $v_\infty$, equal to 0.40 m/s. It emerged that lower values are too influenced by parasite air flows in the environment generated by stochastic natural convective phenomena. Choosing velocities lower than 0.40 m/s leaded to fuzzy iso-velocity surfaces and the control volume of the micro-environment was not clearly definable.

The temperature and air velocity fields were assessed in the laboratory using an automatic positioning system that allowed to cover a Cartesian grid of evenly spaced points. A total of 1080 nodes distributed over 9 parallel planes were used, as schematically represented in Fig. 5. The air velocity was measured by means of a Gill ultrasonic anemometer, which provided the velocity vector and allowed to also analyse – to certain extent (the scan rate was of 4 Hz) – the turbulence intensity. The features of the ultrasonic anemometer are resumed in Table 4. The temperature was measured by means of a J-type thermocouple (a calibration of the whole measurement chain was done. The resulting accuracy is ±0.3 °C).

#### 5.2.1. Identification of the micro-environment

During the tests, besides detecting the micro-environment, the air jets was also characterized in terms of throw (for a terminal velocity of 1.5 m/s), decay of the air velocity and temperature along the axis (these results are not shown here for the sake of conciseness).

Figures from 6 to 8 shows the results of the measurements; the red dot represent the position of the PECS. In these graphs the fluid dynamic micro-environment is bounded by green surfaces (iso-velocity surface at $v_\infty = 0.40$ m/s) and the thermal micro-environment is bounded by blue surfaces (iso-temperature surface at $T_\infty = 22$ °C).

In order to give an information "at a glance" of the inter relation between the micro-environment and a hypothetic occupant, the shape of a human body in sitting position is plotted in Figs. 6–8. It is worth mentioning that these "bodies" are just virtual surfaces; their shape was obtained from the virtual manikin adopted for CFD simulations and refers to an average size person. This means that the sitting manikin in not physically interacting with the thermal and fluid fields. The three

**Table 3**
Set of environmental parameters and subjective variables adopted for the assessment of the $\Delta L^*$.

| $T_a$ [°C] | RH [%] | $v_a$ [m/s] | $T_{mr}$ [°C] | $I_{cl}$ [clo] |
|---|---|---|---|---|
| 8–34 | 30–70 | 0.15–0.90 | 8.3–34.2 | 0.7–1 |

[2] Data shown in Fig. 4 have been calculated assuming that the behaviour and personal preferences of the occupant are those represented by the Fanger comfort model for the average person. Individual sensitivity may lead to variations.

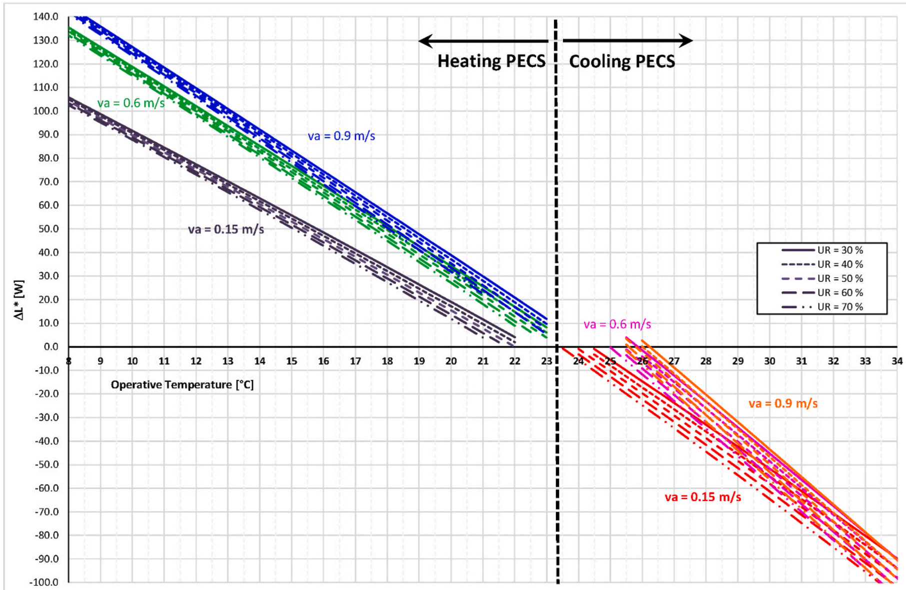



**Fig. 4.** Supplementary power , $\Delta L^{*}$ (referred to one person), for various environmental conditions of the background environment – Supplementary power versus operative temperature.

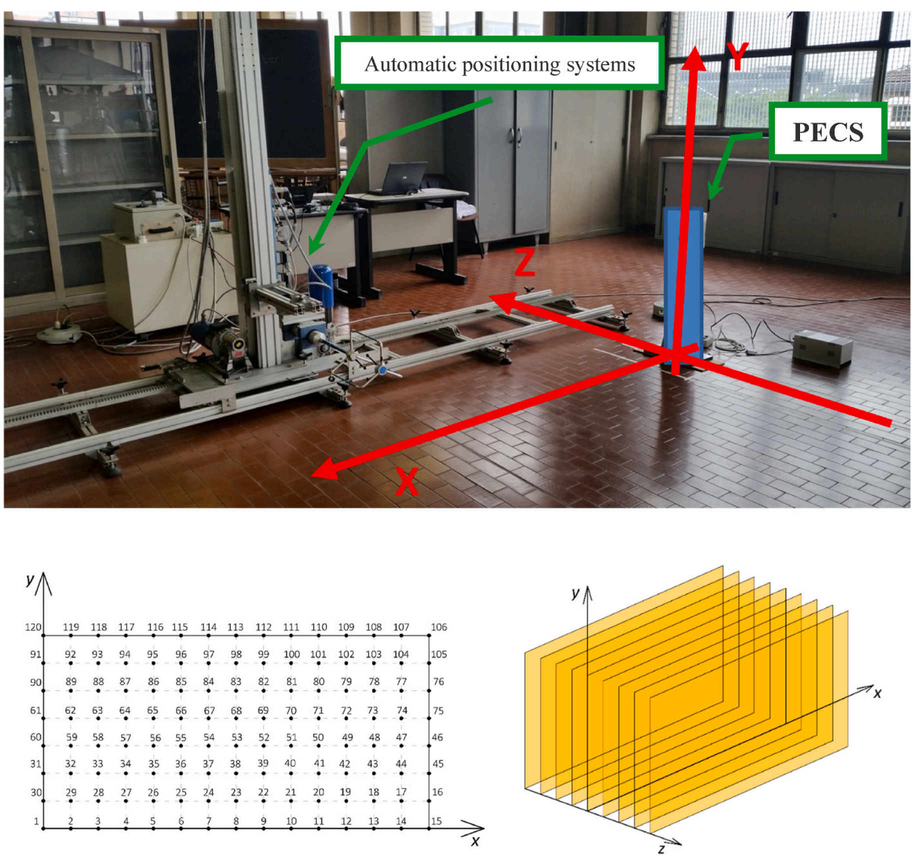



**Fig. 5.** Picture of the laboratory set-up used for determining the air velocity and air temperature fields and scheme of the measurement points.

manikins are located exactly in front of the PECS (axis of the air jet) at a distance, respectively, of 1 m, 2 m and 3 m from the appliance.

*5.2.2. Assessment of the PECS energy efficiency for heating and cooling*

The appliances were located inside typical single office rooms in order to develop objective and subjective comfort analyses and to assess the ideal supplementary power, $\Delta L^{*}$.

For the heating mode, the measurement campaign was done inside a rectangular room having the north-east wall facing to the outdoor and hosting a window with a surface of about 6 m$^2$. All the other three walls

**Table 4**
Features and accuracy of the Gill ultrasonic anemometer.

| Feature | Value |
|---|---|
| Measurement range velocity components (u, v & w) | from 0 m/s to 60 m/s |
| Accuracy (velocity magnitude for u, v & w) | from 0 m/s to 20 m/s: ±1, 5 %<br>from 25 m/s to 35 m/s: from ±1, 5 % to ±3 %<br>from 35 m/s to 60 m/s: ±3 % |
| Air speed resolution | 0.01 m/s |
| Measurement range for the direction | from 0° to 360° |
| Accuracy for the direction | If $v \leq 25$ m/s: ±2°    If $v > 25$ m/s: ±4° |
| Resolution for the direction | 1° |

were bordering with heated rooms. Tests were carried out with the subject sitting on a chair, head-on to the PECS and to the windows. As can be seen in Fig. 9, the bladeless fan heater was located in axis with the subject, at a distance of 2.3 m. Inside the room there were just few offices furniture, that did not interfere with the air flow.

In order to reproduce realistic conditions each test was divided into three steps. Firstly, the room was cooled (by opening the window) to an indoor temperature of about 16 °C. Then the subjects were asked to enter the room and to sit on the chair for 5 min (during which they were briefed on the questionnaire and on the test procedure). After 5 min, the subjects were asked to fill in a comfort questionnaire. Simultaneously, an IR picture of their body surface temperature was taken and the indoor environmental conditions (near the person, in the location highlighted by the red dot in Fig. 9) were recorded (a Bruel and Kjaer Climate Analyzer 1213 was employed [62]). After these 5 min the PECS was switched on at its full nominal power (max. heating power and max. air flow rate). The subjects were asked to stay sitting on the chair and doing office activity (1.2 Met) for 15 min and, at the end of this period, the data collection procedure was repeated (both subjective and objective analysis). The experiment continued for another 45 min, during which the appliances were adjusted in order to keep rather constant air temperature. At the end, the data collection was repeated. Table 5 schematically resumes the phases of the adopted experimental methodology.

For the cooling period, tests had to be done inside another room equipped with a direct expansion system to control the temperature of the background environment. The experimental campaign was done adopting a procedure analogous to the one applied for the heating mode. That is, each test was divided into three steps. At the beginning the room was heated and kept at an average air temperature of about 29 °C, then after 5 min the PECS was switched on, measurements were taken and questionnaire was filled after 15′ and 60’ since the appliance power on. The distance between the subject and the PECS was the same of the tests in heating mode.

A total of 45 tests for each appliance was performed for the heating mode. 17 of these tests were done with the subject that resulted to be in comfort condition (i.e. PMV within ±0.2).

For the cooling mode, a total of 30 tests were done for PECS “A” and “B”, respectively. The tests selected for the analysis (e.g. those during which the subject was in thermal comfort conditions according to the questionnaire) were 17 for PECS “A” and 14 for PECS “B”.

The mean value of the results of these selected tests was used to assess the PECS efficiency.

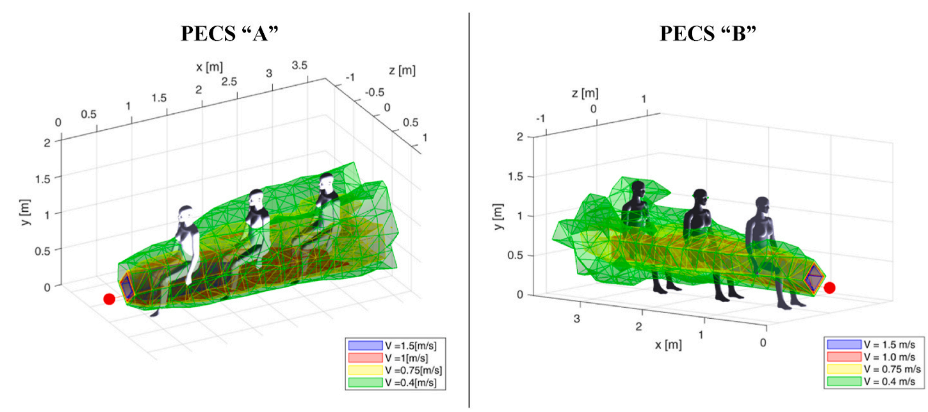



**Fig. 6.** Iso-velocity surface for PECS “A” and “B” – Case: cooling mode (isothermal conditions) – The volume contained inside the iso-velocity at $v_\infty = 0.40$ m/s (green surface) identifies the fluid dynamic micro-environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

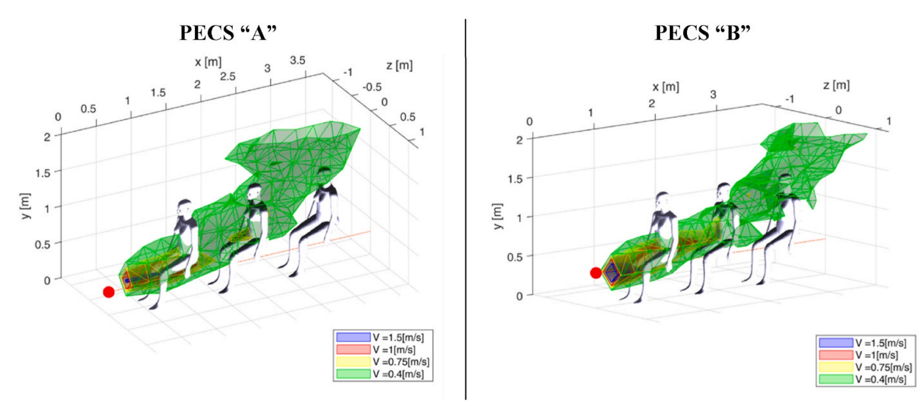



**Fig. 7.** Iso-velocity surface for PECS “A” and “B” – Case: heating mode – The volume contained inside the iso-velocity at $v_\infty = 0.40$ m/s (green surface) identifies the fluid dynamic micro-environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

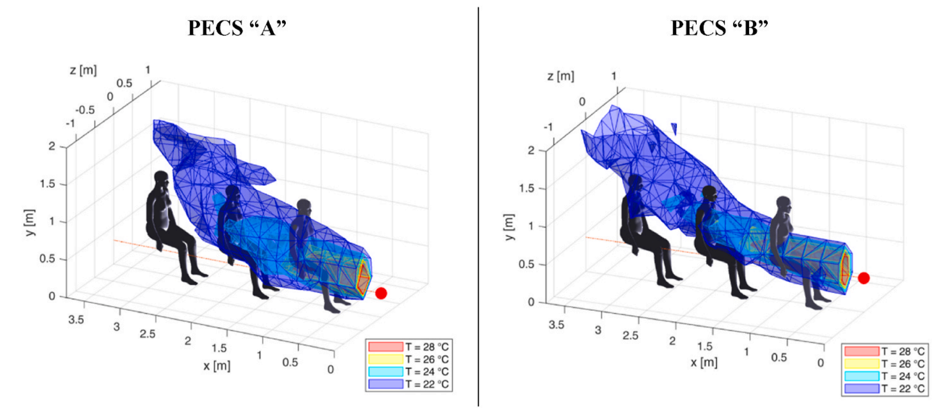



**Fig. 8.** Iso-temperature surface for PECS "A" and "B" – Case: heating mode – The volume contained inside the iso-temperature at $T_\infty = 22$ °C (blue surface) identifies the thermal micro-environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

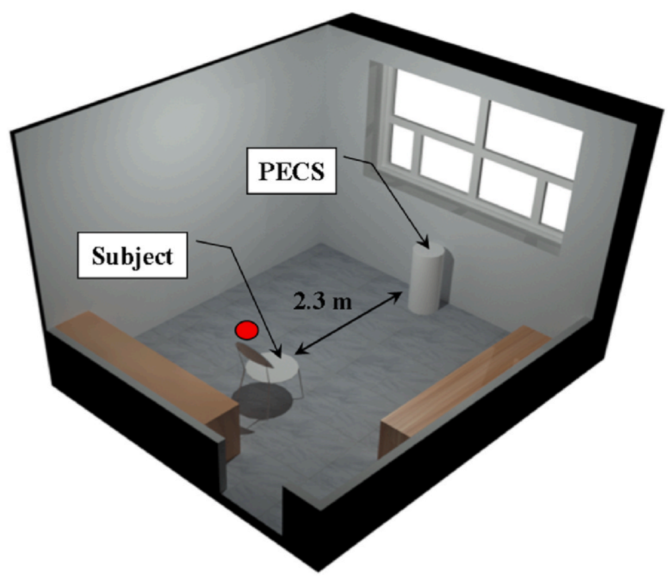



**Fig. 9.** Scheme of the test room.

Table 6 resumes these average data. The values measured at 5 min, that are representative of the background environmental conditions, were used to assess the $\Delta L^*$ according to the procedure introduced in Section 4.1. The $\Phi_{PECS}$ was calculated as the time weighted average of the absorbed power of the PECS during the last 60 min (i.e. 15'+45') of the test. Table 7 shows the obtained supplementary powers and PECS energy efficiencies. The energy efficiency of the bladeless fan resulted to be very low in heating mode (in the range of about 3–4%). This is a reasonable and predictable outcome.

PECS that are using mainly convective heat exchange for providing comfort conditions during the winter cannot guarantee an effective exploitation of the thermal energy. In fact, in order to generate a sufficiently high enthalpy flow, needed to provide a sufficient heat flux to the human body (without increasing too much the air temperature for local discomfort reasons), they need to resort to high flow rates. Consequently, the air speed over the occupants is significantly high. Such increase in the local air speed is undermining the heating capability of the appliance, since it also enhances the latent and sensible heat losses. Moreover, being the PECS usually located at a certain distance from the subject, the size of the micro-environment must be rather large. This leads to inefficiencies, because the PECS has to, uselessly and unproductively, heat up a far larger air volume to create a satisfactory temperature field around the body of the person.

It is worth noting how the conventional wisdom and the findings of studies available in literature [24,63–65], that suggests a poor efficiency of the fan heaters, can now be confirmed in a quantitative and objective way thanks to the concept of the PECS energy efficiency for heating and cooling.

On the other hand, the energy efficiency of the bladeless fan shows remarkably high values in cooling mode, being around 81 % for appliance "A" and 91 % for appliance "B".

Again, this result has its justification in the fact that the "cooling mode" does not actually imply any active air cooling, but it solely relies on the improvement of the heat dissipation from the body. The power absorbed by the fan is typically low (20–25 time less than the power absorbed by the electric heater) and increases the convective heat and moisture transfer thanks to a reinforced local air speed.

## 6. Discussion on results: efficiency vs correction capacity

The main aim of the case study reported in Section 5 was to demonstrate the usefulness of the newly introduced metric ($\eta_{PECS}$) and verify the applicability of the proposed procedure. The tests performed in this study are mainly for the sake of example and future refinement and a deeper validation of the experimental method are needed. Based on the gained experience, it would be advisable to perform the tests

**Table 5**
Experimental phases of the adopted methodology.

| Duration | 5 min | 15 min | 45 min |
|---|---|---|---|
| PECS' power | Switched off | • On at max power (heating).<br>• Fan on at max speed (cooling) | • On modulating at fix Set Point (heating).<br>• Fan on at max speed (cooling) |
| Activity | Acclimatization. Sitting | Office activity (1.2 Met) | Office activity (1.2 Met) |
| Actions at the end of each period | • Fill in the questionnaire<br>• Measurement of the indoor env. parameters and of PMV<br>• IR picture of the subject | • Fill in the questionnaire<br>• Measurement of the indoor env. parameters and of PMV<br>• IR picture of the subject | • Fill in the questionnaire<br>• Measurement of the indoor env. parameters and of PMV<br>• IR picture of the subject |

**Table 6**
Resume of the mean values of the air temperatures and PMV for the selected tests.

| Heating mode (mean values) | | | | | | Cooling mode (mean values) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Appliance "A" | | | Appliance "B" | | | Appliance "A" | | | Appliance "B" | | |
| Time [min] | $T_{air}$ [°C] | PMV | Time [min] | $T_{air}$ [°C] | PMV | Time [min] | $T_{air}$ [°C] | PMV[b] | Time [min] | $T_{air}$ [°C] | PMV[b] |
| 5[a] | 16.7 | −1.2 | 5[a] | 16.5 | −1.1 | 5[a] | 28.9 | 2.1 | 5[a] | 28.9 | 1.6 |
| 15 | 22.9 | −0.2 | 15 | 23.4 | −0.2 | 15 | 29.1 | 0.4 | 15 | 29.1 | 0.1 |
| 60 | 24.1 | 0.2 | 60 | 24.1 | 0.0 | 60 | 29.1 | 0.0 | 60 | 29.2 | 0.0 |

[a] Data at 5 min are representative of the background environment conditions.
[b] For tests in cooling mode the PMV was assessed on the basis of the questionnaire answers. The average $I_{cl}$ was slightly different between tests for appliances "A" and "B".

**Table 7**
Supplementary power and PECS heating/cooling efficiency.

| Mode | Appliance "A" | | | Appliance "B" | | |
|---|---|---|---|---|---|---|
| | $\Delta L^*$ [W] | $\Phi_{PECS}$ [W] | $\eta_{PECS}$ [%] | $\Delta L^*$ [W] | $\Phi_{PECS}$ [W] | $\eta_{PECS}$ [%] |
| **Heating** | 42.0 | 1100 | 3.8 | 43.4 | 1200 | 3.6 |
| **Cooling** | −41.1 | 50 | 81.2 | −36.7 | 40 | 91.8 |

inside a well-controlled thermostatic chamber rather than using a real room. Secondly, it is likely that the use of a thermal manikin can lead to more generalisable and repeatable results compared to the involvement of people. For example, the experimental technique introduced in Ref. [63] could be suitably re-adapted for directly measuring the supplementary power $\Delta L^*$. This approach certainly needs further investigation to better understand the pros and cons compared to tests done with human subjects. In fact, as highlighted in Ref. [24], for identical boundary conditions, the metrics derived from thermal manikin measurements diverge from those obtained with human subjects or evaluated via comfort models and measured environmental parameters (e.g., air temperature, relative humidity, mean radiant temperature, etc.). Thermal manikin tests provide information obtained from a "whole body" perspective and typically underpredict the CP value (this was proved in Ref. [24]. For the whole body, cooling CP is mostly less than −1 K for the velocity below 1 m/s, while for local cooling of body-segments CP values are in the range 4 K–8 K. For heating, whole body heating CP is between 2 K and 5 K, and local heating CP is as high as 7.5 K). Additionally, it is crucial to conduct further research on the optimal and most suitable comfort model for assessing the supplementary power, $\Delta L^*$. In this paper, for the sake of simplicity and reliability [59], the Fanger model was adopted. Nevertheless, this methodology, which is well established, widely accepted, standardized and robust, does not take into account the variability of thermofluidic dynamic conditions across different regions of the body, assuming the neutral thermal sensation as the ideal. In this regard, various studies questioned the meaningfulness of the paradigm of thermal neutrality (see e.g. Refs. [66–70]) and some researchers demonstrated that deliberated non-neutral thermal conditions may have positive effect on the health and/or perceived environmental quality [71].

In any case, the proposed procedure and the definition of the $\eta_{PECS}$ remain valid whichever comfort model is used to compute the term $\Delta L^*$. It only influences the final value of the efficiencies, but the structure of the method does not change.

In relation to the specific results obtained by the analysis of the two bladeless fans, it is interesting to observe how their energy efficiency for heating is comparable and quite low, about 3–4 %. Based on the definition of the $\eta_{PECS}$, this means that 96–97 % of the power absorbed by the appliance is "wasted" and only a small fraction is effectively exchanged with the human body. Conversely, the two PECS demonstrated a cooling energy efficiency of approximately 80–90 %, indicating that the majority of the power consumed by the devices is effectively utilized for cooling the human body. This high efficiency can be attributed to the system operating under isothermal conditions, where the power is primarily absorbed by the fan to increase air velocity, rather than actively cooling the air. Importantly, the power required for enhancing convection through increased air speed is significantly lower than that needed for conventional active cooling methods, thereby improving heat dissipation from the body.

These findings align with the operational principle of bladeless fans, which enhance convective heat transfer. It is widely acknowledged that fan heaters are inherently less effective for heating compared to cooling, since they augment evaporative heat loss from the skin and they require high wattages for a given effect [24].

For example, in Ref. [63] just one appliance based on convection [64] was examined for heating and resulted to absorb about twice the power compared to the other analysed PECS. Besides, Fanger [65] highlighted that it is more convenient to provide personalized heating by radiation or conduction, so that the inhaled air may be still kept cool and pleasant to inhale.

However, quantifying this difference of performance has proven challenging in previous studies and the majority of the available data just specify the total absorbed power and, sometimes, the corresponding CP.

The use of the $\eta_{PECS}$ metrics proved to be an effective method for providing such information in a straightforward, repeatable and systematic manner.

Even though the energy efficiency for heating of bladeless fan is significantly lower than their energy efficiency for cooling, the capacity of thermal correction between the background environmental conditions and the comfort condition is higher in heating mode than in cooling mode (e.g. the CP is higher).

In the analysed case study, the two appliances in heating mode were able to compensate a background air temperature of about 16 °C and to provide comfort conditions. In cooling mode they were able to provide comfort conditions with a temperature of the background environment of about 29 °C.

This experience demonstrated the significance of integrating the assessment of the $\eta_{PECS}$ with the analysis of the extent to which the appliance can compensate a too warm or too cool background environment, thereby providing comfort conditions at the occupant location.

Both the information about the energy efficiency of the PECS and of its capacity in controlling the body's energy balance to accommodate different personal preferences are important in the design phase and for ranking purposes. Such conclusions suggest that the value of the $\eta_{PECS}$ should always be coupled with the assessment of the CP or of an equivalent metric.

One point that deserves some thoughts and reflection concerns the CP concept and definition. It would be advisable, in the opinion of the authors, to change the name of "Corrective Power" – CP to avoid any possible misunderstanding.

In fact, as mentioned in Section 4, this quantity is not a "power", but it is a temperature difference. It was firstly introduced in Ref. [24] as "*the extent to which a PCS can 'correct' a warm or cool ambient temperature toward neutral*". The subsequent definition, still given in Ref. [24], that reads out: "*CP is defined as difference between two ambient temperatures at*

**Table 8**
TCC and TCCE for PECS “A” and “B”.

| Mode | Appliance “A” | | | | Appliance “B” | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_b$ [°C] | $T_{eq,PECS}$ [°C] | TCC [K] | TCCE [W/K] | $T_b$ [°C] | $T_{eq,PECS}$ [°C] | TCC [K] | TCCE [W/K] |
| **Heating mode** | 16.7 | 24.1 | 7.4 | 149 | 16.5 | 24.1 | 7.6 | 157 |
| **Cooling mode** | 28.9 | 25.2 | 3.7 | 13.5 | 28.9 | 25.8 | 3.1 | 12.9 |

*which the same thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use*” could be a little bit confusing and it is indeed well suited for those cooling PECS that are based on increased local convection, but it appears more difficult to be applied to other cases, like cooling PECS based on radiation and/or heating PECS.

For this these reasons we propose to adhere to the first definition given in Ref. [24] and to call this metric “Temperature Correction Capacity” – TCC.

Therefore, the TCC will be the difference between the actual ambient temperature in the case without PECS (or, indifferently, the temperature of the background environment, $T_b$) and the temperature that should have the same environment (keeping constant all the other parameters that influence the thermal comfort conditions) in order to provide the identical neutral sensation achieved by using the PECS ($T_{eq,PECS}$).

Such definition would be more rigorous from the point of view of the metric dimension. Furthermore, the name would more clearly and directly evoke its physical meaning, and its assessment would be easily generalisable to all types of PECS.

In support of these considerations and for the sake of completeness, Table 8 resumes, as an example, the TCC values of the two bladeless fans analysed in this paper.

Finally, it is worth mentioning that a new concept, the Corrective Power Efficiency – CPE was very recently introduced by Rawal [72]. It is defined as the ratio between the $\Phi_{PECS}$ and the CP. In a similar manner to the proposed nomenclature revision of CP into TCC, CPE could be named as “Temperature Correction Capacity Efficiency” – TCCE and can be evaluated by Equation (8).

$$TCCE = \frac{\Phi_{PECS}}{TCC} \quad \left[\frac{W}{K}\right] \tag{8}$$

TCCE provides the information of “how many Watts” are needed to produce 1 K of corrective power (i.e. of temperature correction). An ideal TCCE* may also be assessed using Equation (9).

$$TCCE^{*} = \frac{\Delta L^{*}}{TCC} \quad \left[\frac{W}{K}\right] \tag{9}$$

These quantities can be either evaluated by means of numerical simulations or laboratory measurements and the procedure to do their assessment is analogous to the one proposed in Section 4 to determine $\eta_{PECS}$. An evaluation of TCC and TCCE was conducted for the appliances presented in this paper, resulting in the data collected in Table 8.

In essence, the methodology for a rational and comprehensive analysis of the performance of the PECS should follow the block scheme depicted in Fig. 10. In this paper, the focus was on the branch dedicated to the evaluation of PECS efficiency. However, the proposed methodological framework may also be used for determining the potential energy savings achievable when PECS are combined with and backed up by conventional HVAC systems (e.g. the air conditioning energy use savings during the building operation). This should be achieved through the use of energy simulation and/or field measurements, opening to further investigations in the future.

## 7. Conclusions

It is now well established that PECS offer several advantages over traditional building HVAC systems. These benefits include: improved health, increased productivity, potential energy savings, and greater occupant satisfaction. To quantify these benefits and to compare the performance of this type of appliances, it is however necessary to introduce a common and generalisable metric and adopt replicable methodologies to assess them.

In this paper an organic and rational approach for identifying and defining the spatial domains that characterize the indoor environmental control with PECS was proposed. Three thermodynamic systems have been identified. *The human body* – the object toward which all the actions are (or should be) aimed at, and on which the design of the indoor environmental control should be focused. *The micro-environment* – the space in proximity of the occupant. It is the local volume that surrounds the human body and is significantly influenced by the PECS (heating/cooling/ventilation). *The background environment* – the remaining volume (e.g. the complementary volume) of the room, once the micro-environment is removed/excluded. It is usually air conditioned by means of a traditional HVAC system.

The local environment around the human body, which may be referred to as the micro-environment or the “comfort bubble”, is a concept that is widely recognized and referenced in numerous scientific papers. However, despite this common knowledge, there is not a clear and unambiguous definition of the micro-environment to date. In light of this, a procedure for defining and identifying the micro-environment has been proposed. It gets the idea from the principles adopted to identify the boundary layer in fluid mechanic. Limit values for the

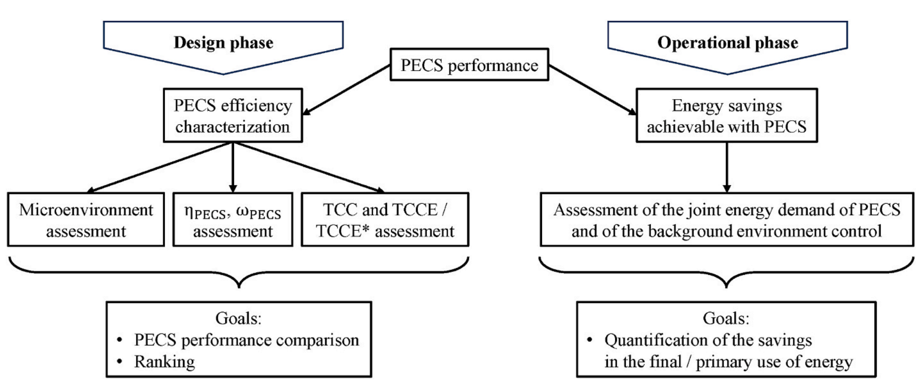



**Fig. 10.** Scheme of the proposed approach for the analysis of the performance of the PECS.

relevant parameters (air velocity – $v_\infty$, air temperature – $T_\infty$, mean radiant temperature – $T_{mr,\infty}$, pollutants concentration, etc.) are preliminarily defined. Subsequently, the flow and thermal fields around the PECS are measured (or numerically simulated) and the micro-environment is identified as that domain $\Omega$ for which each point satisfies the following condition: $\forall$ P(x,y,z) $\in \Omega \Rightarrow$ v(x,y,z) $\geq v_\infty$ or T(x,y,z) $\geq T_\infty$ or $T_{mr}$(x,y,z) $\geq T_{mr,\infty}$ or […][3]. Knowing the shape and size of the micro-environment helps in correctly positioning and orienting PECS to optimize their design and achieve personal comfort within the occupied space.

Afterwards, the concepts of the PECS energy efficiency for heating and cooling, $\eta_{PECS}$, and the PECS ventilation effectiveness, $\omega_{PECS}$, have been introduced based on the mass and energy conservation principles written for the two relevant thermodynamic systems (the human body and the micro-environment). These parameters may be employed to assess the quality of various PECS and to facilitate straightforward comparison of their energy performance. This may be undertaken for the purpose of "product marking" and/or for performance ranking.

A method for the experimental assessment of these efficiencies was also proposed and successfully tested on a case study. Specifically, two bladeless fan heaters/coolers (PECS "A" and "B") available on the market have been selected and analysed. It is interesting to note that personalized heating has received less attention in the research literature than personalized cooling [21]. Moreover, contrarily to the market trend where fan heaters represent a non-negligible quota of the PECS for heating, most of the personalized heating systems that have been so far studied use heating elements incorporated in the furniture (chair and desk) and floor or radiation panels and lamps [73–78].

Tests on PECS "A" and "B" were done inside a real office room, performing both objective and subjective measurements. The energy efficiency for heating and cooling was quantified for both the appliances. demonstrating the robustness of the proposed method.

Results were discussed, with particular emphasis on the new concept of PECS energy efficiency and its ability to overcome the limitations in the existing literature regarding performance assessment, classification and benchmarking of PECS. Finally, the role of the corrective power (CP) metric proposed in the literature was also discussed, suggesting a more coherent and rigorous reformulation of its definition and integrating its use within the proposed methodological framework.

The findings of this study can significantly contribute to evaluating PECS performance. However, they represent just one part of a broader research field, which includes various performance metrics and energy-saving strategies for entire air-conditioned spaces. This paper provides a foundation for further research in evaluating and optimizing PECS. Adopting the methodological framework presented, future research can validate and expand upon the findings of this study, potentially leading to the development of indoor climate control systems that are both more efficient and more comfortable.

## CRediT authorship contribution statement

**Marco Perino:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Matteo Bilardo:** Writing – review & editing, Writing – original draft, Validation. **Enrico Fabrizio:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Formal analysis.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marco Perino reports financial support was provided by European Union. Matteo Bilardo reports financial support was provided by European Union. Enrico Fabrizio reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

The research activity presented in this paper is done in a project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 1561 of October 11, 2022 of Ministero dell'Università e della Ricerca (MUR); funded by the European Union – NextGenerationEU. Award Number: Project code PE00000021, Concession Decree No. 1561 of October 11, 2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP E13C22001890001, according to attachment E of Decree No. 1561/2022, Project title "Network 4 Energy Sustainable Transition – NEST, Spoke 8".

Authors are grateful to the De' Longhi S.p.a. and Dr. Enrica Monticelli for allowing the use of the experimental data collected during a common research activity.

## References

[1] IEA - International Energy Agency, "The Future of Cooling Opportunities for energy-efficient air conditioning Together Secure Sustainable", Accessed: April. 16, 2024. [Online]. Available: www.iea.org/t&c/.
[2] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on buildings energy information: trends, end-uses, fuels and drivers, Energy Rep. 8 (2022) 626–637, https://doi.org/10.1016/j.egyr.2021.11.280.
[3] D.W. Etheridge, M. Sandberg, Building Ventilation: Theory and Measurement, John Wiley & Sons, 1996.
[4] H. Skistad, Displacement Ventilation, Research Studies Press, 1945.
[5] X. Yuan, Q. Chen, L.R. Glicksman, Performance evaluation and development of design guidelines for displacement ventilation, ASHRAE TC 5.3 - Room Air Distribution (1999) [Online]. Available: https://search.worldcat.org. (Accessed 15 April 2024). it/title/performance-evaluation-and-development-of-design-guidelines-for-displacement-ventilation-final-report-to-ashrae-tc-53-room-air-distribution-tc-410-indoor-environment-modeling-on-ashrae-research-project-rp-949/oclc/57290269.
[6] G.N. Spyropoulos, C.A. Balaras, Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches—a case study, Energy Build. 43 (4) (Apr. 2011) 770–778, https://doi.org/10.1016/J.ENBUILD.2010.12.015.
[7] I. Knight, Assessing electrical energy use in HVAC systems, REHVA Journal (01/2012) (2012) 6–11 [Online]. Available: https://www.rehva.eu/rehva-journal/chapter/assessing-electrical-energy-use-in-hvac-systems. (Accessed 15 April 2024).
[8] H. Ma, et al., Analysis of typical public building energy consumption in northern China, Energy Build. 136 (Feb. 2017) 139–150, https://doi.org/10.1016/J.ENBUILD.2016.11.037.
[9] R. Jing, M. Wang, R. Zhang, N. Li, Y. Zhao, A study on energy performance of 30 commercial office buildings in Hong Kong, Energy Build. 144 (Jun. 2017) 117–128, https://doi.org/10.1016/J.ENBUILD.2017.03.042.
[10] B. Yang, X. Ding, F. Wang, A. Li, A review of intensified conditioning of personal micro-environments: moving closer to the human body, Energy and Built Environment 2 (3) (Jul. 2021) 260–270, https://doi.org/10.1016/J.ENBENV.2020.06.007.
[11] ASHRAE, ANSI/ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy, Peachtree Corners, Georgia 30092 US, 2023.
[12] ASHRAE, ANSI/ASHRAE Standard 62.1-2022 - Ventilation and Acceptable Indoor Air Quality, Peachtree Corners, Georgia 30092 US, 2022.
[13] A.K. Melikov, in: Personalized Ventilation, vol. 14, John Wiley & Sons, Ltd, 2004, https://doi.org/10.1111/J.1600-0668.2004.00284.X. SUPPL. 7.
[14] P. Ole Fanger, Indoor air quality in the 21st century: search for excellence, Indoor Air 10 (2) (2000) 68–73, https://doi.org/10.1034/J.1600-0668.2000.010002068.X.
[15] C. Shen, N. Gao, T. Wang, CFD study on the transmission of indoor pollutants under personalized ventilation, Build. Environ. 63 (May 2013) 69–78, https://doi.org/10.1016/J.BUILDENV.2013.02.003.
[16] M.P. Bivolarova, A.K. Melikov, C. Mizutani, K. Kajiwara, Z.D. Bolashikov, Bed-integrated local exhaust ventilation system combined with local air cleaning for

[3] Inequalities become $\leq$ for cooling PECS.

improved IAQ in hospital patient rooms, Build. Environ. 100 (May 2016) 10–18, https://doi.org/10.1016/J.BUILDENV.2016.02.006.
[17] T.L. Madsen, B. Saxhof, An unconventional method for reduction of the energy consumption for heating of buildings, in: Second International CIB Symposium on Energy Conservation in the Built Environment: Preprints : Building Service Systems and Automatic Controls. Session 3 (Page Correction), 1977.
[18] D.B. Greenberger, S. Strasser, L.L. Cummings, R.B. Dunham, The impact of personal control on performance and satisfaction, Organ. Behav. Hum. Decis. Process. 43 (1) (Feb. 1989) 29–51, https://doi.org/10.1016/0749-5978(89)90056-3.
[19] K.E. Heinemeier, G.E. Schiller, C.C. Benton, Task conditioning for the workplace: issues and challenges, in: ASHRAE Trans 96 (Part 2), ASHRAE, 1990, pp. 678–688.
[20] S. Hamilton, Using microenvironments to provide individual comfort, ASHRAE J. (2003).
[21] M. Veselý, W. Zeiler, Personalized conditioning and its impact on thermal comfort and energy performance – a review, Renew. Sustain. Energy Rev. 34 (Jun. 2014) 401–408, https://doi.org/10.1016/J.RSER.2014.03.024.
[22] R. Rawal, M. Schweiker, O.B. Kazanci, V. Vardhan, Q. Jin, L. Duanmu, Personal comfort systems: a review on comfort, energy, and economics, Energy Build. 214 (May 2020) 109858, https://doi.org/10.1016/J.ENBUILD.2020.109858.
[23] J.E. Seem, J.E. Braun, The impact of personal environmental control on building energy use, in: ASHRAE Tans 98 (Part 1), ASHRAE, 1992, pp. 903–909. Accessed: Apr. 15, 2024. [Online]. Available: https://store.accuristech.com/standards/an-92-08-2-the-impact-of-personal-environmental-control-on-building-energy-use?product_id=1716931.
[24] H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, Build. Environ. 91 (Sep. 2015) 15–41, https://doi.org/10.1016/J.BUILDENV.2015.03.013.
[25] R. Kalaimani, M. Jain, S. Keshav, C. Rosenberg, On the interaction between personal comfort systems and centralized HVAC systems in office buildings, Adv. Build. Energy Res. 14 (1) (Jan. 2020) 129–157, https://doi.org/10.1080/17512549.2018.1505654.
[26] H. Zhang, et al., Using footwarmers in offices for thermal comfort and energy savings, Energy Build. 104 (Oct. 2015) 233–243, https://doi.org/10.1016/J.ENBUILD.2015.06.086.
[27] Y. He, W. Chen, Z. Wang, H. Zhang, Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity, Energy Build. 194 (Jul. 2019) 140–162, https://doi.org/10.1016/J.ENBUILD.2019.04.015.
[28] A. Warthmann, D. Wölki, H. Metzmacher, C. van Treeck, Personal climatization systems—a review on existing and upcoming concepts, Appl. Sci. 9 (1) (Dec. 2018) 35, https://doi.org/10.3390/APP9010035, 2019, Vol. 9, Page 35.
[29] IEA EBC Annex 87 - Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems." Accessed: April. 15, 2024. [Online]. Available: https://annex87.iea-ebc.org/.
[30] J. Verhaart, M. Veselý, W. Zeiler, Personal heating: effectiveness and energy use, Build. Res. Inf. 43 (3) (May 2015) 346–354, https://doi.org/10.1080/09613218.2015.1001606.
[31] S. Schiavon, A.K. Melikov, Energy saving and improved comfort by increased air movement, Energy Build. 40 (10) (Jan. 2008) 1954–1960, https://doi.org/10.1016/J.ENBUILD.2008.05.001.
[32] M. Heidarinejad, D.A. Dalgo, N.W. Mattise, J. Srebric, Personalized cooling as an energy efficiency technology for city energy footprint reduction, J. Clean. Prod. 171 (Jan. 2018) 491–505, https://doi.org/10.1016/J.JCLEPRO.2017.10.008.
[33] W. Liu, et al., Exploring the potentials of personalized ventilation in mitigating airborne infection risk for two closely ranged occupants with different risk assessment models, Energy Build. 253 (Dec. 2021) 111531, https://doi.org/10.1016/J.ENBUILD.2021.111531.
[34] Z. Bolashikov, A. Melikov, M. Spilak, Experimental investigation on reduced exposure to pollutants indoors by applying wearable personalized ventilation, HVAC R Res. 19 (4) (May 2013) 385–399, https://doi.org/10.1080/10789669.2013.784645.
[35] W. Su, Z. Ai, A. Melikov, Potential of a bed ventilation system in reducing the risk of exposure to contaminants in infectious wards, J. Build. Eng. 84 (May 2024) 108525, https://doi.org/10.1016/J.JOBE.2024.108525.
[36] European Commission, An EU Strategy on Heating and Cooling. COM(2016) 51 Final, Brussels, 2016 [Online]. Available: https://www.google.com/search?q=European+Commission.+2016a. (Accessed 15 April 2024). +%E2%80%9CAn+EU+Strategy+on+Heating+and+Cooling.+COM(2016)+51+Final.%E2%80%9D&oq=European+Commission.+2016a.+%E2%80%9CAn+EU+Strategy+on+Heating+and+Cooling.+COM(2016)+51+Final.%E2%80%9D&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzM4NGowajSoAgCwAgE&sourceid=chrome&ie=UTF-8.
[37] European Commission, Communication on Pre-enlargement Reforms and Policy Reviews, Brussels, Mar. 2024.
[38] K. Kavvadias, J.P. Jiménez-Navarro, G. Thomassen, Decarbonising the EU heating sector Integration of the power and heating sector (2019), https://doi.org/10.2760/943257. Luxembourg.
[39] European University Institute, Florence School of Regulation, and Robert Schuman Centre, "Sector Coupling and Energy System Integration." Accessed: April. 15, 2024. [Online]. Available: https://fsr.eui.eu/sector-coupling-and-energy-system-integration/.
[40] Lawrence Berkeley National Laboratory (LBNL), "Demand Flexibility | Building Technology and Urban Systems." Accessed: April. 15, 2024. [Online]. Available: https://buildings.lbl.gov/demand-flexibility.
[41] S.C. Sekhar, et al., Findings of personalized ventilation studies in a hot and humid climate, HVAC R Res. 11 (4) (2005) 603–620, https://doi.org/10.1080/10789669.2005.10391157.
[42] A. Lipczynska, S. Schiavon, L.T. Graham, Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics, Build. Environ. 135 (May 2018) 202–212, https://doi.org/10.1016/J.BUILDENV.2018.03.013.
[43] W. Chakroun, N. Ghaddar, K. Ghali, Chilled ceiling and displacement ventilation aided with personalized evaporative cooler, Energy Build. 43 (11) (Nov. 2011) 3250–3257, https://doi.org/10.1016/J.ENBUILD.2011.08.026.
[44] S. Schiavon, A.K. Melikov, C. Sekhar, Energy analysis of the personalized ventilation system in hot and humid climates, Energy Build. 42 (5) (May 2010) 699–707, https://doi.org/10.1016/J.ENBUILD.2009.11.009.
[45] F. Bauman et al., "Localized Thermal Distribution for Office Buildings; Final Report-Phase III," Jul. 01, 1994. Accessed: April. 15, 2024. [Online]. Available: https://escholarship.org/uc/item/2pw6v7dz.
[46] S. Schiavon, A.K. Melikov, Energy-saving strategies with personalized ventilation in cold climates, Energy Build. 41 (5) (May 2009) 543–550, https://doi.org/10.1016/J.ENBUILD.2008.11.018.
[47] W. Song, Z. Zhang, Z. Chen, F. Wang, B. Yang, Thermal comfort and energy performance of personal comfort systems (PCS): a systematic review and meta-analysis, Energy Build. 256 (Feb. 2022) 111747, https://doi.org/10.1016/J.ENBUILD.2021.111747.
[48] M. Schweiker, M. Shukuya, Investigation on the relationship between occupants' individual difference and air-conditioning usage during nighttime in summer, J. Environ. Eng. 73 (633) (Nov. 2008) 1275–1282, https://doi.org/10.3130/AIJE.73.1275.
[49] J. Toftum, Central automatic control or distributed occupant control for better indoor environment quality in the future, Build. Environ. 45 (1) (Jan. 2010) 23–28, https://doi.org/10.1016/J.BUILDENV.2009.03.011.
[50] European Committee for Standardization (CEN), EN 15251:2007 - Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, Brussels, May 2007.
[51] Y. Zhao, H. Zhang, E.A. Arens, Q. Zhao, Thermal sensation and comfort models for non-uniform and transient environments, part IV: adaptive neutral setpoints and smoothed whole-body sensation model, Build. Environ. 72 (Feb. 2014) 300–308, https://doi.org/10.1016/j.buildenv.2013.11.004.
[52] R. Rugani, M. Picco, G. Salvadori, F. Fantozzi, Personal Comfort Systems (PCSs) in offices: efficient utilization threshold based on energy consumption, in: G. Pernigotto, F. Patuzzi, A. Prada, V. Corrado, A. Gasparella (Eds.), Building Simulation Applications BSA 2024 - 6th IBPSA-Italy Conference Bozen-Bolzano, Bolzao-Bozen, Bolzano University Press, 2024.
[53] P.O. Fanger, Thermal Comfort - Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.
[54] G. Alfano, F.R. D'Ambrosio, F. De' Rossi, Fondamenti di benessere termoigrometrico : per la progettazione e la gestione degli impianti di condizionamento, CUEN, 1988.
[55] D. Enescu, A review of thermal comfort models and indicators for indoor environments, Renew. Sustain. Energy Rev. 79 (Nov. 2017) 1353–1379, https://doi.org/10.1016/J.RSER.2017.05.175.
[56] L. Arakawa Martins, V. Soebarto, T. Williamson, A systematic review of personal thermal comfort models, Build. Environ. 207 (Jan. 2022) 108502, https://doi.org/10.1016/J.BUILDENV.2021.108502.
[57] European Committee for Standardization (CEN), EN ISO 7730:2005 - Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, ISO 7730, 2005. Brussels, Nov. 2005.
[58] Q. Zhao, Z. Lian, D. Lai, Thermal comfort models and their developments: a review, Energy and Built Environment 2 (1) (Jan. 2021) 21–33, https://doi.org/10.1016/J.ENBENV.2020.05.007.
[59] D.-I. Bogatu, Resilient Cooling and Ventilation for Buildings and People, PhD Thesis, Technical University of Denmark (DTU), Kgs. Lyngby, 2024 [Online]. Available: https://orbit.dtu.dk/en/projects/resilient-cooling-and-ventilation-for-buildings-and-people. (Accessed 2 July 2024).
[60] D.-I. Bogatu, J. Shinoda, F. Watanabe, Y. Kaneko, B.W. Olesen, O.B. Kazanci, Personalised thermal comfort model for automatic control of a newly developed personalised environmental control system (PECS), E3S Web of Conferences 396 (Jun. 2023) 03008, https://doi.org/10.1051/e3sconf/202339603008.
[61] ASHRAE, ASHRAE Handbook — Fundamentals, SI Edition, ASHRAE, Peachtree Corners, GA, 2021.
[62] Brüel & Kjær, "Indoor Climate Analyzer Model 1213 - Instruction Manual.".
[63] J. Shinoda, D.I. Bogatu, F. Watanabe, Y. Kaneko, B.W. Olesen, O.B. Kazanci, Performance evaluation of a multi-functional personalized environmental control system (PECS) prototype, Build. Environ. 252 (Mar. 2024) 111260, https://doi.org/10.1016/J.BUILDENV.2024.111260.
[64] J. Kaczmarczyk, A. Melikov, D. Sliva, Effect of warm air supplied facially on occupants' comfort, Build. Environ. 45 (4) (Apr. 2010) 848–855, https://doi.org/10.1016/j.buildenv.2009.09.005.
[65] P. Ole Fanger, Human requirements in future air-conditioned environments, Int. J. Refrig. 24 (2) (Mar. 2001) 148–153, https://doi.org/10.1016/S0140-7007(00)00011-6.
[66] M.A. Humphreys, M. Hancock, Do people like to feel 'neutral'?: exploring the variation of the desired thermal sensation on the ASHRAE scale, Energy Build. 39 (7) (Jul. 2007) 867–874, https://doi.org/10.1016/J.ENBUILD.2007.02.014.
[67] M. Fountain, G. Brager, R. De Dear, Expectations of indoor climate control, Energy Build. 24 (3) (Oct. 1996) 179–182, https://doi.org/10.1016/S0378-7788(96)00988-7.
[68] S. Shahzad, J. Brennan, D. Theodossopoulos, J.K. Calautit, B.R. Hughes, Does a neutral thermal sensation determine thermal comfort?, 10.1177/

0143624418754498 39 (2) (Jan. 2018) 183–195, https://doi.org/10.1177/0143624418754498.
[69] M. Schweiker, et al., Challenging the assumptions for thermal sensation scales, Build. Res. Inf. 45 (5) (Jul. 2017) 572–589, https://doi.org/10.1080/09613218.2016.1183185.
[70] R. De Dear, Revisiting an old hypothesis of human thermal perception: alliesthesia, Build. Res. Inf. 39 (2) (Mar. 2011) 108–117, https://doi.org/10.1080/09613218.2011.552269.
[71] W. van Marken Lichtenbelt, M. Hanssen, H. Pallubinsky, B. Kingma, L. Schellen, Healthy excursions outside the thermal comfort zone, Build. Res. Inf. 45 (7) (Oct. 2017) 819–827, https://doi.org/10.1080/09613218.2017.1307647.
[72] R. Rawal, Leaflet for PECS, Apr. 16, 2024. Singapore.
[73] D.-I. Bogatu, O.B. Kazanci, B.W. Olesen, An experimental study of the active cooling performance of a novel radiant ceiling panel containing phase change material (PCM), Energy Build. 243 (Jul. 2021) 110981, https://doi.org/10.1016/j.enbuild.2021.110981.
[74] A.K. Melikov, G.L. Knudsen, Human response to an individually controlled microenvironment, HVAC R Res. 13 (4) (Jul. 2007) 645–660, https://doi.org/10.1080/10789669.2007.10390977.
[75] S. Watanabe, A.K. Melikov, G.L. Knudsen, Design of an individually controlled system for an optimal thermal microenvironment, Build. Environ. 45 (3) (Mar. 2010) 549–558, https://doi.org/10.1016/j.buildenv.2009.07.009.
[76] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Build. Environ. 45 (1) (Jan. 2010) 29–39, https://doi.org/10.1016/j.buildenv.2009.02.016.
[77] Y.F. Zhang, D.P. Wyon, L. Fang, A.K. Melikov, The influence of heated or cooled seats on the acceptable ambient temperature range, Ergonomics 50 (4) (Apr. 2007) 586–600, https://doi.org/10.1080/00140130601154921.
[78] E. Foda, K. Sirén, Design strategy for maximizing the energy-efficiency of a localized floor-heating system using a thermal manikin with human thermoregulatory control, Energy Build. 51 (Aug. 2012) 111–121, https://doi.org/10.1016/j.enbuild.2012.04.019.