Development and initial testing of a Personalized Environmental Control System (PECS)

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Abstract. Personalized Environmental Control Systems (PECS) condition the immediate surrounding of occupants in contrast to conventional HVAC systems. PECS have several advantages including allowing occupants to adjust their immediate surroundings according to their preferences, which could improve their satisfaction with the indoor environment, which may lead to higher productivity. PECS can also lead to noticeable energy savings, if implemented effectively in buildings. The present study explains the development process and initial testing of a novel PECS. The PECS had heating, cooling, and ventilation functions, together with the possibility of adjusting lighting color and brightness. Ventilation and cooling were provided from a desktop air terminal device, and heating was provided by a curved panel covering the lower body from the thigh to the lower leg of a seated occupant. A thermal manikin was used to quantify the heating and cooling performance of the different versions of the PECS. The most recent prototype was able to provide a cooling effect up to 6 K (calculated by the manikin-based equivalent temperature difference) to the left side of the face, and a heating effect of up to 5 K to the left and right thighs. The cooling and heating effect of the whole body was up to 0.3 K and 1.3 K, respectively. A Peltier element was introduced to lower the supply air temperature from the PECS, but had limited effect on the cooling effect despite the large increase in power use. When implementing a Peltier element in PECS, the generated waste heat must be handled so that it does not interfere with the cooling.

Keywords. Personalized system, ventilation, cooling, thermal manikin, equivalent temperature
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1. Introduction

There are large differences among occupants in terms of thermal preference, air movement preference, clothing level, activity, ventilation and air quality preference and also their physiological and psychological responses [1]. Therefore, Personalized Environmental Control Systems (PECS) allow controlling the localized environment at occupant's workstation by their preference instead of conditioning an entire room to uniform conditions. This has the potential to improve comfort, health, and productivity of the occupants, and has the potential to improve the energy efficiency of the entire heating, ventilation and air-conditioning (HVAC) system substantially.

Personalized ventilation will also protect against cross contamination, which is critical in open-plan offices and work places with close distance [1]. There is currently an increasing interest for PECS as buildings are needed to be pandemic-proofed. The application is for work places with mainly sedentary activity such as open-plan offices, banks, and control centers. Due to the COVID-19 pandemic, where many people have been working from home, there will also be an increase in home working places where PECS could be a solution as well.

In these regards, PECS has advantages in large spaces such as open-plan offices where it substantially improves the local comfort and the energy efficiency of the entire system [2]. Generally, PECS is more energy-efficient and economically-feasible than conventional HVAC systems because it can extend the standardized temperature range related to HVAC, which is specified in ISO 7730 [2], [3]. Previous studies pointed out that with the suitable application of PECS, it is possible to achieve comfort (dissatisfaction lower than 20%) in a temperature range between 18 and 32°C [4].

Despite the proven benefits, there are currently a very limited number of commercially-available PECS and their applications have not reached the broader market. Therefore, development and performance specifications of new types of PECS are needed.

The present study reports the results from physical measurements of a newly developed PECS prototype. A thermal manikin was used to evaluate the heating and cooling performance of the PECS on a human body. The obtained results were also compared with measurement data of previous prototypes, and to their respective power use for each of their function.

2. Methodology

2.1 PECS prototypes

Three prototypes of a desk-type PECS have been developed until now. Each prototype was evaluated based on its heating and cooling performance using the manikin-based equivalent temperature at different operation settings. The measurement procedure will be described in the following subsection.

The first prototype (v1) had an air terminal device (ATD) for cooling and ventilation, and three separate heating panels to heat the lower body. The ATD recirculated the room air, and was equipped with a simple filter. Cooling was provided by increasing the air supply, and hence the velocity, from the ATD. For heating, one panel was placed above the thighs of the occupant (i.e., the bottom side of the table), another panel was placed perpendicular to the floor, facing the lower leg of the occupant, and the other panel was placed on the floor where occupants would place their feet.

In the following prototype (v2), improvements were mainly made to the ATD. A Peltier element was introduced to provide additional cooling. Therefore, the ATD could be operated in both "ventilation" and "cooling" modes. During the ventilation mode, room air was recirculated through a filter in the ATD. The Peltier element was turned on during the cooling mode, and the waste heat from the Peltier element was dissipated to the room air through the sides of the ATD (not interacting with the supply air from the ATD).

The heating panels of v2 consisted of three panels, similar to that of v1. In parallel to the measurements of the two prototypes, a mockup of an alternative system to integrate the three panels into one panel was developed and tested. The mockup (flexible heating panel, FHP) consisted of a single curved surface that covered the lower body from the thighs to the lower leg, with a flexible heating element pasted on the surface. This heating element heated all of the lower body parts simultaneously.

The most recent prototype (v3) integrated the improvements made in v2 and the FHP. The heating panels were integrated into a single, flexible panel with a similar geometry as the FHP. The ATD had a Peltier element but water pipes were installed to remove the waste heat. The recirculated air for ventilation was cleaned by means of ultraviolet germicidal irradiation (UVGI). The ventilation setting could be adjusted from 1 to 10, the cooling setting could be adjusted from 1 to 5 (only when the ventilation was turned on), and the heating setting could be adjusted from 1 to 10. The overview and its setup is shown in Fig. 1.

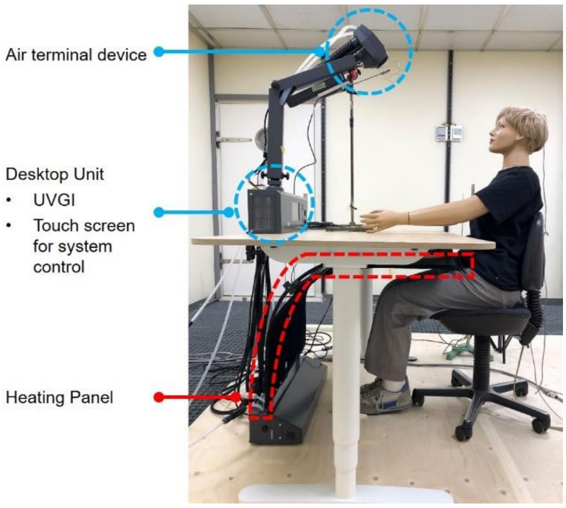

Fig. 1 – Overview of developed PECS (v3) and its setup in the chamber.

It must be noted that the "ventilation" function in all the prototypes provides recirculated air cleaned by filters and/or UVGI, and does not provide fresh air (outdoor air). The term "ventilation" is used for simplicity within the text, and air quality was not analyzed in the present study.

2.2 Measurement setup

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. A displacement ventilation system supplied air at a very low velocity from the floor to the chamber. Air was also supplied between the wall and finishing fabric so that the surrounding surface temperatures would be nearly equal to the room air temperature. PECS v3 was mounted on a desk with dimensions of 160 × 80 × 80 cm ($L \times W \times H$). The floor beneath the PECS was covered with a wooden board with dimensions of 2.44 × 2.44 m to reduce the effects of the ventilation system on the measurement results.

A thermal manikin was used to study the heating and cooling effects of the PECS on the human body. Only the thermal performance was analyzed, and indoor air quality was not within the scope of the present study. The manikin had a body shape representing an average Scandinavian female with a height of 1.7 m.

The manikin had 24 individually controlled body parts: left and right foot, left and right low leg, left and right front thigh, left and right back thigh, pelvis, back side, 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. An illustration of the body parts is shown in Fig. 2 (note that the back of the manikin was divided into two parts in the current measurements). The manikin was seated on an office chair with a clothing insulation corresponding to 0.10 clo [5]. The manikin was dressed in light summer clothes in cooling mode measurements, and in medium winter clothes in heating mode measurements. The clothing insulation for the different clothes are listed in Table 1.

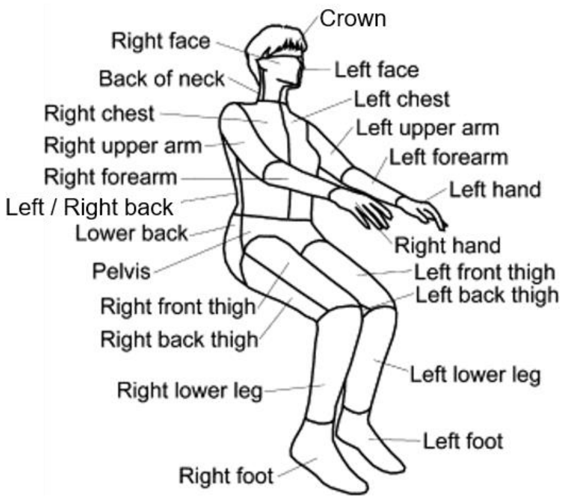

Fig. 2 – Body parts of the thermal manikin (based on the illustration from Watanabe et al. [6]).

A PT100 temperature sensor with an accuracy of ±0.03 K was positioned next to the desk at a height of 0.6 m for room temperature monitoring. Air and operative temperature sensors were positioned 0.5 m behind the manikin at the height of 0.6 and 1.1 m. A watt meter was used to monitor the system power use during the measurement.

2.3 Experimental conditions

Table 2 summarizes the experimental conditions with PECS. Measurements were conducted for both cooling and heating scenarios. For each room temperature setting, thermal manikin measurements were conducted with the PECS turned off, which was used as the reference case. For the test cases with PECS turned on, at each room temperature setting, 12 cases were conducted with the cooling scenario and 20 cases with the heating scenario. Each test case was conducted at steady state, and the average value over 5 min was used for analysis. All measurement equipments were logging at 10 s intervals. Prior to the measurements, a smoke visualization was conducted to determine the optimal position of the ATD. The position of the ATD was fixed at a position in which the supply air reaches the breathing zone (mouth) of the manikin.

Table 1 – Clothing insulation (*Icl*) values for different clothes

Garment	*Icl* (clo)
Light summer clothes	
T-shirt (short sleeves)	0.09
Normal trousers	0.25
Socks	0.02
Shoes (thin soled)	0.02
Panties	0.03
Standard office chair	0.10
Total	0.51
Medium winter clothes	
Normal shirt (long sleeves)	0.25
T-shirt (short sleeves)	0.09
Normal trousers	0.25
Socks	0.02
Shoes (thin soled)	0.02
Panties	0.03
Standard office chair	0.10
Total	0.76

Table 2 – Experimental conditions with PECS

Tested component/ Room condition	Operational Settings
Cooling scenario (light summer clothes)	
Room temperature	23, 24, 26, 28, 30 °C
Ventilation (ATD)	1, 5, 7, 10
Cooling (ATD)	0, 1, 5
Heating scenario (medium winter clothes)	
Room temperature	16, 18, 20, 22, 23 °C
Ventilation (ATD)	0, 1, 5, 7, 10
Heating (Panel)	2, 4, 7, 10

2.4 Data analysis

The thermal manikin gives the surface temperature and power use to maintain that surface temperature (which can be interpreted as the heat loss for a given condition) for each of the 24 body segments. The output was then used to calculate the manikin-based equivalent temperature (t_{eq}) for each body segment. ISO 14505-2 [7] defines the equivalent temperature to be a "temperature of a homogeneous space, with mean radiant temperature equal to air temperature and zero air velocity, in which a person exchanges the same heat loss by convection and radiation as in the actual conditions under assessment". The following equations were used to calculate t_{eq}.

$$h_{bp} = \frac{P_{bp}}{t_{bp} - t_a} \quad (1)$$

$$t_{eq} = t_{bp} - \frac{P_{bp}}{h_{bp}} \quad (2)$$

Where:

h_{bp} : combined heat transfer coefficient for the body part (W/(m²·K))

P_{bp} : heat loss from the body part (W/m²)

t_a : reference room temperature (°C)

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

Equation (1) was used to calculate the combined heat transfer coefficients of each body part of the reference cases (without PECS) in all room temperature conditions. The average value for each body part was used in equation (2) to calculate t_{eq} in all measurement cases. To show the cooling and heating effect of the PECS, the equivalent temperature difference (Δt_{eq}) was calculated by subtracting the t_{eq} of the reference case from the t_{eq} of the cases with the PECS turned on.

3. Results and Discussion

3.1 Power use

Tables 3 and 4 list the power use during the cooling and heating cases. The values are the average over all the tested conditions. The power use of the ventilation (without cooling) was in the range of 8 – 11 W, and turning on the cooling function added another 8 – 57 W to the power use. The power use for the heating panel was in the range of 25 – 128 W.

3.2 Manikin-based equivalent temperature

Fig. 2 shows the manikin-based equivalent temperature difference for the cooling scenario, at a room temperature of 28 °C. Negative values indicate cooling, and positive values indicate heating. The largest cooling effects were seen around "L. Face" (left part of the face), "R. Face" (right part of the face), and "Back of Neck". Among these body parts, the left side of the face was cooled the most due to the design of the ATD, as it was positioned to the left side of the PECS unit instead of at the center. In lower room temperature settings, the cooling effect to the left side of the face increased to about Δt_{eq} = -5 K, and also a small cooling effect (up to Δt_{eq} = -1 K) was seen at "L. Chest" (left part of the chest). In general, the cooling effect became larger in lower room temperature settings as the supply air from the ATD becomes lower as the room temperature decreases.

The comparison between the cooling settings and the no cooling settings (only ventilation) suggests that the cooling provided from the Peltier element at the ATD had a limited or negligible cooling effect on the manikin (occupant). However, the results in these figures were conducted at steady state, meaning the PECS had been running in each operational setting for at least 30 minutes. A slight decrease in the supply air temperature during the first few minutes of operation was observed, which could result in a difference in actual use (with humans at dynamic conditions). This aspect will be investigated further.

Table 3 – Power use of all cooling cases (V: ventilation, C: cooling settings)

Setting	Power [W]	Setting	Power [W]
V10-C5	68	V5-C5	65
V10-C1	19	V5-C1	13
V10-C0	11	V5-C0	10
V7-C5	66	V1-C5	64
V7-C1	18	V1-C1	16
V7-C0	10	V1-C0	8

Table 4 – Power use of all heating cases (H: heating, V: ventilation settings)

Setting	Power [W]	Setting	Power [W]
H10-V10	137	H4-V10	62
H10-V7	137	H4-V7	61
H10-V5	136	H4-V5	61
H10-V1	134	H4-V1	59
H10-V0	128	H4-V0	51
H7-V10	98	H2-V10	36
H7-V7	98	H2-V7	35
H7-V5	96	H2-V5	35
H7-V1	95	H2-V1	34
H7-V0	88	H2-V0	25

Despite the cooling effect on the face, the equivalent temperature difference of the overall body was nearly zero in all cases. This is due to the small surface area of the cooled body segments compared to the total surface area of the manikin. However, as the breathing zone and the head area is being cooled, it is possible that an actual person will perceive a larger cooling effect than that indicated by the manikin based equivalent temperature.

Fig. 3 shows the manikin-based equivalent temperature difference for the heating scenario, at a room temperature of 18 °C (both heating and ventilation without cooling was active). The largest heating effects were seen around the "L. Front thigh" and "R. Front thigh", with an equivalent temperature

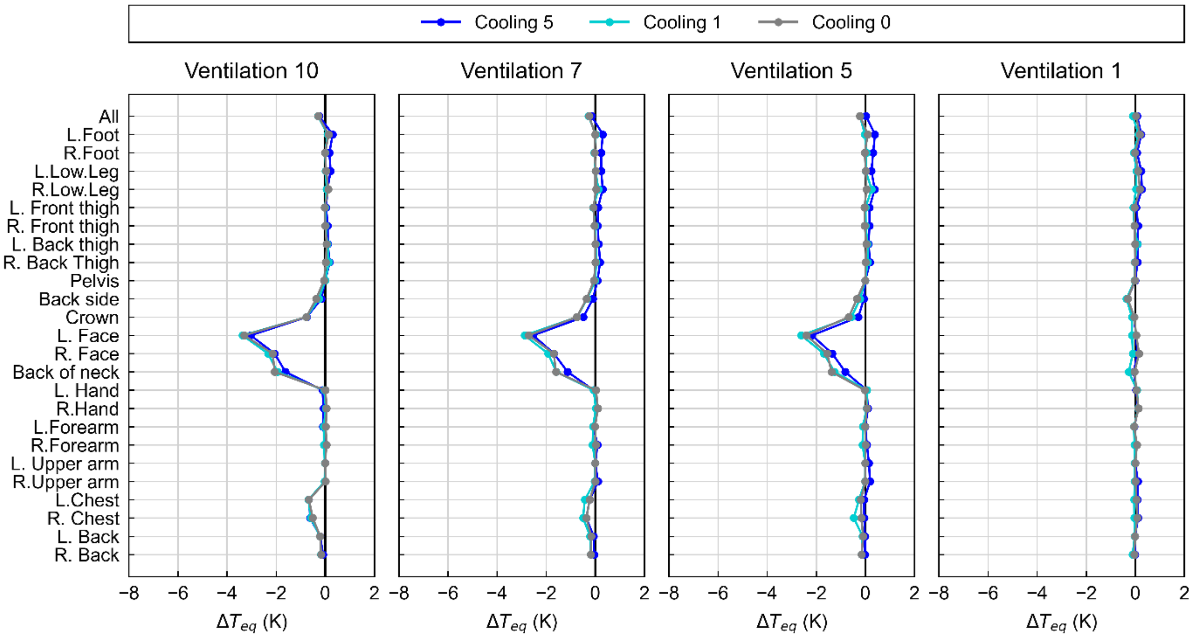

Fig. 2 – Equivalent temperature difference at 28 °C room temperature (cooling scenario).

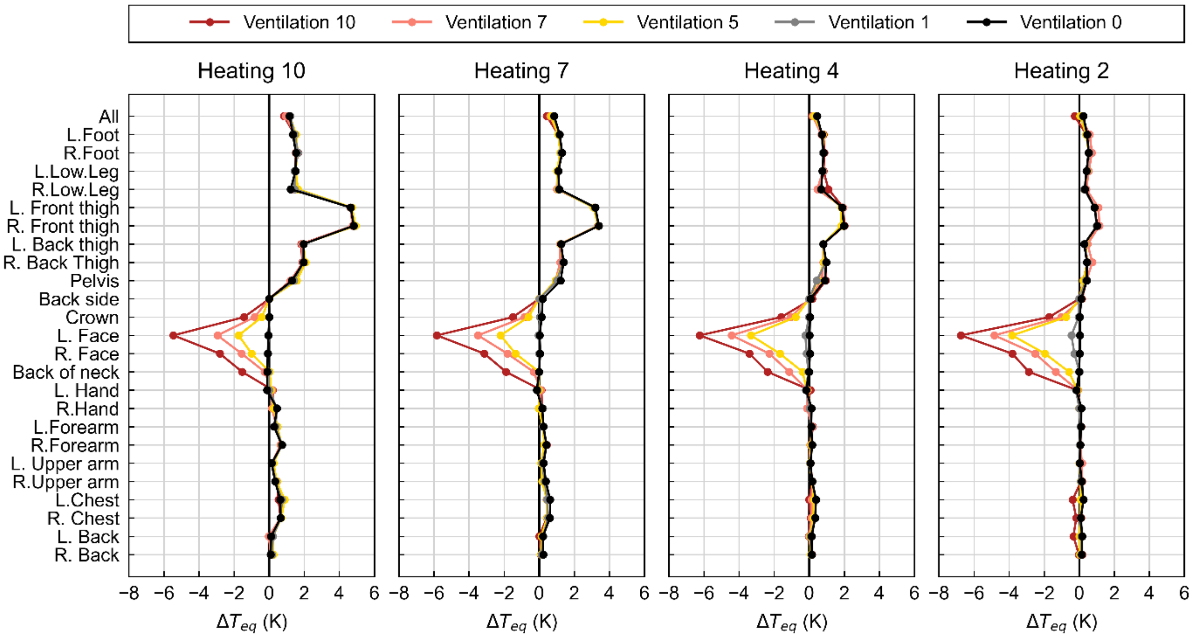

Fig. 3 – Equivalent temperature difference at 18 °C room temperature (heating scenario).

difference up to about 4 – 5 K. For the other lower body parts, such as the ”L./R. Foot”, “L./R. Low Leg” and ”L./R. Back Thigh”, the heating effect was up to 1 – 2 K. In higher heating settings (i.e., 7 or 10), a slight increase in the equivalent temperature difference can be seen around the chest, which could be the effect of warm air from the heating panel below the desk.

During the combined use of the ventilation and heating, no interaction was seen between the operations of the two components. The heating effect was uninfluenced by the ventilation setting, and the cooling effect from the ventilation followed the same trend as seen the cooling scenario. Therefore, it was concluded that the heating component does not interfere with the airflow to the breathing zone.

3.3 Power use and equivalent temperature difference

The extent of cooling or heating PECS can provide is a critical characteristic for the system. The amount of power required to provide the cooling or heating is also a key parameter. Therefore, the comparison of the power use and equivalent temperature difference can be a viable option to compare different PECS. Sections 3.1, 3.2 reported the results of the measurement for PECS v3. The same measurement procedure with the same room temperature settings were conducted for the previous prototypes (v1, v2, and FHP), and therefore a comparison could be made.

Fig. 4 shows the comparison of the power use and equivalent temperature difference in the cooling scenario, using all the collected measurements from each prototype (v1 – v3). The equivalent temperatures of the whole body, left and right face, crown and back of neck were selected. Each point represents the measured value at different conditions, i.e., room temperature and operation settings of the fan or cooling. For example, for PECS v3, the measurement data with the combination of a room temperature setting of 23 – 30 °C, fan setting of 1 – 10, and cooling setting of 1 and 5 was plotted (i.e., the cooling scenario in Table 2). The cases with cooling were distinguished from the cases with air flow only (ventilation cases).

From the ventilation cases, it can be seen that the power use between different ventilation settings were small. Using the cooling function of the PECS resulted in a large increase in the power use but with little to no enhancement of the cooling (in terms of equivalent temperature difference). This was observed for both PECS v2 and v3. For v3, the average power use for the ventilation cases was 10 W, while the average power use for the cooling cases at the maximum setting was 66 W. For v2, the corresponding average power use were 4 W and 44 W, respectively. The power use of v3 was higher than the previous versions due to the UVGI for ventilation, whereas the others only had a simple filter.

Despite not having a dedicated active cooling function, v1 was able to provide the largest cooling effect. The differences with the other prototypes were the air velocity and the shape of the ATD. This suggests that further improvement in the air distribution (both in terms of air velocity and flow pattern) would be possible.

The comparison of different body parts show that the cooling effect of v3 was mostly to the left and right sides of the face, with a cooling effect up to about 6 and 4 K, respectively. The cooling effect to the crown was up to about 2 K, and about 3 K for the back of the neck. It can also be seen that v3 had the widest range of equivalent temperature differences for the face and back of neck, which would mean that occupants could have a better control over the PECS.

Fig. 5 shows the comparison of the power use and equivalent temperature difference in the heating scenario, using all the collected measurements from each prototype and mockups (v1 – v3 and FHP). The equivalent temperatures of the whole body, left and right front thigh, and left and right lower leg were selected. As was with the cooling scenario, each point represents the measured value at different conditions, i.e., room temperature and operational settings of the heaters, including the operation of different heating panels in v1 and v2. The v3

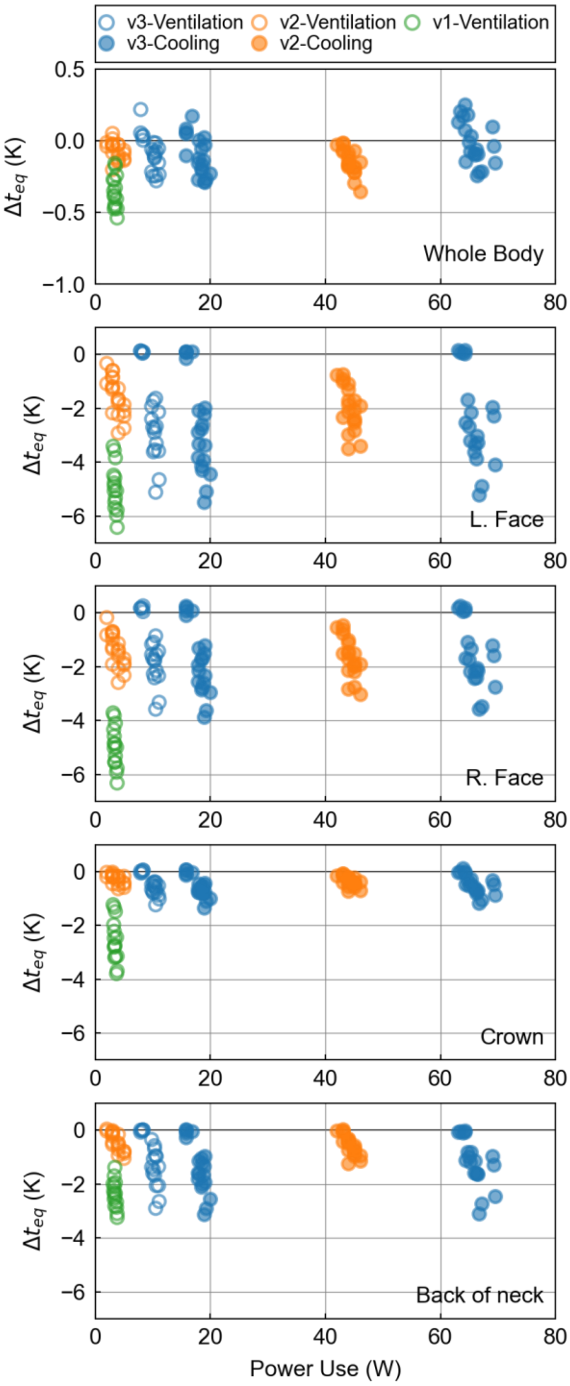

Fig. 4 – Power use and equivalent temperature difference in cooling scenario.

measurement cases with the combined use of the ventilation system and the heater was excluded to limit the comparison to the heating output of the heaters.

The results show that the heater of PECS v3 was able to replicate the performance of the FHP both in terms of power use and equivalent temperature difference of the manikin. It can also be seen that the FHP and PECS v3 was able to provide more heating to the whole body (mainly on the lower body), resulting in an equivalent temperature difference up to about 0.5 K higher than those of v1 and v2. For the individual body parts, as v1 and v2 had multiple panels that

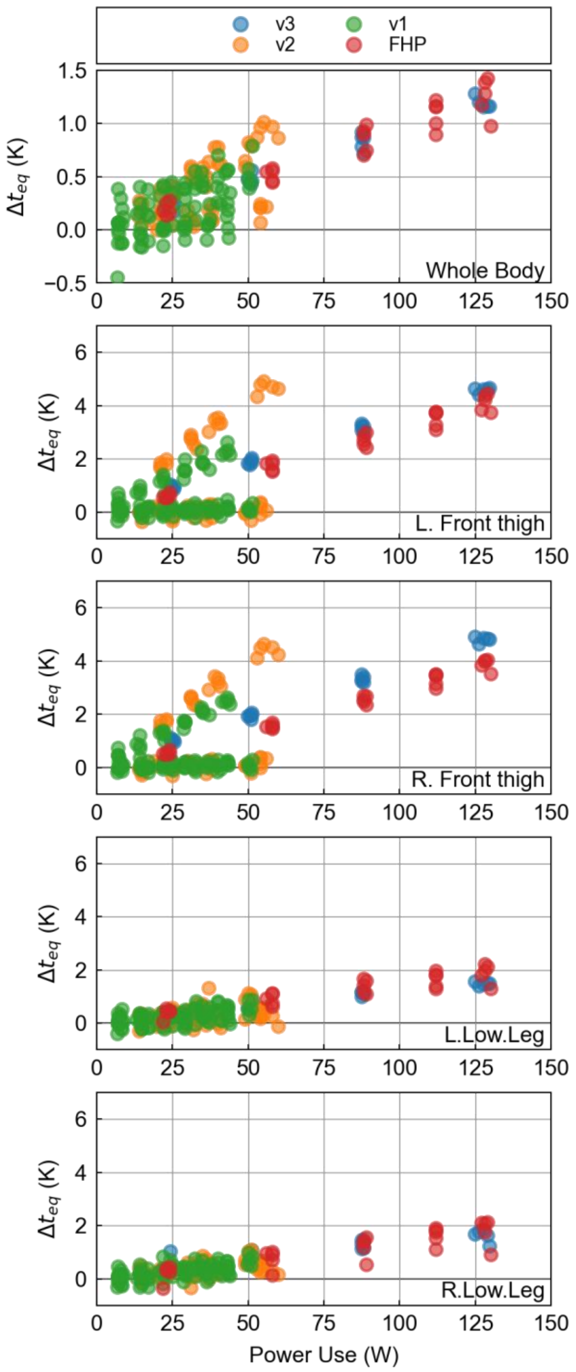

Fig. 5 – Power use and equivalent temperature difference in heating scenario.

heated different parts of the body, in some cases they were able to provide up to 5 K of heating to the front thighs with less power use as compared to v3 or FHP. The relationship between the power use and heating effect was similar across all prototypes, but v3 and FHP were able to provide more heating with the use of more power.

It should be noted even though a thermal manikin is a viable tool for studying the effects of the PECS, the actual heating and cooling effects might be much larger in reality, as the heating has focused on the lower body parts and the cooling has focused on the head region. This requires further studies with human subject experiments.

4. Conclusion

Thermal manikin measurements were conducted in a climate chamber to evaluate the cooling and heating effect of a prototype of a novel PECS on the human body. The thermal performance of the ventilation, cooling and heating components were evaluated based on their power use and manikin-based equivalent temperature. A comparison was made with previous prototypes to evaluate the improvements made during the development process.

The cooling component of the developed PECS provided a cooling effect of up to 6 K to the left side of the face, 2 K to the crown, 3 K to the back of the neck, and 0.3 K to the whole body. The heating panel was able to provide a heating effect of up to 5 K to the front thighs, 1 K to the lower legs, and 1.3 K to the whole body.

For the ventilation component, the power use increased by about 5 W due to the added UVGI. The use of a Peltier element for cooling the supply air increased the power use by about 66 W. However, little to no enhancement of the cooling performance in terms of equivalent temperature was observed. When implementing a Peltier element for cooling within the PECS, the generated waste heat must be handled so that it does not interfere with the cooling. For the heating panels, introducing a curved panel covering the thighs and lower leg was able to provide heating up to about Δt_{eq} = 1.3 K, showing clear improvement from the previous prototypes.

The results presented in the present study are interim results and further development on the PECS is ongoing. Human subject measurements are planned to be conducted to evaluate the performance of PECS v3. Both subjective and objective outputs from the human subjects will be collected and compared with the results reported in this paper.

5. Acknowledgements

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6. Data Access Statement

The datasets generated during and/or analyzed during the current study are not available because of a non-disclosure agreement but the authors will make every reasonable effort to publish them in near future.

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