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Performance evaluation of a multi-functional personalized environmental control system (PECS) prototype

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ABSTRACT

A prototype of a multifunctional, stand-alone Personalized Environmental Control System (PECS) was developed and evaluated. The prototype comprised an electric heating panel and an air terminal device (ATD) for supplying air cleaned by a filter and ultraviolet germicidal irradiation. A Peltier element was installed in the ATD for cooling the supply air. Experiments were conducted in a climate chamber to evaluate the performance of the prototype. Thermal manikin measurements were conducted to quantify the heating and cooling effects of the PECS. Tracer gas measurements using nitrous oxide with a breathing thermal manikin were conducted to evaluate the air distribution performance of the ATD. A human subject experiment was conducted with 24 university students (12 male and 12 female) at 18–28 °C room temperatures. The whole body heating and cooling effects of the PECS, in manikin-based equivalent temperature differences, were up to 1.3 K and 0.3 K, respectively. The ventilation effectiveness of the ATD was up to 1.4. The prototype was able to increase thermal acceptability at all tested temperatures for female subjects. For the male subjects, the thermal acceptability decreased with PECS at 28 °C, possibly due to their cooling expectations not being met. The Peltier element did not provide a noticeable cooling enhancement despite its high power use. The noise generated by the ATD fan and the smell of the ATD supply air acted as factors limiting the use of PECS. A holistic assessment of the IEQ factors and ergonomic factors is important for future development of PECS.

1. Introduction

A Personalized Environmental Control System (PECS) allows occupants to control their immediate surroundings according to their preferences in terms of various indoor environmental quality (IEQ) factors, i.e., thermal, air quality, visual, and acoustical. Depending on the targeted IEQ factor, such systems can be further categorized as e.g., personal comfort systems, personal (or personalized) ventilation (PV) systems, task/ambient lighting systems [1]. The current study will refer to PECS as a system that “allows individual occupants to control thermal comfort (heating/cooling) and/or air quality (ventilation) at workstation level”, as defined in EN 16798-2 [2]. As summarized by Melikov [3], previous studies have identified a wide range of individual differences in terms of preferences to air temperature [4] and air movement [5], and the perception of air quality [6]. The use of PECS can address individual needs to the indoor environment, and therefore it is expected to improve comfort, and subsequently health and productivity [7]. Furthermore, PECS with a ventilation function (i.e., PV) can protect occupants from cross infection [8,9].

By conditioning the local environment of occupants and accommodating individual needs, PECS enables the background room temperature to be extended from the comfort range. A field study conducted by Bauman et al. [10] showed that occupants were able to maintain comfort with the use of PECS within a wider range of the room temperature. It was suggested that providing occupants with the possibility to control their local environment may also contribute to a wider range of tolerance to the surrounding temperature. The thermal performance of various PECS has been studied in literature, and according to a review conducted by Rawal et al. [7], studies have reported that PECS can provide thermal comfort within a room temperature range of 18–32 °C. As another example, ISO 17772-1 [11] allows the correction of indoor operative temperature up to 2.2 K in the presence of increased air

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velocity with personal control. This characteristic of PECS allows offsetting the control set point temperature for the background heating, ventilation, and air-conditioning (HVAC) system, which leads to significant energy savings. An early study by Madsen and Saxhof [12] (based on data from Nielsen [13]) showed that relaxing the set point of the room temperature by 1 K corresponded to about 10 % of energy saving for heating. A simulation study by Hoyt et al. [14] showed that a set point relaxation from 22.2 to 25.0 °C and from 21.1 to 20.0 °C resulted in an average energy saving of 29 and 34 % for cooling and heating, respectively. The energy use of the PECS itself must be examined as well, as a simulation study by Seem and Braun [15] showed that the use of PECS resulted in a range of a 7 % energy saving to a 15 % energy penalty, depending on the power requirements of the PECS components and their usage pattern. However, in their study it was concluded that a 15 % energy penalty could be compensated with an annual increase in productivity of 0.08 %. Therefore, it is critical that PECS can meet the needs of each individual occupant.

As the main feature of PECS is to address individuals, its performance has been evaluated commonly through human subject experiments. Previous studies have collected psychological responses such as overall and local thermal sensation, comfort, acceptability, and preference votes, perceived air quality, sensation of air movement, and sick building syndrome symptoms [16]. Some studies developed indicators comparing the questionnaire results with a reference condition, where subjects were not provided with PECS. Veselý et al. [17,18] calculated the increase in the thermal sensation vote with the use of personal heating. Zhang et al. [19] proposed the corrective power, which is defined as the "difference between two ambient temperatures at which the same thermal sensation is achieved". This is obtained by comparing the thermal sensation votes with and without PECS at temperature conditions within and out of thermal neutrality. Other studies have proposed modifications to the corrective power, such as corrective energy and power, expressed as power use per degree of corrective power [20], or the coefficient of performance, expressed as corrective power per power use [21].

Another common method for the performance evaluation of PECS is the use of a thermal manikin. A thermal manikin is typically divided into multiple body segments, and the surface temperature and heat input necessary to maintain a certain surface temperature are given as output. This allows the calculation of the manikin-based equivalent temperature, which can be used to quantify the sensible heating and cooling effects of PECS for both the whole body and individual body parts [22]. A thermal manikin can also be coupled with an artificial lung to replicate the breathing of an occupant. The thermal plume of an occupant may also be generated with a breathing thermal manikin, and therefore the interaction of the thermal plume and supply air from the PECS may be evaluated. For this reason, breathing thermal manikins have been used for evaluating the ventilation performance of PV systems [23]. Tracer gas measurements are conducted with the breathing thermal manikin, and the tracer gas concentration is measured at different points, e.g., inhaled and exhaled air from the manikin, supply and exhaust air of the chamber. The measured concentrations are then used to derive indicators such as ventilation effectiveness, personal exposure effectiveness [23], pollution exposure reduction [24], and intake fraction [25]. The ventilation effectiveness can be used to calculate the amount of fresh air supply that could be reduced as compared to a mixing ventilation system [2,26]. For the evaluation of hot environments, sweating thermal manikins have also been used. Sweating thermal manikins have a fabric layer representing the skin of a human body, and water is distributed uniformly along the manikin surface to mimic sweat. This allows the evaluation of evaporative heat loss, and they have been used to evaluate wearable cooling solutions such as ventilation jackets [27,28].

Extensive work has been carried out in terms of personalized ventilation. Such studies have focused on a more efficient distribution of fresh air, and its secondary effect on the thermal environment. There is also a growing interest in supplementing the ventilation system with air cleaning technologies [29]. This opens possibilities for developing a stand-alone PECS that is independent from the HVAC system of the building (i.e., without any physical connections through pipes or ducts). A stand-alone PECS enables easier implementation, as its layout is not limited by piping or ducting to the building HVAC system and can be treated like a furniture or an electrical appliance. There are several stand-alone heating or cooling PECS that have been developed, such as chair types [30–33] and fan types [34,35]. However, most studies have focused on functions addressing a single IEQ factor, either heating/cooling or ventilation. Therefore, the objective of this study was to develop and evaluate a stand-alone PECS prototype with multiple functions. The present study reports the performance of the prototype, evaluated by both thermal manikin measurements and human subject experiments. The present study mainly focused on the heating, cooling, and ventilation functions. Challenges in developing a stand-alone PECS in terms of different IEQ factors are identified and discussed.

2. Prototype specifications

Fig. 1 shows the multifunctional, stand-alone PECS prototype tested in this study. The development of previous prototypes is described in Ref. [36]. The prototype comprised a desktop unit with an air terminal device (ATD) and an under-desk unit with an electric heating panel. The desktop unit had a touch panel on the front side for controlling the PECS functions. The ATD mounted on the desktop unit supplied recirculated room air cleaned with a filter and an ultraviolet germicidal irradiation (UVGI) component. The room air intake was positioned on the side of the desktop unit. The ATD had an opening size of 4.5×10^{-3} m^2. The ATD design follows the recommendations given by Melikov [3], providing air from the front against the face, and with the possibility for the users to control the flow rate as well as adjusting the angle and positioning freely. An arm-like construction was selected for the ATD, similar to the Movable Panel design studied by Kaczmarczyk et al. [37] and Melikov et al. [23], which were reported to have a good balance between ventilation performance and avoiding discomfort from the airflow.

A Peltier element was also installed in the ATD, close to the supply air opening, for actively cooling the air. Since the aim of the prototype

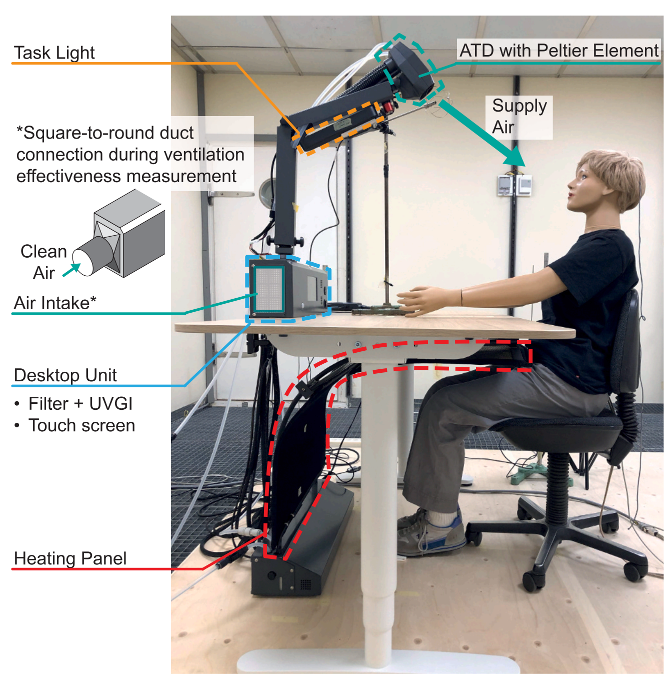


Fig. 1. Developed PECS prototype.

was to have no connection with the background system (i.e., standalone), a Peltier element was selected as the active cooling function, as it can provide cooling through electricity and with simple installation. The waste heat removal of the Peltier element was done through water pipes connecting the ATD and the water tank stored in the under-desk unit. A task light, which had functions to control light intensity and color, was attached to the ATD. The under-desk unit had an electrical radiant heating panel curved along the lower body of a seated occupant, facing the thighs, lower leg and feet.

Three components of the prototype were evaluated in this study, i.e., heating, ATD fan, and cooling. The lighting function was not evaluated. The heating panel and ATD fan could be controlled in discrete settings from 1 to 10. The cooling function was only operable when the ATD fan was turned on and could be controlled in discrete settings from 1 to 5. The settings for all functions were split equally by electrical power, with the highest setting corresponding to the maximum rated power use for each component. The setting of each function was logged every minute in the single-board computer inside the desktop unit. The electrical power use corresponding to the use of each function at the maximum setting was 128 W for heating, 11 W for the ATD fan, and 68 W when both the ATD fan and the cooling were at the maximum setting (i.e., 57 W for the Peltier element). The base electrical power use when all three functions were turned off was 38 W. This corresponds to the sum of the power use for the UVGI component, the touch screen, and the single-board computer.

3. Experimental methods

The present study comprises three experimental campaigns. A thermal manikin experiment was conducted to evaluate the heating and cooling performance of the PECS prototype. The ventilation performance of the ATD was evaluated through tracer gas measurements with a breathing thermal manikin. Finally, a set of human subject experiments was conducted to obtain feedback on the effect of PECS on various IEQ factors.

3.1. Thermal manikin experiments

3.1.1. Chamber setup

A series of measurements were conducted in a climate chamber at the Technical University of Denmark. The chamber had a floor area of 28 m^2 and a height of 2.5 m. An underfloor ventilation system supplied air at low velocity (0.01 m/s in this study) from the entire floor of the chamber. The inner side of the chamber wall consisted of a 16 mm air layer and a fabric layer. Part of the air supplied to the chamber was supplied through the air gap layer to ensure that the air and mean radiant temperatures were equal [38]. The PECS prototype was placed on a desk with dimensions of 160 × 80 cm ($L \times W$) and a height of 80 cm. A wooden board with dimensions of 2.44 × 2.44 m was placed on the floor beneath the desk to reduce the effects from the ventilation system on the measurements, and to ensure that the results reflected only the effects of the PECS. A PT100 temperature sensor with an accuracy of ±0.03 K was positioned next to the desk at a height of 0.6 m to monitor the room temperature during the measurements.

A thermal manikin was used to study the heating and cooling effects of the PECS on the human body. The manikin was built to represent an average Scandinavian female with a height of 1.7 m, and had 24 individually controlled body parts: left and right foot, left and right lower leg, left and right front thigh, left and right back thigh, pelvis, lower back, crown, left and right face, back of neck, left and right hand, left and right forearm, left and right upper arm, left and right chest, and left and right back. The manikin was seated on an office chair that corresponds to a clothing insulation of 0.14 clo [39]. Prior to the measurements, a smoke visualization was done to adjust the ATD position so that the supply air reached the breathing zone of the manikin. At the determined position, the distance between the ATD opening and the mouth of the manikin was 60 cm.

The heating and cooling measurements were followed by another set of thermal manikin measurements with tracer gas to evaluate the performance of the ATD to deliver air to the breathing zone. The air-cleaning performance of the filter and UVGI was not evaluated in this study. The same thermal manikin described above was coupled with an artificial lung that imitated the inhalation and exhalation of a seated occupant. The breathing thermal manikin was operated with a breathing frequency of 10 times/min, air volume of 6 L/min, and a breathing cycle consisting of 2.5 s inhalation from the nose, 1.0 s pause, and 2.5 s exhalation from the mouth [23]. This corresponds to the breathing pattern of an average sedentary occupant performing light physical work. The nostril opening was 50.2 mm^2 each, and the mouth opening was in semi-ellipsoid form with an area of 100.4 mm^2 [40]. The air speed of the inhaled and exhaled air both correspond to 1.0 m/s. The temperature and humidity of the breathing air were not controlled, and therefore conditions were close to that of the room air. As described by Melikov [40], temperature and humidity control of the exhaled air is necessary to study the re-inhalation of exhaled air, but not critical to study the inhalation of the surrounding air. As the objective of the current study was the latter, the current setup was assumed to be an acceptable simplification.

Nitrous oxide (N_2O) was selected as the tracer gas. N_2O was supplied with a constant dose of 0.3 dm^3/min to the supply air duct of the chamber, resulting in a concentration of 17.0 ppm in the chamber. The chamber was equipped with another supply air duct for supplying clean outdoor air, which was connected directly to the PECS (Fig. 1). This enabled the supply air from the ATD to be distinguished from the background room air, and the precise control of the supply air temperature from the ATD. As the air cleaning components implemented in the PECS cannot remove N_2O, a connection to the ventilation system was necessary for the purpose of this study. The N_2O concentration was sampled at the ATD supply and exhaust room air, as well as the air inhaled by the manikin. INNOVA Photoacoustic Multi-gas Monitor (accuracy 5 % of the reading, detection limit 0.5 ppm for N_2O) with an RS-232C sampler was used for sampling the tracer gas concentration.

3.1.2. Experimental settings

Table 1 summarizes the experimental settings of the thermal manikin measurements, and Table 2 lists the clothing insulation of the different clothing ensembles used in the study. The experimental conditions were divided into cooling, heating, and ventilation scenarios. The manikin was dressed in light summer clothes corresponding to 0.55 clo in the cooling scenario, and medium winter clothes corresponding to 0.80 clo in the heating scenario. The heating and cooling scenarios each consisted of five room temperatures within the range of 16–23 and 23–30 °C, respectively. At each temperature, different functions of the

Table 1
Experimental settings of thermal manikin measurements.

Tested Component/ Condition	Cooling Scenario	Heating Scenario	Ventilation Scenario	
			Isothermal	Non-isothermal
Clothing Insulation [clo]	0.55	0.80	0.80	0.55
Room Temperature [°C]	23, 24, 26, 28, 30	16, 18, 20, 22, 23	20	26
Fresh Air Supply Temperature* [°C]	-	-	20	20
ATD Fan Setting [−]	1, 5, 7, 10	0, 1, 5, 7, 10	4, 7, 10	4, 7, 10
ATD Cooling Setting [−]	0, 1, 5	-	-	-
Heating Setting [−]	-	2, 4, 7, 10	-	-
Total Number of Conditions [−]	60 (+5 reference)	100 (+5 reference)	3	3

* Temperature control of the fresh air supply was done by the HVAC system connected to the PECS, and not the PECS itself.

Table 2
Clothing insulation (I_{cl}) values for different clothing ensembles (Unit: clo).

Garment	Cooling Scenario	Heating Scenario
T-shirt (long sleeves)	-	0.25
T-shirt (short sleeves)	0.09	0.09
Normal trousers	0.25	0.25
Socks	0.02	0.02
Shoes (thin soled)	0.02	0.02
Panties	0.03	0.03
Standard office chair	0.14	0.14
Total	0.55	0.80

PECS prototype were tested. The ATD fan and active cooling settings were evaluated in the cooling scenario, and the ATD fan and heating panel settings were evaluated in the heating scenario. The ATD fan was evaluated in the heating scenario, as the ATD was intended to be used for supplying clean air, and not just for cooling purposes. As the reference condition, measurements were conducted with all PECS functions turned off at all room temperatures with the corresponding manikin clothing. The thermal manikin was operated in comfort mode, where the surface temperature of each body part was controlled to be equivalent to that of a human at thermal comfort [41]. Both the thermal manikin and the reference thermometer were logging at 10 s intervals. All measurements were conducted at steady state, and the average values over 5 min were used for analysis.

For the ventilation scenario, experimental conditions followed those of Melikov et al. [23]. The supply air temperature from the ATD was fixed at 20 °C, while the room temperature was set to either 20 or 26 °C for isothermal and non-isothermal supply air conditions. At both supply air conditions, three settings of the ATD fan were tested. The air flow rate from the ATD at the selected settings corresponds to 2.6, 3.7, and 4.5 L/s (0.58, 0.84, and 1.00 m/s). The air speed at the breathing zone (i.e., mouth and nose level) was between 0.4 and 0.7 m/s during the tested conditions, which was above the minimum target of 0.3 m/s, recommended by Melikov [3]. Tracer gas concentrations were sampled at 4-min intervals. All measurements were conducted at steady state (both in terms of temperature and tracer gas concentration), and the average values over 30 min were used for analysis.

3.1.3. Data analysis

The thermal manikin gives the surface temperature and power use to maintain that surface temperature for each of the 24 body segments as outputs. Power use represents the heat loss from the corresponding body part in each condition. These outputs can be used to calculate the manikin-based equivalent temperature (T_{eq}) for the whole body and for each body segment. The following equations were used to calculate T_{eq}.

$$h_{bp} = \frac{P_{bp}}{T_{bp} - T_a} \tag{1}$$

$$T_{eq} = T_{bp} - \frac{P_{bp}}{h_{bp}} \tag{2}$$

Where:

h_{bp}: combined heat transfer coefficient for the body part at reference condition (W/(m^2·K))

P_{bp}: heat loss from the body part (W/m^2)

T_a: reference room temperature (°C)

T_{bp}: surface temperature of the body part (°C)

Eq. (1) and (2) both assume steady state, and average values for each measurement were used in the calculation. Eq. (1) was used to calculate the combined heat transfer coefficients of each body part. The reference conditions, where all PECS functions were turned off, were used to calculate the combined heat transfer coefficient for each room temperature setting. Eq. (2) was used with the heat transfer coefficients from the reference conditions to calculate the T_{eq} in all measurement conditions. The heating and cooling effects of PECS were shown by subtracting the T_{eq} of the reference condition from the T_{eq} of the conditions with the PECS turned on. This was referred to as the manikin-based equivalent temperature difference (ΔT_{eq}).

The tracer gas concentrations from the breathing thermal manikin measurements were processed to obtain the ventilation effectiveness of the ATD, using Eq. (3). In EN 16798-3 [42], the indoor air quality (IAQ) thresholds are given assuming a ventilation effectiveness of 1, which corresponds to a fully mixed air. As the source of fresh air in this experiment was the ATD, the N_2O concentration of the ATD supply air was used instead of that of the polluted chamber supply air for c_S.

$$\varepsilon_V = \frac{c_R - c_S}{c_P - c_S} \tag{3}$$

Where:

ε_V: Ventilation effectiveness of the ATD (-)

c_R: Concentration of pollution in exhaust room air (-)

c_S: Concentration of pollution in supply air from the ATD (-)

c_P: Concentration of pollution in the inhaled air (-)

3.2. Human subject experiments

3.2.1. Chamber setup

A human subject experiment was conducted in the same climate chamber as the thermal manikin experiments to further evaluate the performance of the PECS prototype. Fig. 2 shows the chamber setup during the human subject experiment. The chamber was configured as a four-person office. Four workstations with laptop computers were set up, and partitions with a height of 1.5 m were positioned to separate the desks. Two desks were equipped with the PECS prototype, and the other two without the PECS served as the reference. Wooden floor plates were laid on the floor to reduce the influence of airflow on the occupants. The thermometer for controlling the room conditioning system and the PT100 temperature sensor for room temperature monitoring were positioned in the center of the room. Stands with sensors to measure air and globe temperature, relative humidity, and air speed were placed beside each desk in respective positions indicated in Fig. 2.

3.2.2. Experimental settings

A total of 24 university students (12 male and 12 female) participated in the study. Overall healthy, non-smokers were selected. The subjects were between 23 and 31 years old. The mean and standard deviation of their height, weight, and body mass index were 172.4 ± 10.8 cm, 70.9 ± 18.7 kg, and 23.7 ± 4.6, respectively. The subjects were only exposed to conditions that do not cause strain that is worse than in a building in practice (i.e., subjects were not exposed to extreme conditions), as confirmed in a statement from the regional ethics review board (KA 04741). A written consent was filled out by the subjects prior to the experiments, and the subjects were paid for their participation. Personal information collected during the measurements was handled in compliance with GDPR (General Data Protection Regulation) rules.

Table 3 lists the experimental settings of the human subject experiment. Measurements were conducted over five weeks, from 14th of February to 19th of March 2022. The chamber temperature was controlled at different set point temperatures each week, between 18 and 28 °C. Prior to the measurements, subjects participated in an explanatory session where the PECS functions and questionnaire contents were introduced. All subjects participated in two experimental

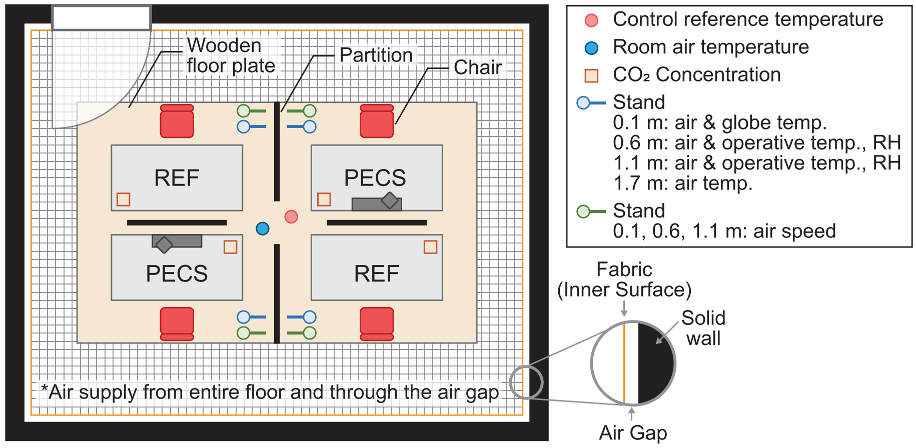


Fig. 2. Chamber setup during human subject experiment.

Table 3
Experimental settings of human subject experiment.

Week	Room Setpoint [°C]	Approximate Clothing Insulation* [clo]
1	18	1.0
2	26	0.50
3	20	1.0
4	28	0.50
5	23	0.75

*0.50: Base (Underwear, socks, pants, T-shirt).
0.75: Base + long sleeve shirt.
1.0: Base + long sleeve shirt + sweater.

sessions per week, one with PECS and the other without PECS (REF condition). Each subject therefore participated in 10 sessions in total. For each session, subjects were instructed to participate in the session with the corresponding clothing ensembles listed in Table 3. The subjects were not informed of the room temperature set point and were instructed to bring their long sleeve shirts and sweaters all the time. The clothing ensemble was therefore announced after they had arrived at each session. Two sessions were conducted each day, and subjects participated in sessions with the same time slot each week. Subjects had at least 24 h between their first and second sessions within the same week.

Fig. 3 shows the timeline of one session of the experiment. Each session lasted 180 min, and subjects arrived 30 min before the session for preparation. Subjects filled in the pre-questionnaire and attached sensors for physiological measurement prior to entering the chamber. The first 1 h of the session was assumed to be the acclimatization period. Subjects were instructed not to adjust their clothing during the entire session, but they were allowed to change the PECS operation and ATD position and angle at any time. During the acclimatization period, questionnaires were given every 10 min on their computers. Short questionnaires with a reduced number of questions were given every other time to ensure enough time between each questionnaire. Subjects were allowed to do their own work or study on the laptop computer that was set up at each desk, as long as they remained seated. After every hour, subjects were instructed to walk up and down a step box with two steps for 3 min, to prevent the metabolic rate from decreasing over the course of the 3-h session. At the end of the session, subjects were asked to remain seated at their workstation and fill in the full questionnaire and proceed to the post questionnaire.

3.2.3. Questionnaire items

Four types of questionnaires were given during the measurements, i. e., pre, full, short, and post questionnaires. The content of each questionnaire is listed in Table 4. The pre-questionnaire was given prior to entering the chamber and asked for the subjects' general health condition that day, the time they went to sleep and woke up, and the clothing in which they arrived with. On the first session, subjects were also asked to report their general thermal preference, i.e., their perception of whether they tend to feel warmer or colder than others. Subjects were also asked to report sick building syndrome (SBS) symptoms such as fatigue, headache, concentration (difficulty of concentrating), and nose irritation. A continuous scale from no symptoms (0) to severe symptoms (1) was used for the SBS symptoms.

In both the full and short questionnaires, the thermal responses of the occupants were recorded. The thermal sensation of the whole body was voted on a continuous seven-point scale corresponding to cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (1), warm (2) and hot (3) [43,44]. Thermal acceptability was voted on a scale comprising two continuous scales, one ranging from just acceptable to clearly acceptable, and the other from just unacceptable to clearly unacceptable [45]. The thermal preference was voted on a discrete scale, from warmer (+8) to cooler (−8). The local thermal sensation was recorded for 21 body parts, namely head, face, neck, chest, left and right upper arm, pelvis, abdomen, left and right lower arm, left and right hand, left and right

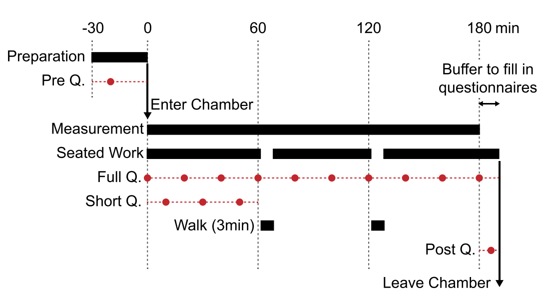


Fig. 3. Human subject experiment timeline (one session).

Table 4
Questionnaire contents for each type.

Type	Content
Pre	general health condition, sleep time, clothing, SBS symptoms, general thermal preference (tend to feel warm/cold)
Both Short & Full	thermal sensation/acceptability/preference, local thermal sensation/acceptability
Full only	air quality/lighting/noise acceptability, main source of noise, SBS symptoms
Post	SBS symptoms, acceptability of overall environment/thermal environment/air quality/noise/lighting/PECS control/satisfaction with PECS

thigh, left and right lower leg, left and right ankle, left and right foot, and back. A figure of a human body was shown on the screen, and subjects ticked the body parts where they felt a warm or cold sensation, and whether that sensation was acceptable or not. Subjects were instructed not to tick any body parts that had a neutral thermal sensation. In the full questionnaire, subjects reported their SBS symptoms and the acceptability of the air quality, light, and noise. For the noise, subjects also selected the main source of noise from the following: "background system", "PECS", "other", or "no noise". The acceptability votes all used the same scale as the thermal acceptability votes.

At the end of each session, subjects remained in the chamber and responded to the post questionnaire. Subjects reported their SBS symptoms and the acceptability of the overall environment, thermal environment, air quality, noise, light, and the control of PECS (if they were assigned to a workstation with PECS) for the entire session. The overall satisfaction with PECS was also assessed on a continuous scale from satisfied to unsatisfied. Subjects were also given the option to provide open-ended feedback on the PECS.

4. Results and discussion

4.1. Manikin-based equivalent temperature difference

Fig. 4 shows the manikin-based equivalent temperature difference at 18 and 28 °C room temperatures. Positive values indicate a heating effect, and negative values indicate a cooling effect. Fan setting 1 was

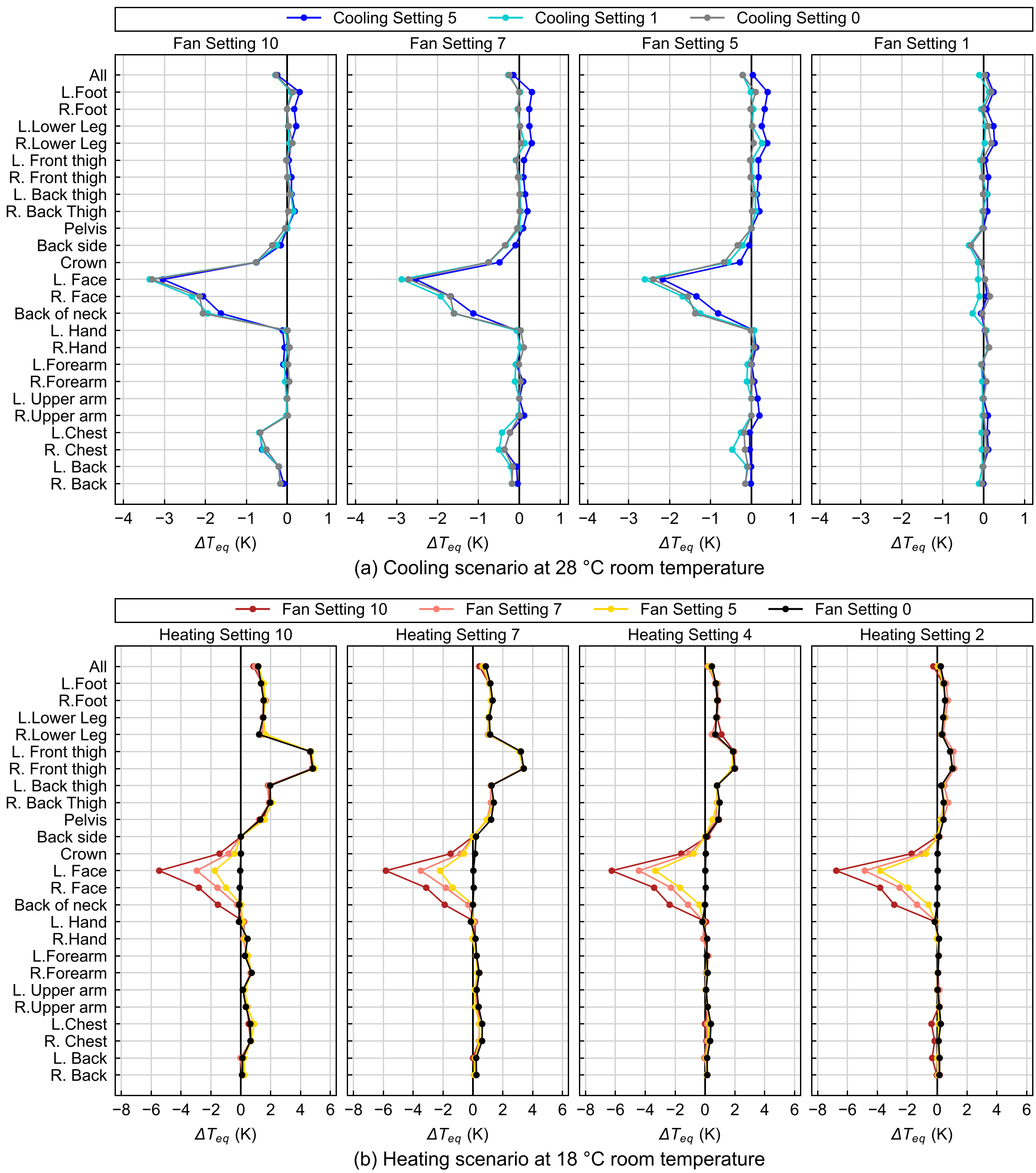


Fig. 4. Equivalent temperature difference at different PECS settings and representative ambient conditions (L.: Left, R.: Right).

omitted from the heating scenario, as the results from the cooling scenario showed that the airflow from the ATD did not reach the manikin. Results from 18 to 28 °C room temperatures were chosen, as they were the coldest and warmest temperatures in the human subject experiments. Overall trends in terms of the affected body parts were consistent regardless of the room temperature, for each of the heating and cooling scenarios.

For the cooling scenario, larger cooling effects were seen at both sides of the face and around the back of the neck. Smaller cooling effects were seen on both sides of the chest. The left part of the face had the largest cooling effect due to the design of the ATD, which was positioned towards the left side of the desktop unit, supplying air towards the left side of the body. At 28 °C room temperature, the cooling effect at the left side of the face was approximately 3.4 K when the fan was at maximum setting, and without the active cooling function. As shown in Fig. 4(a), the use of the active cooling function provided negligible enhancement (up to 0.2 K) to the cooling effect. In certain conditions, the cooling effect at some body parts decreased with the cooling function. A possible cause of the limited cooling enhancement (or dampened cooling effect) is the waste heat of the Peltier element. The current prototype attempted to remove waste heat from the Peltier element with water circulation, however there was no active cooling solution for the circulating water. Hence, the circulating water temperature had likely increased during the operation of PECS. Other methods of waste heat removal, or a more efficient means of cooling (e.g., cooling by surface contact) could be considered for improving the active cooling function.

As the cooling function did not provide a noticeable cooling enhancement, the supply air from the ATD was close to isothermal in all conditions. Therefore, the cooling effect of the PECS was highly dependent on the ambient temperature, with lower cooling effects at higher ambient temperatures. The cooling effect on the left side of the face ranged from 5.5 to 2.3 K at ambient temperature ranges of 23–30 °C. The cooling effect on the whole body was negligible in all conditions, ranging from 0.1 to 0.3 K. This is likely due to the limited area that the ATD targets, namely the face and head area (the breathing zone). As the equivalent temperature of the whole body is weighed based on the surface area of each body part, the cooling (or heating) effect at small body parts have little influence on the whole body, despite its large effect on thermal sensation. However, it must be noted that the manikin-based equivalent temperature is strictly based on sensible heat exchange at the body surface. Therefore, other modes of heat transfer for the human body such as respiration, or the interaction between local thermal discomfort and overall thermal sensation (e.g., the effect of cold sensation on the extremities to the overall thermal sensation), are not accounted for. Hence, both the heating and cooling effects may be larger for an actual person compared to what is estimated with a thermal manikin. Other methods such as human subject experiments must be taken to consider such effects. Nevertheless, as the equivalent temperature is a pure physical quantity representing the whole-body heat exchange [46], it is reproducible and serves as a useful indicator to compare heterogeneous environments and hence the performance of PECS.

For the heating scenario, heating effects were seen on the lower body, namely the feet, lower legs, thighs, and pelvis, which were the target with the current heating panel design. The largest heating effect was seen on the left and right front thighs, which were closest to the heating panel. Contrary to the cooling function, the heating effect was less influenced by the ambient temperature, and the heating effect of the thighs were within the range of 4.4–5.1 K in the tested conditions. The heating effect on the whole body ranged between 1.2 and 1.3 K when the ATD fan was turned off. As the room temperature was lower than in the cooling scenario, the cooling effect was larger around the head area when the ATD fan was turned on. At the maximum fan setting, the cooling effect on the left side of the face was in the range of 5.5–6.8 K. The cooling effect of the ATD decreased as the heating setting increased. This is likely due to the thermal plume created by the heating panel interacting with the flow from the ATD fan.

4.2. Manikin-based equivalent temperature difference and power use

Fig. 5 shows the relationship between the PECS power use and the manikin-based equivalent temperature difference of the whole body. The values include all temperature conditions, and they were grouped by function. Measurements with the ATD fan setting at 1 were excluded, as results in Fig. 4(a) showed that the airflow from the ATD did not reach the manikin at this setting. The heating effect of the heating panel showed a linear relationship with the power use, ca. 0.1 K for every 10 W. The ATD had a smaller range of power use, between 10 and 11 W, with a smaller cooling effect up to 0.3 K. When the heating panel was used together with the ATD, the heating effect decreased by up to 0.5 K, as the ambient temperature was lower. In certain conditions with low heating settings, the cooling effect of the ATD became larger than the heating effect of the panels. When the cooling function was used with the ATD fan, the power use increased to 19 and 67 W at cooling settings of 1 (minimum) and 5 (maximum), respectively. However, the use of the cooling function did not result in any noticeable enhancement of the cooling effect, as previously mentioned. Considering the electrical power use of the Peltier element and the effort required to handle the waste heat, isothermal flow with fans may be a more feasible solution at the tested conditions. However, it must be noted that cooling effect from isothermal flow depends highly on the ambient temperature.

4.3. Ventilation effectiveness

Fig. 6 shows the obtained ventilation effectiveness values, compared with a previous study [23] that evaluated five different ATDs. The ventilation effectiveness in the present study ranged from 1.2 to 1.4 in isothermal conditions, and from 1.3 to 1.4 in non-isothermal conditions. As the ventilation effectiveness of 1.0 corresponds to a full mixing of room air [42], the results show that the ATD prototype was able to supply air more effectively than a conventional mixing ventilation system. Despite the air flow rate being smaller than those of previous studies, the current prototype yielded values similar to certain ATDs, especially the horizontal desk grill (HDG). Increasing the supply air flow rate is expected to increase the ventilation effectiveness up to a certain

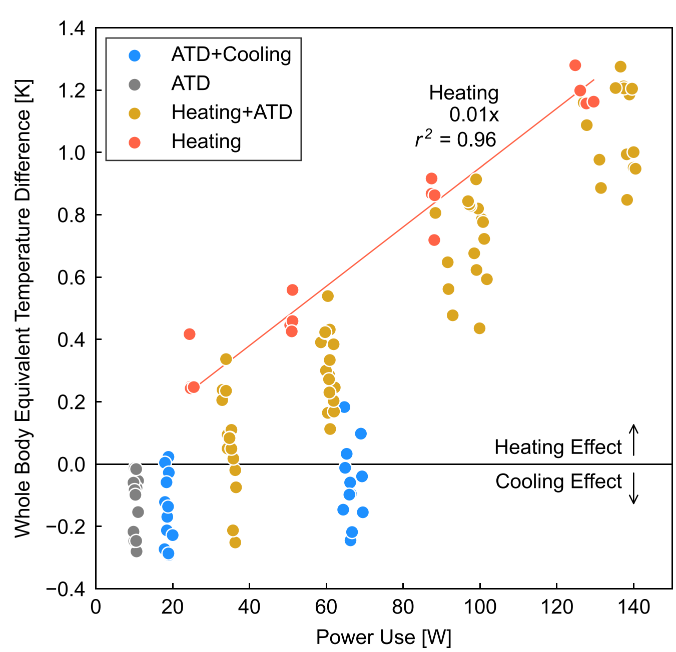


Fig. 5. PECS power use and whole body manikin-based equivalent temperature difference (all conditions except ATD fan setting 1).

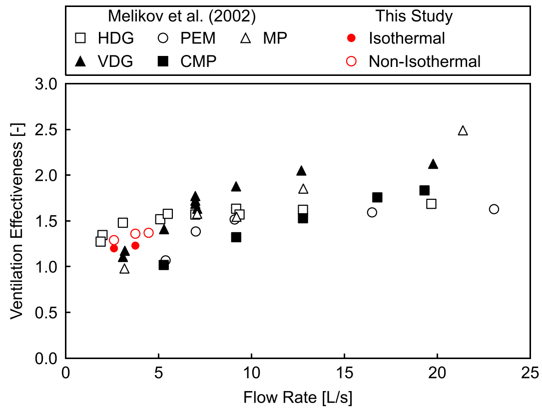


Fig. 6. Ventilation effectiveness and flow rate (in comparison with results from Melikov et al. [23], HDG: Horizontal Desk Grill, VDG: Vertical Desk Grill, PEM: Personal Environments® Module, CMP: Computer Monitor Panel, MP: Movable Panel).

value, however other IEQ parameters such as the cooling effect and fan noise, as well as energy performance should be further examined to determine the optimal air flow rate. Another possibility would be to increase the opening size. The current ATD had an opening area of 4.5 × 10^{-3} m^2, similar to that of the HDG. On the other hand, ATDs with better performance at higher flow rates in Fig. 6, such as the movable panel (MP), had an opening area of 1.8 × 10^{-2} m^2 (ca. 4 times larger).

4.4. Questionnaire responses

4.4.1. Overall thermal sensation and acceptability votes

Fig. 7 shows the thermal sensation and acceptability votes (TSV and TAV) for the whole body. The results were grouped into four by the sex of the participants and the availability of PECS (REF or PECS) in each ambient temperature. Responses from the whole duration of each session were used, including the acclimatization period (first hour), as PECS was used most frequently in this timeframe. Each group therefore consisted of 156 votes (12 male and 12 female subjects, each with 13 votes in every session). A Wilcoxon signed-rank test was performed to compare the distribution of votes from the REF and PECS conditions, and a Mann-Whitney *U* Test was performed to compare the distribution of votes from male and female subjects. The statistical analyses were done using the Pingouin package of python [47].

In terms of thermal sensation, the female subjects tended to have a lower thermal sensation compared to male subjects. Especially at low ambient temperatures (18 and 20 °C), the TSV of female subjects increased in the PECS conditions with a significant difference. The mean TSV of male subjects were already neutral at these temperatures in the REF conditions, which may have been a result of the high clothing insulation (1.0 clo). A larger effect may have been observed if subjects were dressed in lighter clothing. At 28 °C, the thermal sensation decreased for female subjects with PECS. However for male subjects, the thermal sensation increased when PECS was used at 28 °C. This may have been a result of their cooling expectations not being met, or a confounding effect of other IEQ factors such as air quality and noise. In terms of the differences between male and female subjects, at low ambient temperature (18 and 20 °C), the TSV of female subjects were significantly lower than that of male subjects, regardless of the presence of PECS. At 23 °C, the TSV of male participants were higher, towards the slightly warm side. At warmer ambient temperatures (26 and 28 °C), no significant differences of TSV were seen among the reference groups, but female participants with PECS had a significantly lower thermal sensation vote, compared to male participants with PECS.

The thermal acceptability votes yielded similar trends as the thermal sensation votes. The female subjects had higher acceptability with PECS in all temperatures, with the differences being larger at lower ambient temperatures. For male subjects, though the thermal acceptability increased in 18 and 23 °C settings with PECS, the thermal acceptability slightly decreased with PECS at 28 °C. This may have been associated with their expectations of cooling not being fulfilled due to the limited cooling capability of the PECS, which may have also contributed to their thermal sensation being higher with PECS. In the open-ended responses in the post questionnaires, many subjects reported the lack of cooling

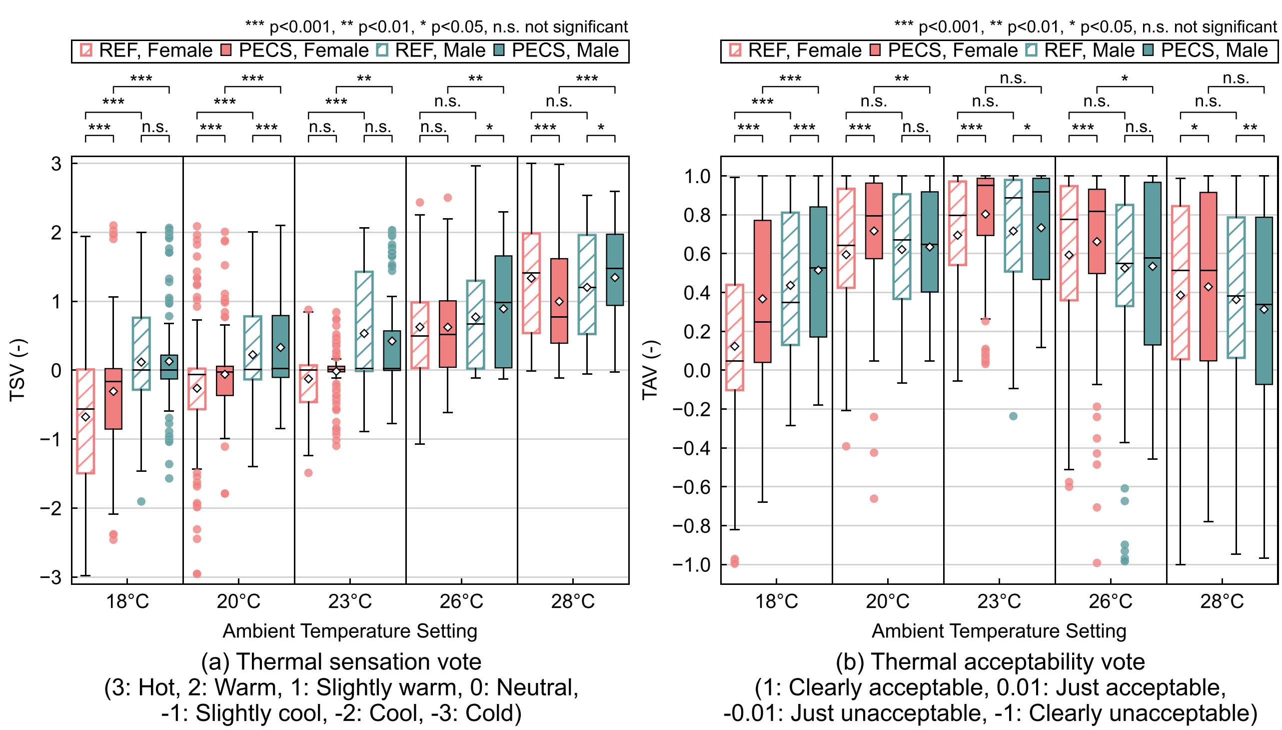


Fig. 7. Questionnaire responses for the whole body.

capability of PECS. This was consistent with the results from the thermal manikin measurements, i.e., the cooling effect of the PECS prototype was much smaller than its heating effect. Between male and female subjects, significant differences among the REF groups were only seen at 18 °C, where the female subjects showed lower thermal acceptability. For the groups with PECS, male subjects had a significantly higher thermal acceptability vote at 18 °C, but female participants had higher thermal acceptability votes at 20 and 26 °C. The differences were non-significant at other temperatures.

In terms of the percentage of unacceptable votes, the largest difference between the PECS and REF conditions were seen at 18 °C, where the percentage of unacceptable votes decreased from 23 to 9 % with PECS. There were no unacceptable votes with PECS at 20 and 23 °C, and 7 % voted unacceptable at 26 °C. For the REF conditions, the unacceptable votes ranged between 2 and 8 % at 20, 23, and 26 °C. At 28 °C, the percentage of unacceptable votes were 21 % for both PECS and REF conditions.

4.4.2. Local thermal sensation votes

Fig. 8 shows the local thermal sensation votes of during all sessions. For both the REF and PECS conditions, the number of unacceptable votes were summed and divided by the total number of votes per ambient temperature and sex, i.e., 156 votes (13 responses from 12 male or female subjects). In most cases, the percentage of unacceptable votes were lower when subjects had PECS. At 18 °C, high unacceptability rates above 25 % were seen on the extremities (i.e., hands and feet) of female subjects in the reference condition. The vertical temperature difference of the head and ankle levels for a seated occupant (1.1 and 0.1 m, respectively) was largest during the measurement at 18 °C, with values of 1.4 ± 0.5 K, which was within Category I of ISO 17772-1 [11] and corresponding to a percent dissatisfied of 3 %. Therefore, the high unacceptable votes at 18 °C could be associated more with the overall room temperature. In the PECS condition, the unacceptability votes decreased in the extremities and thighs, where the heater was primarily targeting. Some subjects wrote in the open-ended comments that they would prefer to have more heating on their upper body (e.g., back), in addition to the hands and feet. Unacceptability rates for both REF and PECS were overall low at 23 °C room temperature. Especially the male subjects had an overall lower unacceptability rate with PECS at 23 °C. At 26 and 28 °C, differences in unacceptability votes at PECS and REF conditions were minimal for female subjects. For male subjects, at 26 °C, the use of PECS resulted in a reduction of unacceptability rates, especially for the lower arms, head, and face areas. However at 28 °C, the unacceptability rates of the REF and PECS were similar. This suggests that the cooling performance of PECS was insufficient at higher temperatures, as the PECS prototype relied on isothermal airflow for cooling.

4.5. PECS operation

Fig. 9 shows the use of each PECS function by all subjects during the experimental sessions. The numbers annotated in the figure represent the setting of that function. During low ambient temperatures of 18 and 20 °C, the heating function was turned on for 60–70 % of the time, of which the maximum setting (10) was used for around 20–35 % of the time. The use of the ATD fan was at the highest at ambient temperatures of 26 and 28 °C, at around 65–70 %. The active cooling setting was used for about 50–65 % of the time. Despite the need for more cooling, as was shown in the thermal sensation votes in Fig. 7, higher fan settings of 8 or above were only used for 10–20 % of the time. In the open-ended feedback at the end of each session, some subjects pointed out that the noise of the fan hindered them from using PECS, especially at high settings. Though smaller in percentages, the ATD fan and cooling were also used at low ambient temperature of 18 and 20 °C. This could be due to the improved air quality, as air with lower enthalpy tend to result in higher perceived air quality [48]. At 23 °C, all functions were used, though the percentage of use was small. This shows that there were needs for both heating and cooling for a small group of subjects even during conditions where neutral thermal conditions were intended.

Fig. 10 shows the occurrence of the operational changes of each PECS function during the measurements. The number of times the subjects changed the PECS operation were counted and grouped in bins of 15 min. Results are shown in both number of changes and cumulative occurrences. All three PECS functions were adjusted the most in the beginning of each session, especially in the first hour. This is in line with

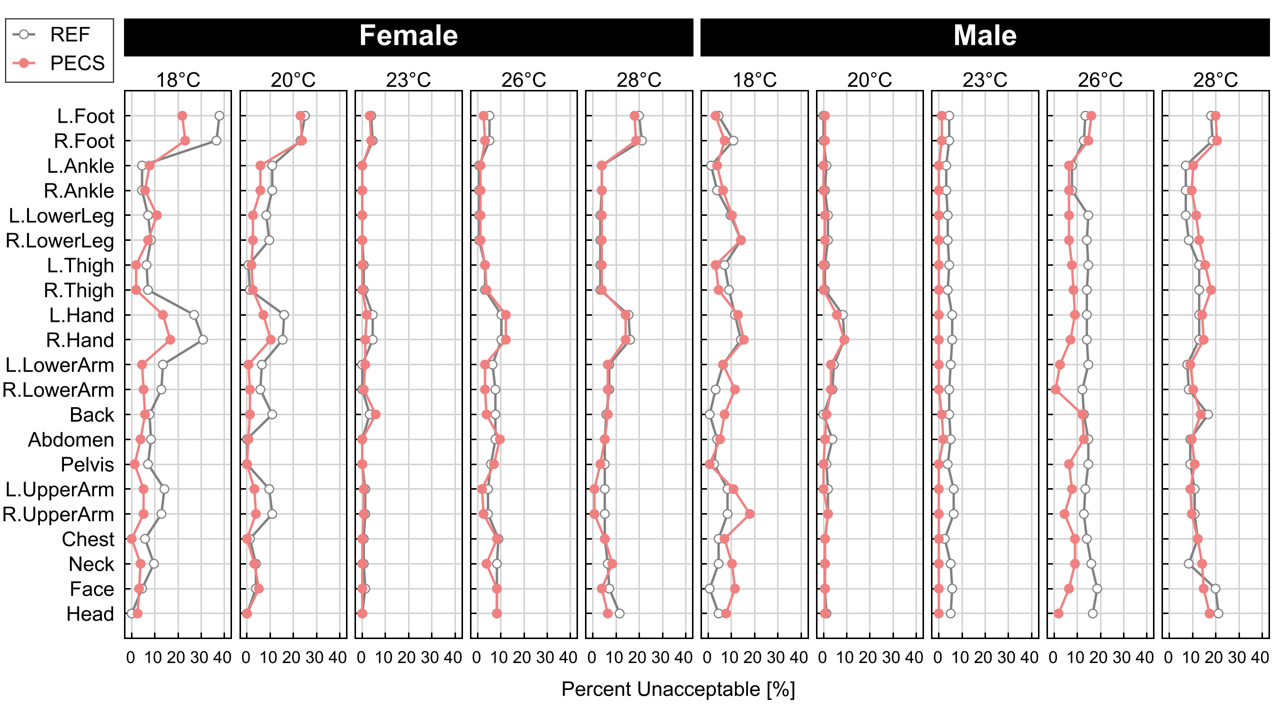


Fig. 8. Percentage of unacceptable local thermal sensation votes (L.: Left, R.: Right).

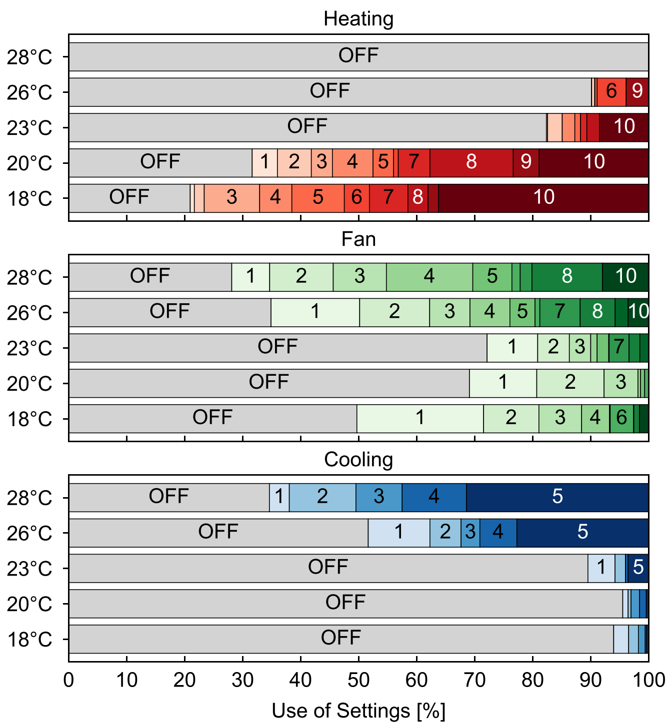


Fig. 9. Use of each PECS setting during all sessions.

findings in the literature, such as the results from Verhaart et al. [49], where it was reported that subjects interacted with a personal cooling system the most in the first 30 min at their workstations.

Subjects changed the heating settings most often at 18 °C, and 74 % of the operational changes were made in the first hour. Once the heating was turned up to a high setting, it was seldom turned down, i.e., they were kept constant for the remainder of the session. At 20 °C, the operational changes were more spread out over the 3-h session, and 44 % of the operational changes occurred in the first hour. The fan settings were adjusted the most in the first 15 min of the session, with highest numbers at 28 °C. The cumulative occurrence over time showed similar trends in all five temperatures for the fan, with 56–70 % of the operational changes happening in the first hour. The cooling function was mainly used in higher temperatures of 26 and 28 °C, with trends similar to that of the fan. In addition, for the fan and cooling settings, a small increase in the operational changes was observed after walking up and down the steps at 60 and 120 min. On average, each subject made 2–3 operational changes of the primarily used function (heating at 18 and 20 °C, and ATD fan and cooling at 26 and 28 °C) during each 3-h session.

5. Overall discussion

5.1. PECS performance

Overall results from both thermal manikin and human subject experiments were consistent in that the current prototype had a higher heating performance than its cooling performance. The heating function had a more noticeable effect on the female subjects and contributed to a higher thermal acceptability in 18 and 20 °C room temperatures. However, there were still instances with TSV lower than −2, and therefore a higher heating effect may be necessary to accommodate individual differences. Cooling and ventilation with the ATD were more challenging. The ventilation effectiveness of the ATD was comparable with previous studies with relatively low air flow rates, however the thermal manikin measurement showed whole body cooling effect as low as 0.3 K. Though the PECS was able to reduce unacceptability votes in some body parts at 26 °C, it was not able to shift thermal sensations to neutrality. As the Peltier element required a substantially larger electricity use, the use of isothermal flow with fans may be a more promising solution to obtain more cooling effect with minimal power under the conditions tested in the present study. In such cases, the ambient temperature will play a critical role in its cooling performance. It may also

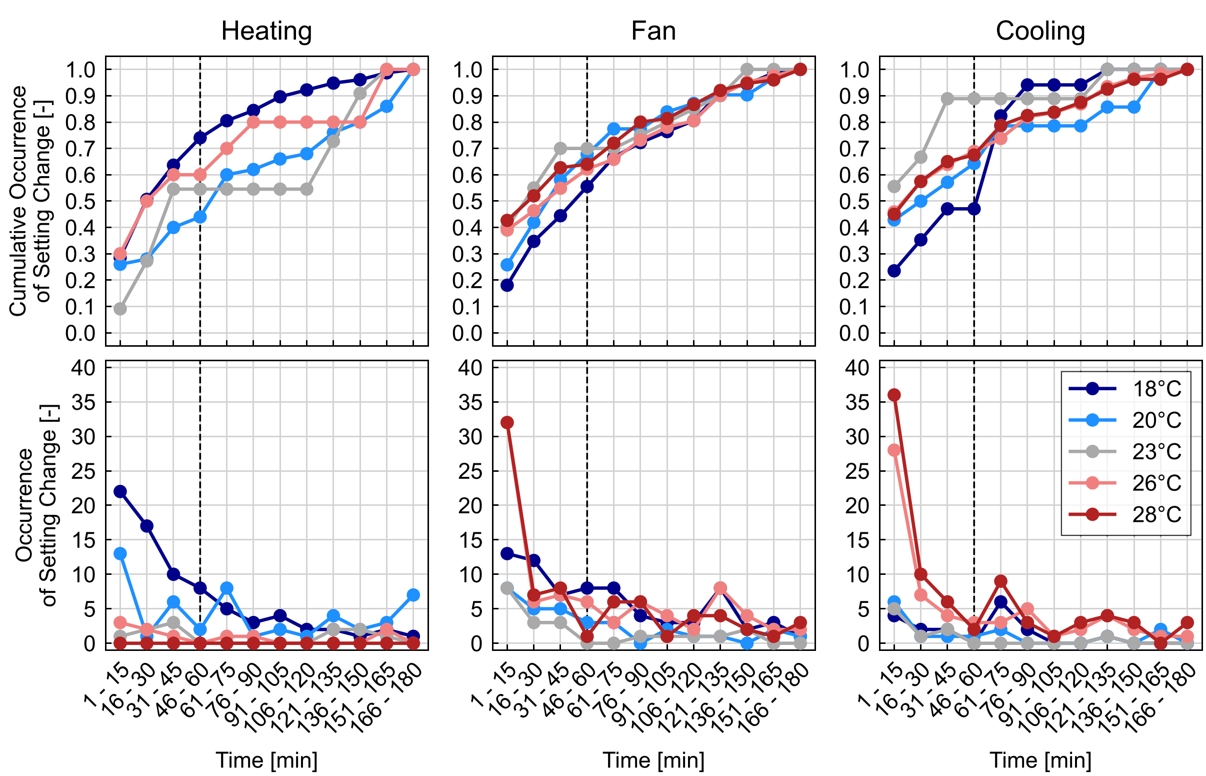


Fig. 10. Occurrence of operational changes over time for each PECS function.

be necessary to target a larger area of the body instead of limiting the flow to the breathing zone.

For PECS to be an energy efficient solution, it must be able to provide heating, cooling, and ventilation with low power use. When PECS is able to provide sufficient heating or cooling effects, it allows the set point temperature of the background system to be offset (i.e., relaxed). When PECS is able to provide personalized ventilation, the background ventilation rate may be reduced proportionally to the increase in ventilation effectiveness. The energy required for PECS operation must be lower than the energy saved by the set point or flow rate relaxation to achieve overall energy saving. As a reference, a literature review by Rawal et al. [7] showed that the maximum power requirement of various PECS ranged from 16 to 1000 W (average 205 W, median 100 W) for heating and from 3 to 84 W (average 39 W, median 38 W) for cooling and ventilation. The PECS prototype in the current study had power requirements (128 W for heating and 68 W for the combined use of the ATD fan and Peltier element) that were higher than the median values in literature, pointing to a need of solutions that use less power. Further analyses using both the PECS performance (e.g., heating/cooling effect, ventilation effectiveness) and the corresponding power use to achieve that effect, are needed to identify the maximum allowed power use of PECS to achieve energy savings. For example, a previous study by Schiavon and Melikov [50] adopted this approach and estimated the maximum allowed power use of a fan to obtain energy saving through set point relaxation to be 20 W.

Indicators that express heating or cooling effects in temperature differences can be easily interpreted in the context of set point temperature relaxation, and therefore manikin-based equivalent temperature and corrective power may be promising indicators. The corrective power could not be obtained in this study, as the mean TSV at the lowest temperature was still above −0.5, and the TSVs were not shifted to neutrality at higher ambient temperatures. However, there were small differences among the TSVs with and without PECS. At 18 °C, the TSV of subjects that used heating increased by 0.28 on average, and at 28 °C, the TSV of subjects that used the ATD decreased by 0.06 on average. If PMV and TSV are assumed to be linear, these differences correspond to a 1.2 K increase and a 0.2 K decrease in the operative temperature, respectively. These values were similar to that of the manikin-based equivalent temperature difference.

It must be noted that the equivalent temperature difference and corrective power are obtained using two different approaches, the former calculated based on heat loss from the body and the latter calculated based on occupant feedback. As the relationship between heat loss and thermal sensation is not necessarily linear [19], it may not be possible to use these two indicators interchangeably. The difference between a manikin-based approach and human subject-based approach may become larger in scenarios such as warmer conditions where latent heat loss plays a larger role or in conditions leading to local thermal discomfort. Further studies on the relationship between these two approaches, and possibly a method to adapt the results obtained from thermal manikins to estimate the human response, would be necessary. Nevertheless, even considering the differences in these two indicators, a review by Zhang et al. [19] showed that the corrective power of PECS ranged from 2 to 10 K for heating and −1 to −6 K for cooling, pointing for a need for the enhancement of the heating and cooling performance of the PECS prototype in the present study.

5.2. Factors limiting the use of PECS

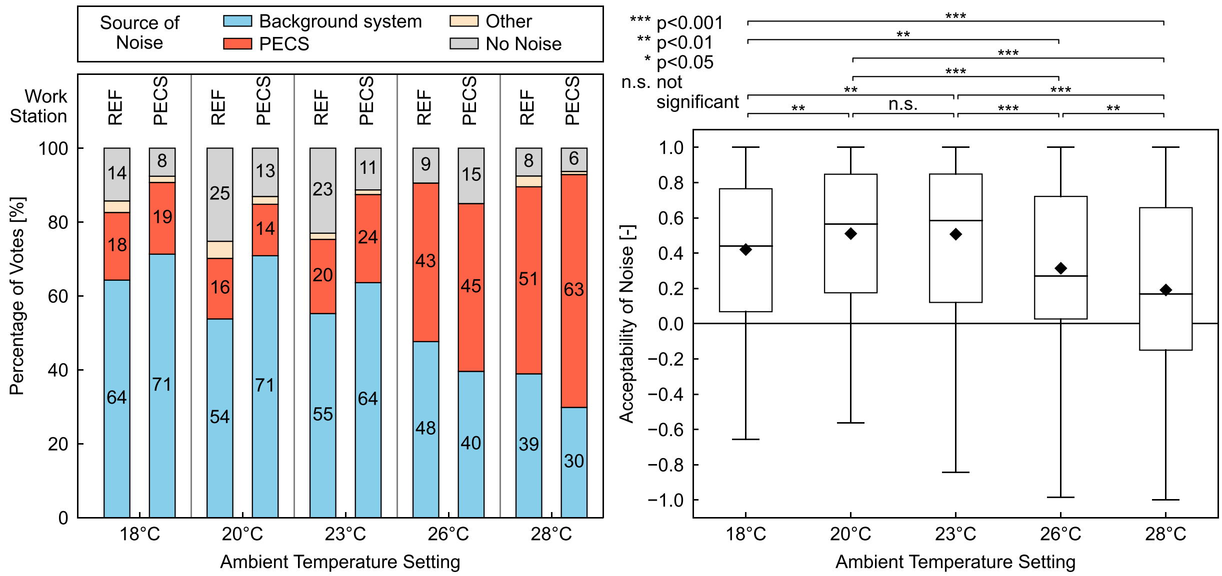
In addition to the performance of PECS, the way in which occupants interact with PECS is also an important factor to consider. As was shown in Fig. 9, the percentage of times when PECS was used at its highest setting was up to 36 %, and intermediate settings were used more often. This may partially be due to interpersonal differences in thermal preference, in which case it would not be an issue if the subjects were satisfied. However, if there were other factors that limited the use of PECS when there was a need for it, such factors must be identified and removed. An example of such a factor would be the user interface of PECS. As the current prototype had a touch screen for controlling the PECS function at the center of the desktop unit, the screen was covered with the laptop computer and therefore some subjects reported that it was inconvenient to change settings. Therefore, ergonomic factors should also be considered in the future design of PECS.

The factor that was reported most as a disturbance factor was the noise from the ATD. Fig. 11 shows the questionnaire responses regarding noise during the human subject experiment. The percentages of votes indicating the main source of noise is shown in Fig. 11(a). The votes were separated by the subjects' workstation (REF or PECS). Fig. 11(b) shows the acceptability of noise per ambient temperature. A pairwise Games-Howell post-hoc test [47] was conducted to test the significant differences among the group of votes.

In all conditions, most of the responses indicated that the major source of noise in the chamber was either the background system or the PECS. The percentages of votes for PECS being the main source of noise became higher at 26 and 28 °C ambient temperatures. In these temperatures, the acceptability of the noise also decreased with a significant difference. The low acceptability of noise may have been influenced by the ambient temperature as well, as previous studies have pointed out the interaction of thermal and acoustic conditions on occupant comfort, especially at higher temperatures [51–53]. Though slightly smaller in percentages, subjects that did not have PECS also voted that PECS was the main source of noise with a similar trend as those that had PECS. This suggests that the noise from the PECS was sufficiently large to affect other occupants in the room. As the votes indicating PECS as the main source of noise increased in higher ambient temperatures, it is likely that the ATD fan and cooling settings were the main sources of noise. In the open-ended responses of the post questionnaire, some subjects responded that the fan noise became too loud after setting 4, and some wrote that despite the need for more cooling, they turned down (or turned off) the fan due to the noise. This could be one of the reasons why fan settings above 5 were only used 25–30 % of the time at 26 and 28 °C (Fig. 9).

The sound pressure level in the chamber when PECS was turned off was 40 dB (A), which corresponds to the upper limit value of Category III for small offices and Category II for landscape offices in EN 16798-1 [54]. When one PECS was running at the maximum fan setting of 10, the sound level measured at the workstation with the corresponding PECS was 50 dB (A). This rise in sound pressure level corresponds to the upper limit of the allowed fluctuation of 10 dB (A) [54]. Hence, when the chamber was occupied with the subjects and with both PECS turned on, it is likely that there were instances where the sound pressure level exceeded the recommended values. As the acoustic properties of the PECS influenced the use of PECS and consequently the cooling performance of PECS, it is necessary for future PECS to operate at lower sound pressure levels. If the PECS is to be implemented in open plan offices, the noise generated by PECS would be even more critical.

Another potential factor that limited the use of PECS was the quality of the air supplied by the ATD. Fig. 12 shows the percentages of unacceptability votes for air quality during the measurements. As the mean value of the acceptability votes did not show any significant differences between subjects with and without PECS, the values were converted to binary variables, i.e., unacceptable or acceptable. The results showed larger percentages of unacceptable votes at higher temperatures of 26 and 28 °C. This is in agreement with previous studies that showed a decrement of air quality acceptability with higher air temperature [48, 55]. However, the percentage of unacceptable votes was 8 % higher for subjects with PECS at 28 °C. Some subjects reported a distinct smell from the supply air, and this could be one of the reasons for a lower acceptability of indoor air. As the prototype was equipped with a UVGI component, secondary pollutants (particles and gas phase compounds) may have formed [56]. Further studies should be conducted to identify both the efficiency to remove particles or pollutants and the potential forming of by-products [57]. Another possible source of smell could be



(a) Source of Noise
(REF: subjects without PECS;
PECS: subjects with PECS)

(b) Acceptability Vote for Noise
(1: Clearly acceptable, 0.01: Just acceptable,
-0.01: Just unacceptable, -1: Clearly unacceptable)

Fig. 11. Perception of noise during human subject experiment.

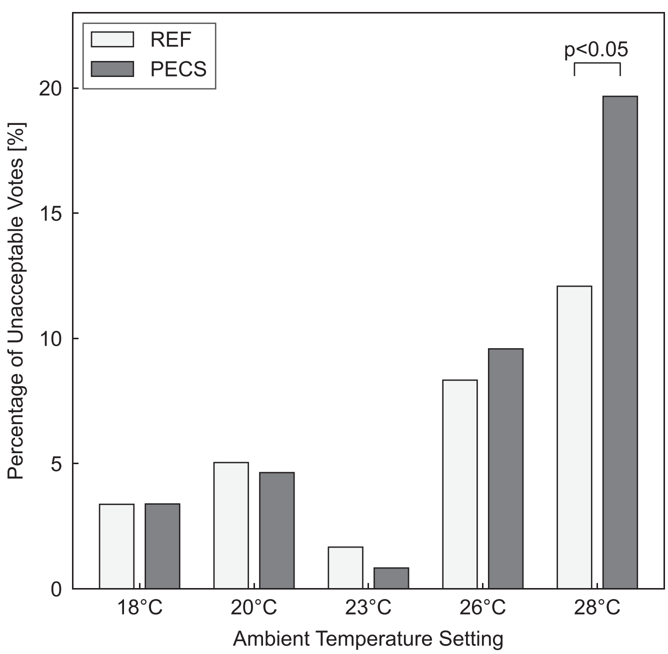


Fig. 12. Unacceptability votes of air quality (significance calculated with Fischer exact test using the SciPy library of python [58]).

the electronics within the desktop unit. Sensory assessment with human subject experiments with and without the UVGI component may be necessary to identify whether the source of smell was the UVGI or other internal materials within the unit.

5.3. Limitations and future research

Compared to other PECS reported in literature, the prototype in the present study has yet to improve its performance, especially for the heating and cooling performance. However, challenges for the further development of a multifunctional, stand-alone PECS have been identified in the present study.

The current study revealed the challenges in the active cooling function of the PECS prototype. In the tested scenarios, the Peltier element was not able to lower the supply air temperature, possibly due to the accumulation of waste heat and not being able to reject this heat to a proper heat sink. The power use also increased substantially, by about 5 times the power use of the ATD fan. Future studies using Peltier elements should study the waste heat rejection carefully, as well as investigate efficient modes of cooling, such as contact cooling. Another option would be to use only isothermal airflow, targeting a larger area of the body. This could be a promising solution in terms of low power use. To improve the heating function, contact heating to certain body parts (e.g., the extremities) could be effective for providing heating with less electrical power use. In terms of the evaluation methods, the obtained TSV gathered around neutral even in the REF settings at low temperatures, and therefore the corrective power could not be obtained. If the corrective power is to be obtained, clothing should be kept constant to observe a wider range of TSV. Furthermore, the general thermal preference of the subjects was skewed (Prefer warmer: 6 female, 1 male; Prefer cooler: 1 female, 2 male; Neither: 5 female, 9 male), and no conclusive relation with the questionnaire responses were observed. Further studies could aim to have a better balance of the participants' thermal preference.

One of the core functions for a stand-alone PECS is the air cleaning function, as a properly functioning air-cleaning component would eliminate the need for PECS to be connected to a duct providing fresh air. The current study only investigated how effectively the supply air from the ATD reached the breathing zone of the manikin. However, for it to be able to assist the background ventilation system, the effectiveness of the air cleaning technologies (e.g., UVGI) must be evaluated. This would require investigation on perceived air quality and particles, as well as the target pollution sources. In addition to the air quality, the present study showed that the noise from the PECS affects the use of PECS and hence its performance. Attention should be given to noise caused by each component, e.g., fans, especially if larger air flow rates are to be used. In such cases, solutions to dampen the noise caused by PECS should be considered. Finally, for the PECS to be a total IEQ solution, the lighting function should be considered as well.

6. Conclusion

In the present study, the performance of a prototype of a multi-functional (heating, cooling, and ATD with air cleaning), stand-alone PECS was evaluated with both thermal manikin and human subject experiments in a climate chamber. The conclusions were as follows:

- The current prototype had a cooling effect of up to 0.3 K and a heating effect of up to 1.3 K, in manikin-based equivalent temperature difference of the whole body.
- The ventilation effectiveness of the ATD, measured by a breathing manikin, was up to 1.4.
- The electrical heating panel provided approximately 0.1 K of heating for every 10 W of power use (up to 1.3 K with 128 W). The fan power use was approximately 11 W, and the use of a Peltier element to cool the air increased the power use up to 67 W. However, the Peltier element did not provide any noticeable cooling enhancement in the current prototype construction due to its limitations in rejecting the accumulated heat.
- In the human subject experiments, the heating function was able to provide a mean thermal sensation of neutrality for female subjects at 18 °C. At 26 and 28 °C, the prototype was not able to provide a mean thermal sensation of neutrality, confirming the prototype's lack of cooling performance.
- For female subjects, the use of PECS resulted in a higher thermal acceptability for all temperatures. For male subjects, the thermal acceptability increased at 18 °C with PECS, but decreased at 28 °C, possibly due to their cooling expectations not being met.
- In most cases, the occupants adjusted the PECS settings most often in the first hour after being seated at their workstations.
- The maximum setting of the ATD fan was rarely used, i.e., up to 8 % of the time. The noise and smell from the ATD fan hindered the occupants from using the PECS at high settings. The position of the touch screen for controlling the PECS was also mentioned as a limiting factor in the open-ended responses. A holistic assessment of the IEQ factors and ergonomic factors is important for the development of PECS.

As the current PECS prototype is still under development, its performance is not yet optimal. However, the series of measurements revealed the challenges in the development of a stand-alone PECS. One of the challenges is to obtain sufficient cooling with low energy use. The results from the current study suggest that the use of isothermal flow could be a promising solution. Another challenge is to address factors limiting the use of PECS, which in the present prototype was likely to be the noise generated by the fan at high settings and the smell from the supply air of the ATD. Further investigation as to whether the use of UVGI contributed to the smell would be necessary. The abovementioned findings will aid in the development of future prototypes of PECS.

CRediT authorship contribution statement

Jun Shinoda: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Dragos-Ioan Bogatu:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Futa Watanabe:** Software, Resources. **Yosuke Kaneko:** Software, Resources. **Bjarne W. Olesen:** Writing – review & editing, Supervision, Conceptualization. **Ongun B. Kazanci:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Whole-body Manikin-based Equivalent Temperature Difference

Table A1 and Table A2 show the whole-body manikin-based equivalent temperature difference in all settings for the heating and cooling scenario explained in Table 1.

Table A1
Whole-body manikin-based equivalent temperature difference in all cooling scenarios (Unit: K)

Fan Setting [−]	Cooling Setting [−]	Room Temperature [°C]				
		30	28	26	24	23
10	5	0.0	−0.2	−0.2	−0.2	−0.2
	1	0.0	−0.3	−0.2	−0.3	−0.3
	0	−0.1	−0.3	−0.2	−0.2	−0.2
7	5	0.1	−0.1	−0.1	−0.1	−0.1
	1	0.0	−0.3	−0.1	−0.2	−0.2
	0	0.0	−0.2	−0.1	−0.1	−0.1
5	5	0.2	0.0	0.0	−0.1	−0.1
	1	0.0	−0.2	−0.1	−0.2	−0.1
	0	0.0	−0.2	−0.1	−0.1	−0.1
1	5	0.3	0.1	0.1	0.2	0.2
	1	0.2	−0.1	0.1	0.1	0.1
	0	0.2	0.0	0.1	0.0	0.0

Table A2
Whole-body manikin-based equivalent temperature difference in all heating scenarios (Unit: K)

Heating Setting [−]	Fan Setting [−]	Room Temperature [°C]				
		23	22	20	18	16
10	10	1.0	1.0	0.9	0.8	0.9
	7	1.2	1.1	1.0	1.0	1.0
	5	1.2	1.1	1.1	1.2	1.2
	1	1.3	1.1	1.2	1.2	1.2
	0	1.3	1.2	1.2	1.2	1.2
7	10	0.7	0.6	0.5	0.4	0.6
	7	0.8	0.6	0.6	0.6	0.8
	5	0.8	0.7	0.6	0.7	0.8
	1	0.9	0.9	0.8	0.8	0.8
	0	0.9	0.8	0.7	0.9	0.9
4	10	0.2	0.1	0.2	0.2	0.1
	7	0.3	0.2	0.4	0.2	0.2
	5	0.3	0.3	0.4	0.3	0.3
	1	0.4	0.4	0.5	0.4	0.4
	0	0.4	0.5	0.6	0.5	0.4
2	10	0.0	−0.1	−0.1	−0.3	−0.2
	7	0.1	0.0	0.0	0.1	0.0
	5	0.1	0.0	0.1	0.1	0.1
	1	0.2	0.2	0.3	0.2	0.2
	0	0.2	0.2	0.4	0.2	0.2

Appendix B. Additional PECS specifications

Table B1 lists the power use, air speed at the ATD opening, and heating panel surface temperature with the respective PECS settings. The panel surface temperature was influenced by the room temperature, and therefore the average and standard deviation of the surface temperatures within the range of 16–23 °C room temperature are shown. In steady-state conditions, the supply air temperature of the ATD fan was isothermal in all settings, including those with the cooling function turned on. When the cooling setting was on maximum (setting 5), the supply air temperature decreased by up to 0.5 K in the first 5 min but converged to room temperature after approximately 20 min.

Table B1
PECS specifications corresponding to tested scenarios

Fan Setting	Cooling Setting	Heating Setting	Power Use [W]	Air Speed at ATD opening [m/s]	Panel Surface Temperature [°C]
10	5	0	68	1.00	-
	1		19		
	0		11		
7	5		66	0.84	
	1		18		
	0		10		
5	5		65	0.75	
	1		13		
	0		10		
1	5		64	0.09	
	1		16		
	0		8		
10	0	10	137	-	38.5 ± 3.5
7			137		
5			136		
1			134		
0			128		
10		7	98		34.0 ± 3.1
7			98		
5			96		
1			95		
0			88		
10		4	62		29.3 ± 2.8
7			61		
5			61		
1			59		
0			51		
10		2	36		25.9 ± 2.7
7			35		
5			35		
1			34		
0			25		

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