Heating and cooling the human body with energy-efficient personal comfort systems (PCS)

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SUMMARY
Personal comfort systems (PCS) aim to efficiently fulfill building occupants' personal thermal comfort demands, but to date not many have been manufactured and evaluated. Based on the observation that foot/hand warming are most effective in cool conditions, and head cooling is most effective in warm environments, we built and tested a suite of PCS devices--heated insole, heated/cooled wristpad, small deskfan, heated/cooled chair--and evaluated the thermal effect of each device and of combinations of the four. Human-subject and thermal-manikin tests in a climate chamber under cool and warm conditions (18ºC and 29ºC) investigated the thermal comfort improvement and heating/cooling performance of these devices. The results show the devices to have remarkable heating/cooling efficiencies, with combined cooling COP of 3.6 and heating COP of 0.88. They significantly improved subjects' whole body thermal acceptance and thermal comfort perception, with more than 80% of people accepting the tested ambient temperatures. The application of these PCS devices can correct up to 2.6K heating and 4.2K cooling of the ambient temperature towards neutral which may contribute to remarkable HVAC energy savings in buildings.

KEYWORDS
Thermal comfort; personal comfort system; local heating/cooling; building energy saving

1 INTRODUCTION
Advances in heating, ventilation and air conditioning (HVAC) technologies have dramatically improved indoor thermal environment, yet attention should be paid to ease the rapidly increasing energy expenditure in space conditioning. Considering the significant amount of energy consumed by HVAC services in large economic entities such as United States (US EIA, 2017), Europe (EPC 2010), and China (Xiong et al., 2015), it is essential to explore energy efficient alternatives to meet occupants' thermal demands, rather than simply maintaining thoroughly neutral thermal conditions. Analysing the ASHRAE database field study data, Arens et al. (2013) showed that tight "class A" temperature control does not necessarily translate into higher thermal comfort evaluation comparing with less tight "Class C" control. About 20% building occupants reported their thermal environment uncomfortable no matter how tightly their thermal environment was controlled.

Thermal discomfort originates largely from interpersonal thermal differences, and from local thermal discomfort. Multiple literatures report the different individual thermal requirements due to variation in gender (Karjalainen, 2012), age (Indraganti, 2010), dress custom, and activity level (Luo, 2018). In general, interpersonal differences cause a deviation of 1-2 scale units on thermal sensation vote (TSV), even when all the participants experience the same thermal condition (Mclntyre, 1976). For local heating/cooling of parts of the body, previous human subject tests (Arens et al., 2006; Zhang et al., 2010) show that cold foot/hand discomfort dictates whole-body discomfort and therefore foot/hand warming is critical for maintaining whole-body thermal comfort in cool environments, while the head and back/seat are the key locations for cooling in warm environments.

"Personal comfort systems" (PCS) use small amounts of energy to heat or cool those parts of an individual's body that are most influential at restoring comfort (Zhang et al., 2015). That would allow the ambient temperature to be set at a wider range, minimizing ambient air-conditioning and saving energy. A simulation study (Hoyt et al, 2015) indicated that allowing the indoor ambient temperature to vary by a few degrees results in large HVAC energy savings because the building is conditioned less intensely and less often, and can more often use unconditioned outside air for space conditioning.

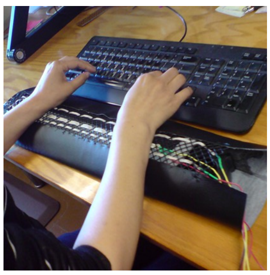
This paper describes: (1) four new PCS devices—the heating/cooling chair, heating/cooling wrist pad, heating insole and a cooling deskfan. (2) thermal manikin tests of the heating and cooling performance of these devices. (3) human subject tests evaluating the comfort improvement caused by these devices. (4) energy saving potential of PCS applications.

2 METHODS

2.1 Description of PCS devices

(a) The *heated/cooled chair* (Figure 1) has been under development for several years (Pasut et al. 2014). It is battery-powered, with seat and back separately controlled to four levels of heating or cooling. The total maximum input power is 14W for heating and 3.6W for cooling. Heating and cooling the human torso is effective even though skin temperatures in the region do not change much—the torso is especially sensitive to its skin temperature change (Zhang 2003, Watanabe et al., 2009; Kogawa et al., 2007; Pasut et al., 2013). ***(b)*** The *heating/cooling wristpad* provides heating and cooling to the wrists, hands, and fingers. The maximum input power is 7W for heating and 2.4 W for cooling. The heating function of the wristpad is designed to counter the large variation in hand temperature normally caused by vasoconstriction, which is a source of local discomfort and loss of dexterity. In cooling mode, extensive blood circulation under the inner wrist surface allows a high rate of heat extraction from the hand and arm. As with the chair, the heating is provided by conduction from resistive strips, and the cooling by convective stripping of the warm boundary layer beneath the seat surface. ***(c)*** The *heated insole* was similarly designed to offset vasoconstriction-caused cooling of the feet, which is a major source of discomfort both locally and whole-body. The maximum input battery power for both insoles together is 2.4W, delivered via discrete conductive elements in the insole upper surface. The insole is wirelessly charged, and is based on the observation that foot warming is critical for whole-body thermal comfort in cold conditions (Zhang 2003, 2010). ***(d)*** The small *deskfan*, based on a USB-powered fan with <2W power input, cool the face and upper body under warm conditions. A warm face is perceived as uncomfortable in neutral and warm ambient conditions, and a small area of air movement in the head/neck region has an outsized comfort effect (Huang et al., 2014; Zhai et al., 2013).

a) 

b) 

c) 

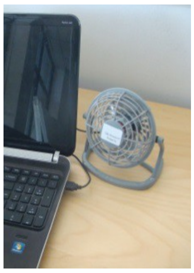
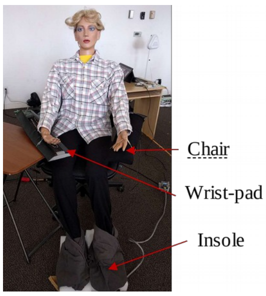
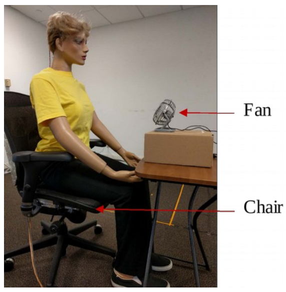
d) 

Figure 1. Images of the PCS devices, a) heating/cooling chair, b) heating/cooling wristpad, c) heating insole, d) cooling deskfan.

2.2 Thermal manikin heat transfer test

Thermal manikin tests were conducted to quantify the heat transfer effect of the PCS devices. Table 1 shows the heating and cooling scenarios. Chair heating, insole heating, wristpad heating and the combination of the three were tested in cool ambient conditions of 18°C and 40% RH. The clothing represented normal wintertime office wear: T-shirt, long-sleeve shirt, long pants, and socks. With the chair, the clothing insulation was 0.65 Clo. For the cooling scenario, chair cooling, wristpad cooling, deskfan cooling, and the combination of the three, were tested at ambient conditions of 29°C and 40% RH. The clothing represented normal summer casual office wear: short-sleeved T-shirt, long pants, and socks. The equivalent clothing insulation was about 0.5 Clo.

Table 1. Thermal manikin test

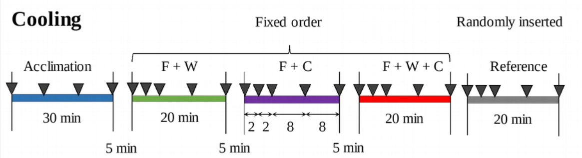
Heating scenarios (18°C, 40% RH)	Test scene	Cooling scenarios (29°C, 40% RH)	Test scene
● Chair heating ● Insole heating ● Wrist-pad heating ● (Chair +Insole+ Wristpad) heating		● Chair cooling ● Insole cooling ● Wrist-pad cooling ● (Chair +Insole+ Wristpad) cooling	

2.3 Human subject thermal comfort test

20 college-aged subjects (10 females and 10 males) were recruited to participate in thermal comfort performance evaluation tests of the 4 PCS devices under both warm and cool conditions. As listed in Table 2, each subject experienced 7 heating scenarios and 4 cooling scenarios in 4 chamber visits. Each visit lasted for 2~2.5 hours. Table 2 also shows the test protocol of cooling scenarios as an example. In that case, each subject participated in four formal sessions after a 30-minute acclimation. Each session lasted 20 minutes and followed by a 5 minutes break interval. During each session, participants were trained to report on the CBE thermal comfort questionnaire tool (Zhai et al. 2013) the magnitude of thermal acceptance, whole-body and local thermal sensations, and whole-body and local thermal comfort. Questions were presented at the 0^{th}, 2^{nd}, 4^{th}, 12^{th} and 20^{th} minute of each session. Subjects' clothing conditions were the same as in the manikin test, e.g. 0.65 Clo for heating and 0.5 Clo for cooling. Ten temperature sensors (WZYCH4, Tianjianhuayi, China) were taped to ten skin sites of the body (cheek, forearm, abdomen, lower back, left and right lower back, thigh, dorsal hand,

finger, left and right dorsal foot). Since the effect of the heated/cooled chair had been evaluated by Pasut et al. (2014), the chair-alone test was not included in the current study.

Table 2. Human subject test

<table>
<tr><th>Heating scenarios (18ºC, 40% RH)</th><th>Test scene</th><th>Cooling scenarios (29ºC, 40% RH)</th><th>Test scene</th></tr>
<tr><td rowspan="3">● Reference condition
● Insole
● Wristpad
● Insole+ Wristpad
● Insole+Chair
● Wristpad+Chair
● Insole+ Wristpad+ Chair</td><td rowspan="3"></td><td>● Reference condition
● Deskfan +Wristpad
● Deskfan +Chair
● Deskfan +Wristpad +Chair</td><td></td></tr>
<tr><td colspan="2">Test protocol example</td></tr>
<tr><td colspan="2">
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3 RESULTS

3.1 Thermal manikin heat transfer test results

Table 3 summarizes the heating and cooling effects of PCS devices. The test results are interpreted as ‘corrective power’ (Zhang et al. 2015) and ‘coefficient of performance’ (COP). The human-sensation-based corrective power represents the capability of PCS devices to correct ambient temperature towards a person’s thermal neutrality. For chair cooling alone, it can compensate 2K ambient temperature deviation (first row in Table 2). For the combination of all three cooling devices, the corrective power can be as high as 4.2K. We also present a thermal-manikin-based corrective power for the PCS devices that is expressed in terms of watts, indicating how much they can enhance or reduce human body heat loss. For example, the deskfan cooling can increase 12.3W heat loss while the combination of the three cooling devices can help to dissipate 36W extra heat (second row in Table 2). Finally, the COP reflects the energy efficiency of heating and cooling. For the deskfan cooling, 1 unit of energy consumption can produce 6.2 units of human body heat dissipation and thus the COP of fan cooling can be as high as 6.2 (third row in Table 2). The heating performance is presented in the lower part of the table. Heating COPs are smaller than cooling COPs, because fan cooling works by amplifying natural convective heat loss to ambient air, and is therefore capable of very high performance.

Table 3. COP and corrective power of PCS devices

	Metrics	Deskfan	Wristpad	Chair	Chair+Deskfan+Wristpad
Cooling performance	Corrective power on ambient temperature (K)	1.45	0.52	2.01	4.24
	Corrective power on body heat loss (W)	12.33	4.47	17.13	36.13
	COP	6.2	2.2	2.9	3.6
Heating performance	Metrics	Insole	Wristpad	Chair	Chair+Deskfan+Wristpad
	Corrective power on ambient temperature (K)	0.26	0.75	1.25	2.66

	Corrective power on body heat loss (W)	2.22	6.38	10.68	22.25
	COP	0.92	0.71	0.67	0.88

3.2 Thermal comfort performance of PCS devices

Figure 2 summarizes the thermal comfort effects of the 4 PCS devices in terms of acceptance of the environment, whole-body and local body part thermal sensations. Figure 2a shows the acceptance vote of different heating and cooling combinations. The vertical axis represents acceptance vote, ranging from clearly unacceptable (-4) to clearly acceptable (+4). At 29ºC, without PCS, the acceptance vote distribution is shown as the grey box with many votes located on the unacceptable side. The overall acceptance rate was merely 60%. When the subjects were allowed to take advantage of some combinations of a deskfan, wristpad, and chair cooling, their acceptance vote was remarkably improved. An apparent increasing trend can be observed on the right side of Figure 2a. The corresponding acceptance rate increased to 86%, 95%, and 100% respectively, higher than the 80% required by thermal environmental standards (ASHRAE 55, 2017). Similar phenomena can be seen in cold condition. If no PCS devices were provided, the acceptance rate was as low as 65%. When insole, wristpad, and chair heating were introduced, the acceptance rate rose up to 97.5%. The wristpad-heating alone improved the acceptance rate less than the other devices. We believe that though the wristpad warms the wrist, people's fingers are less warmed.

One explanation for the acceptance rate increase is the improved thermal sensation. Figure 2b shows the statistics of subjects' thermal sensation vote in each cooling and heating combinations. The vertical axis represents thermal sensation vote ranging from very cold (-4) to very hot (+4). Under the 29ºC condition, the PCS devices cooled down subjects' whole-body thermal sensation from warm to neutral and slightly cool. The grey box represents the reference case without PCS and other boxes represent deskfan and wristpad cooling, deskfan and chair cooling, and the combination of these three. Similarly, in cold condition, PCS warmed up subjects' whole-body sensation from cool to neutral and slightly warm. According to the trend shown in Figure 2b, it can be seen that as more PCS devices were utilized, the stronger the cooling/heating effects they had.

Considering that different PCS devices add heat and coolth to different body parts, the local body part thermal sensations shown in Figure 2c provide another angle to analyze the thermal comfort effect of the different devices. The grey boxes are reference case without any PCS devices. In 29ºC, these grey boxes were 1~2 units scale warmer than other color boxes. It means that the PCS devices cooled the hand, face and seat area. Likewise, in 18ºC, PCS devices warmed up the foot, hand and seat area.

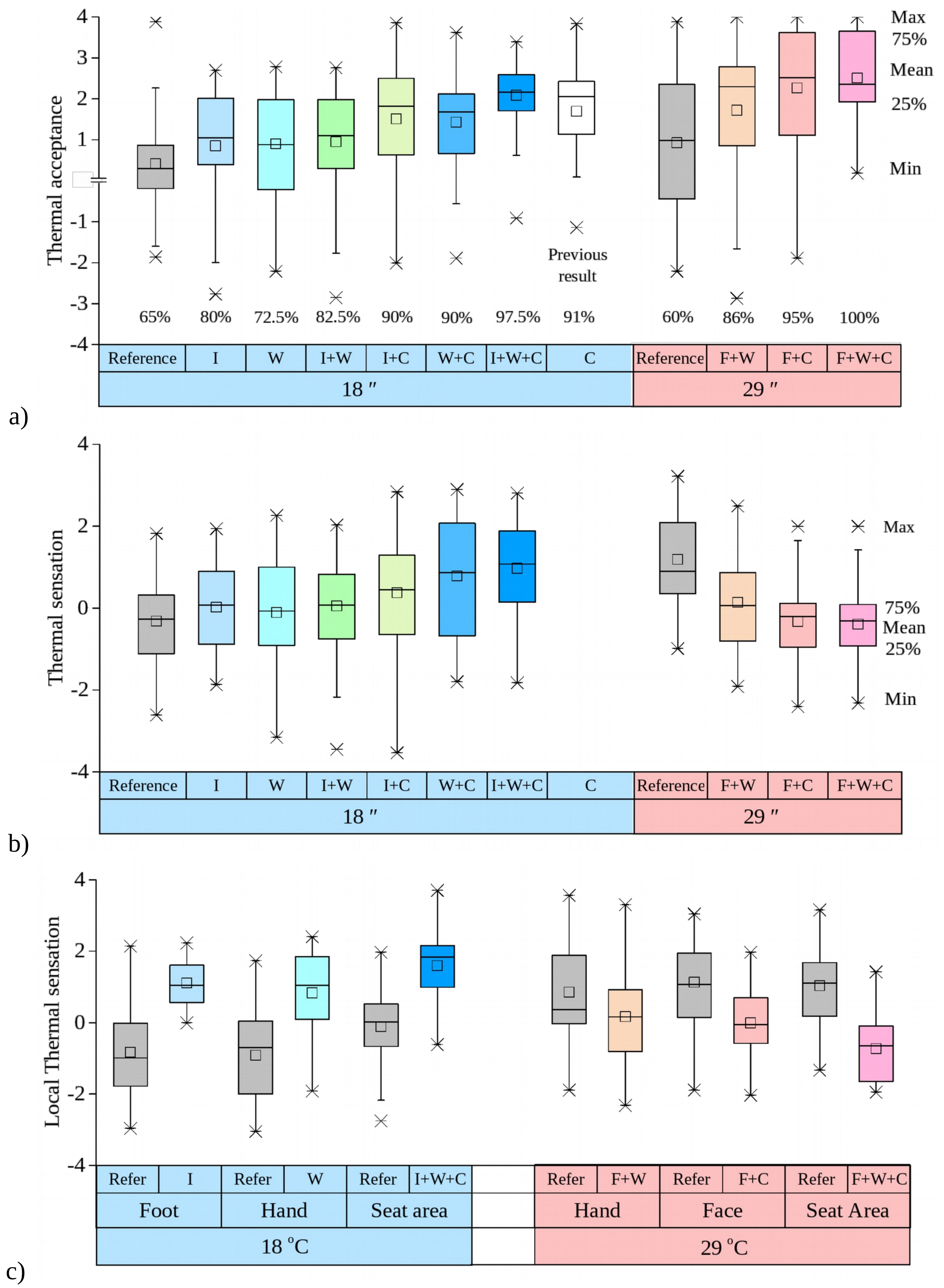

Figure 2. Thermal comfort effects of PCS devices, a) Whole-body thermal acceptance, b) Whole-body thermal sensation, c) Local thermal sensation examples. (Note: the voting results shown in this figure represent the last two votes of each test session)

Figure 3 shows local skin temperature changes under different PCS applications. Skin temperature changes shown in the vertical axis are calculated from the skin temperature with a PCS minus the skin temperature at the reference case. Positive values represent higher skin temperature than the reference case. Otherwise, skin temperature was lower than the reference case. As marked by the red brackets, the heating function of the insole, wristpad, and chair warmed up the hand, finger, and feet. The skin temperatures in these body parts were significantly higher than the reference case. The skin temperatures on other body parts (e.g. face, belly) are unchanged. Similar phenomena can be observed in warm condition as well. The cooling of deskfan, wristpad, and chair cooled down the face, forehead, hands, and forearms.

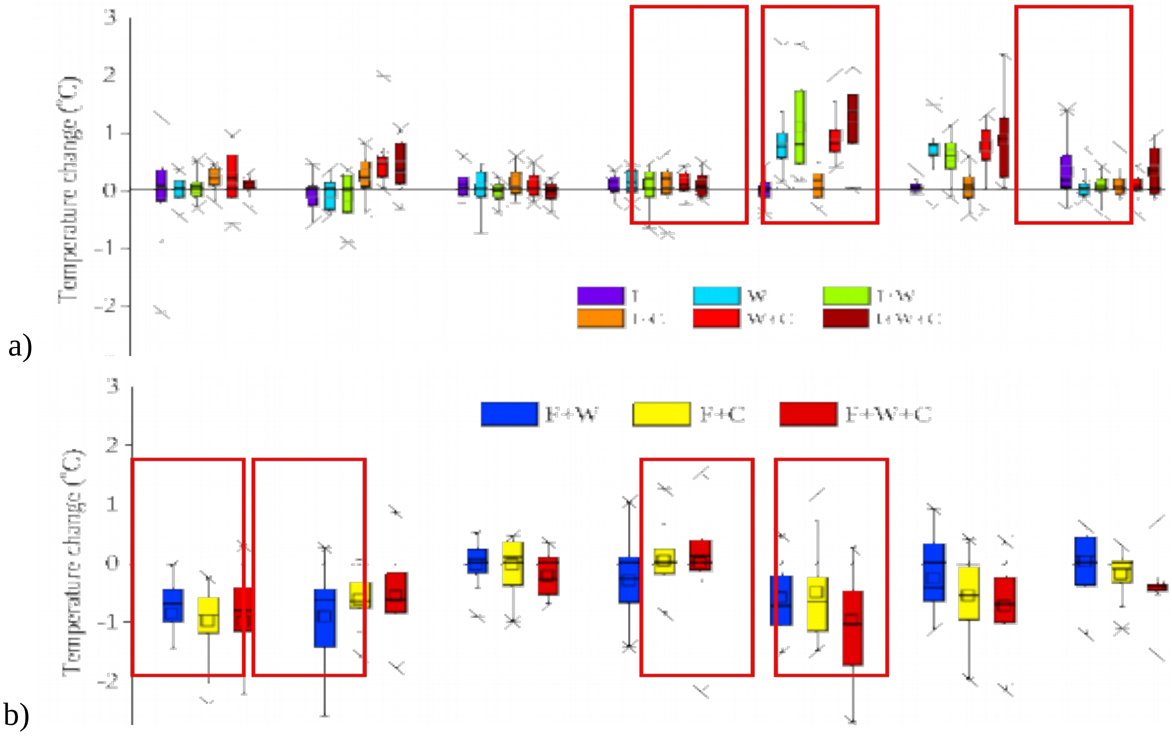

Figure 3. Skin temperature changes caused by PCS devices, a) heating scenarios, b) cooling scenarios.

4 DISCUSSION

The above results present the heating and cooling performance and thermal comfort improvement of the four PCS devices. Figure 4 shows the energy saving potentials of PCS devices. The dashed lines are extracted from the building simulation study by Hoyt et al (2015), quantifying HVAC energy savings by widening temperature dead-bands of the HVAC system. Different colors in this cup-shape represent different climate locations. The solid lines indicate HVAC energy savings including the energy consumed by the PCS devices themselves. The tiny differences suggest that the energy intensity of the PCS is so small that it can be neglected when compared to the HVAC system. Together with the consideration of their corrective power in ambient temperatures, the new PCS devices can contribute to 3%~40.7% heating energy saving and 24.4% to 61.6% cooling energy saving in different climate zones.

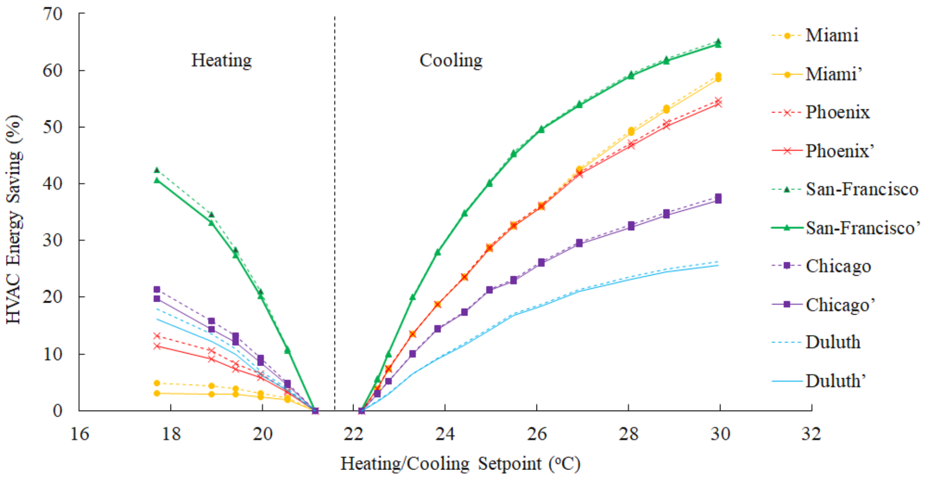

Figure 4. Potential energy saving of PCS devices. (Note, the solid line represent the energy saving potential with PCS devices)

5 CONCLUSIONS

This study investigates the heating and cooling performance of four PCS devices developed by CBE. The following findings and suggestions emerged: (1) PCS devices can provide local heating and cooling to the human body efficiently. Thermal manikin tests showed that the four devices have combined heating COP of 0.88 and cooling COP of 3.6. With such remarkable heating/cooling efficiency, the application of PCS devices can correct up to 2.6K heating and 4.2K cooling of ambient temperature towards neutral. (2) Applications of these PCS devices significantly improved subjects' whole body thermal acceptance and thermal comfort perception in the non-neutral thermal conditions of 18°C and 29°C. (3) The energy-saving potentials of PCS devices are very promising because they can widen the current tightly controlled building temperature range. Based on the estimation of this study, the application of PCS devices can contribute to 3%~40.7% heating energy saving and 24.4%~61.6% cooling energy saving for U.S. cities in different climate zones.

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