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Article

Experimental investigation of thermal micro-environments and local thermal sensations in enclosed and semi-enclosed localized heating systems

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Abstract: Traditional building heating warms entire rooms, often leaving some dissatisfied with uneven warmth. Recently, the personalized heating system has addressed this by providing targeted warmth, enhancing comfort and satisfaction. The personalized heating system in this study is a new enclosed personalized heating system consisting of a semi-enclosed heating box and an insulated chair covered with a thick blanket. The study compares the heating effects of semi-enclosed and enclosed localized heating systems on the body and examined changes in subjects' thermal sensations. Due to the lower heat loss of the enclosed personalized heating system compared to the semi-enclosed version, it created thermal micro-environments with higher ambient temperatures. The maximum air temperature increase within the enclosed system was twice that of the semi-enclosed system, with the heating film surface temperature rising by up to 6.87 °C. Additionally, the temperature of the skin could increase by as much as 6.19 °C, allowing individuals to maintain thermal neutrality even when the room temperature dropped as low as 8 °C. A two-factor repeated measures analysis of variance revealed differences in temperature sensitivity across various body regions, with the thighs showing a notably higher response under high-power heating conditions. The corrective energy and power requirements of the enclosed personalized heating system also made it more energy-efficient than other personalized heating systems, with a minimum value reaching 6.07 W/K.

Keywords: localized heating system; personalized heating; thermal sensation; personal comfort system; heating box

1. Introduction

In the hot-summer and cold-winter regions south of the Qinling Mountains and Huai River in China, winters are characterized by cold and cloudy weather. Common heating methods in these regions include traditional heating, ventilation, and air conditioning (HVAC) systems. However, these systems often fail to meet everyone's thermal comfort requirements due to individual variability [1–6].

Localized heating systems referred to systems that did not directly heat an entire room but instead provided personalized heating to specific parts of the body, achieving the goal of warmth with lower energy consumption. Localized heating systems provide a promising alternative by offering personalized heating solutions [7]. Some researchers found that open hybrid heating devices and open radiation foot warmers improve thermal comfort and work performance [8,9]. Further research by Liu et al. [10], Luo et al. [11], Zhang et al. [12], Yang et al. [13], Yu et al. [14], and Ren [15] emphasized the effectiveness of localized heating in enhancing thermal comfort and reducing energy consumption. Specifically, semi-enclosed localized heating systems demonstrated superiority over conventional heating methods in alleviating thermal discomfort and achieving energy savings [16–19]. Enclosed localized heating systems, in particular, offer improved heat retention compared to open systems, as observed by Zhou et al. [20] and Van Loy et al. [21] Hooshmand et al. [22] discovered that many studies on PCS focused on temperatures above 14 ℃. Most PCS systems operated in open indoor environments, utilizing radiant or convective heating for the human body without creating an enclosed space around the heated area. Wu et al. [23] examined outdoor temperatures around 5 ℃ and found that clothing-based PCS in open car environments could not fully meet thermal demands. Wang et al. [9] reported that in environments below 13 ℃, the thermal sensation provided by an open-style leg warmer diminished. Mahmoud Gaber Morsy [24] found that at ambient temperatures of 0 ℃, 5 ℃, and 10 ℃, open radiant PCS could meet thermal demands but required a minimum energy consumption of 580 W.

In previous studies, localized heating systems did not create fully enclosed spaces, which we referred to as semi-closed localized heating systems. In contrast, systems that formed enclosed spaces were termed enclosed localized heating systems. For simplicity, these were abbreviated as semi-closed systems and enclosed systems throughout this paper. Yet, there remains a gap in studies on the heating and energy-saving effects of enclosed systems at lower temperatures. This study introduced a novel enclosed personalized heating system, which created a fully enclosed space consisting of a semi-enclosed heating box and an insulated chair covered with a thick blanket. In the enclosed space created by the localized heating system, thermal micro-environments refer to the specific temperature conditions within various parts of this space, including the air temperature, wall temperature, and film temperature. These micro-environments are essential for assessing the insulation and heating efficiency, as well as evaluating the extent of heat loss in this study. The research compared the heating performance of semi-enclosed and enclosed systems, as well as their effects on subjects when room temperatures dropped to 10 ℃ and 8 ℃. Additionally, the study calculated the Corrective Energy and Power (CEP) of the system to assess its energy-saving potential and compared the energy consumption of the enclosed and semi-enclosed systems. Experimental results confirmed the system’s strong heating performance, showing that it ensured thermal comfort even at room temperatures as low as 8 ℃ while offering better energy savings. The study demonstrated the superior heating performance of the enclosed system by comparing the thermal micro-environments and skin temperatures between the semi-enclosed system and the enclosed system. It also validated the feasibility of heating at lower ambient temperatures using the enclosed system. Finally, by calculating the CEP (Coefficient of Energy Performance), the study confirmed that the enclosed system achieves lower energy consumption. This further demonstrates the feasibility of personalized heating at low temperatures, with important implications for implementing energy-saving measures in buildings.

2. Methodology

2.1. Localized heating system

The localized heating system primarily comprised two components, as shown in **Figure 1**. The semi-enclosed personalized heating device consists of a table and chair, featuring a semi-enclosed heating box beneath the table and an insulated panel surrounding the underside of the chair, as shown in **Figure 2** Inside the heating box, there are two electric heating films designed for independent efficiency control. The power of the heating films is adjustable, with the side film offering settings of 35 W, 55 W, or 75 W, and the bottom film adjustable to 20 W, 30 W, or 40 W, allowing for flexible heat management. When a thick blanket (120 cm × 200 cm) was placed between the person and the table, covering the gaps, it created a fully enclosed thermal environment for the lower body, thus constituting an enclosed personalized heating system, as shown in **Figure 3**.

Temperature monitoring within the box was comprehensive, focusing on the heating films' surface temperatures, the box's inner wall temperatures, and the internal air temperature. The temperature was measured using a copper-constantan thermocouple and recorded with an Agilent 34970A data acquisition instrument. Temperature readings were taken from several key points: Two on the side heating film (Tj-1 and Tj-2), one on the bottom heating film (Tj-3), the box's upper surface (Td-1), the lower surface (Td-2), the left wall (Tb-1), the rear wall (Tb-2), and two air temperatures measured at distances of 20 cm (Ta-1) and 40 cm (Ta-2) from the box's upper surface， and air temperature under the seat (Ta-3). This detailed temperature arrangement facilitated precise control and monitoring, as depicted in **Figure 4**.

The primary focus of the heating system tested in this research was the lower body. To simplify the measurement process and ensure consistency in assessing the temperature of the human lower body, temperatures were exclusively measured on the left leg. Therefore, three specific locations on the lower body surface—the left thigh, left leg, and sole of the left sole—were chosen for temperature measurement.

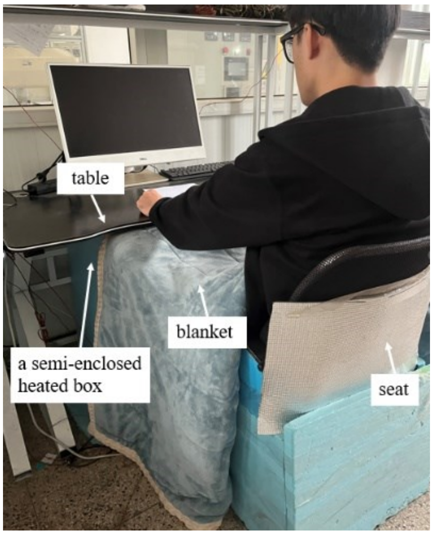

Figure 1. Blanket installation diagram.

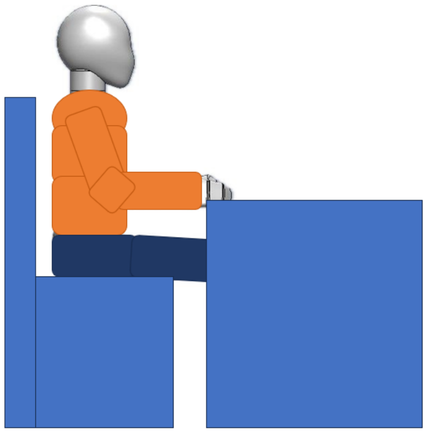

Figure 2. Schematic diagram of semi-localized heating system.

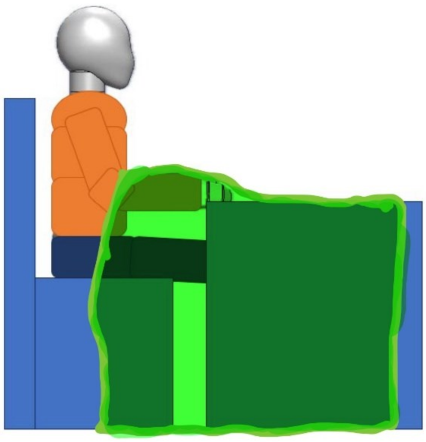

Figure 3. Schematic diagram of enclosed localized heating system.

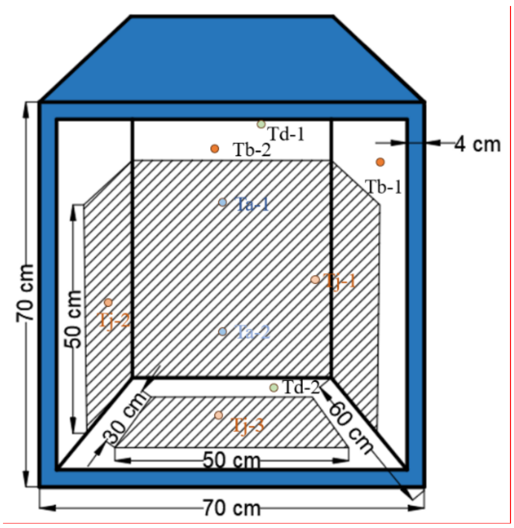

Figure 4. Layout of temperature measurement points inside the heated box.

2.2. Ethical consideration and participants

The participants in this experiment were eight college students, comprising an equal number of males and females. During the experiment, participants were required to wear standardized clothing, including a down jacket, sweater, casual jeans, athletic socks, and sneakers, with a thermal resistance of approximately 1.37 clo. The participants were in a sedentary working state, with a metabolic rate of around 65 W/m². The average relative humidity was maintained at 55.9% and was considered constant throughout the experiment. These measures ensured that other variables affecting skin temperature and thermal sensation, including humidity, clothing insulation, and activity level, were controlled during the experiment. The basic information of the eight subjects in this experiment is shown in **Table 1**. Before the experiment, informed consent was obtained from all subjects.

Table 1. Basic subject parameters.

	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m^2)
Average value	24.33	171.33	67.22	22.80
Standard deviation	1.05	5.29	13.96	4.08

2.3. Experimental procedure

At the beginning of the experiment, heat flow sensors were attached to the thighs, legs, and soles of the subjects to detect the heat flux exchanged between different body parts and the experimental environment. During the experiment, the subjects completed a questionnaire every 10 min regarding the thermal sensation of each part (thigh, leg, sole) and the whole. The Thermal Sensation Voting (TSV) scale from ASHRAE [25], ranging from −3 to 3 (corresponding to cold, cool, slightly cool, neutral, slightly warm, warm, and hot), was adopted in our experiment to evaluate thermal sensation. The first experiment investigated the changes in the thermal micro-environments within the system and the local skin changes of the subjects when using semi-enclosed and enclosed localized heating systems. The experimental conditions for assessing the thermal effect are shown in **Table 2**. The flowchart of this process is depicted in **Figure 5**. Entry into the laboratory marked the start of the experiment, during which measurements were taken.

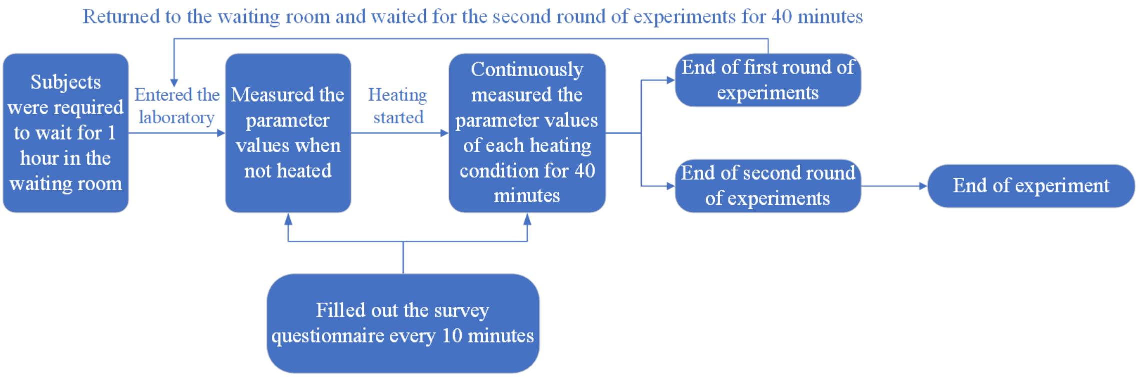

Figure 5. Experimental flowchart.

The second experiment focused on investigating the heating effect at low room temperatures, specifically analyzing the performance of the localized heating system under colder indoor conditions. The experimental setup is detailed in **Table 3**. The experiment was conducted in Shanghai during November when the average indoor temperature ranged from 8 °C to 10 °C. Consequently, the experimental conditions were set to 10 ℃ and 8 ℃. The experimental procedure followed a similar approach to the one described above.

Table 2. Comparison of semi-enclosed and enclosed localized heating systems.

Working conditions		Indoor temperature	Systems	Side heating film power + Bottom heating film power
The first round	1	12 ℃	Semi-closed system	0W
	2			Side 35 W + Bottom 20 W
	3			Side 55 W + Bottom 30 W
	4			Side 75 W + Bottom 40 W
The second round	5		Enclosed localized heating system	0W
	6			Side 35 W + Bottom 20 W
	7			Side 55 W + Bottom 30 W
	8			Side 75 W + Bottom 40 W

Table 3. Experimental conditions for heating effect of enclosed system at low temperatures.

Working condition	Indoor temperature	Power
1	10 ℃	0 W
2		Side 35 W + Bottom 20 W
3		Side 55 W + Bottom 30 W
4		Side 75 W + Bottom 40 W
5	8 ℃	0 W
6		Side 35 W + Bottom 20 W
7		Side 55 W + Bottom 30 W
8		Side 75 W + Bottom 40 W

2.4. Statistical analysis

All statistical analyses were conducted using Statistical Product and Service Solutions（SPSS）, with the significance level set at $\alpha = 0.05$. Before performing analysis of variance (ANOVA), Mauchly’s sphericity test was applied to the skin temperatures of different heating conditions and body parts to verify whether the data satisfied the sphericity assumption. A two-factor repeated measures ANOVA was used to assess the effects of heating conditions and body parts on skin temperature responses. The heating conditions included four levels: No heating, Side 35 W + Bottom 20 W, Side 55 W + Bottom 30 W, and Side 75 W + Bottom 40 W. The body parts included three levels: Foot sole, lower leg, and thigh, to evaluate the main effects of each variable. Post hoc pairwise comparisons between groups were conducted using Bonferroni-corrected t-tests.

2.5. Energy consumption

Zhang et al. [26] introduced the term “Corrective Power” (CP) to quantify the degree to which a Personal Comfort System (PCS) can adjust hot or cold ambient temperatures to neutral levels. CP was defined as the difference between the environmental temperatures with and without the use of PCS, under the same thermal sensation. Building on Zhang's work, He et al. [27] proposed the concept of Corrective Energy and Power (CEP), which is formulated as shown in Equation (1). CEP is a key indicator in the energy efficiency evaluation of PCS, representing the amount of energy required to adjust thermal sensation to a comfortable level. This measures the ratio of an individual's average heating or cooling power (Q) to the CP of the PCS, indicating the energy consumption level of the PCS.

$$\mathrm{CEP} = \mathrm{Q}/\mathrm{CP} \tag{1}$$

The units of Q are watts (W), and thus, the units of CEP are watts per kelvin (W/K). The units of CP are kelvin (K). The ambient air temperature was set at 24 ℃ when the subjects reached a neutral thermal sensation.

3. Results

3.1. Comparison of semi-enclosed and enclosed systems

Two temperature measuring points were designated for the side heating film: The left surface Tj-1 and the rear surface Tj-2. The side heating film's surface temperature was determined by averaging these two points. Meanwhile, the bottom heating film's temperature was measured at point Tj-3. **Table 4** showed the surface temperature of the heating film in the heating box under unheated conditions. From the table, we can observe that under unheated conditions, the heating film temperature of the enclosed system was consistently higher than that of the semi-closed system. Although the temperature difference was minor, it was generally around 1 ℃ between the two systems. The largest temperature difference, 1.2 ℃, was noted in the rear wall heating film. This indicates that even without active heating, the enclosed system maintained a higher heating film temperature due to the addition of a thick blanket, which helped reduce heat loss.

Table 4. The surface temperature of the initial heating film inside the heated box under no heating conditions with an indoor temperature of 12 ℃.

Working condition	Bottom heating film temperature (℃)	Rear wall heating film temperature (℃)	Sidewall heating film temperature (℃)	The average temperature of side heating film (℃)
Enclosed system	15.4	15.4	15.1	15.2
Semi-closed system	14.4	14.2	14.1	14.1

Figure 6 illustrates that the surface temperature of the heated film is higher than in the initial condition without heating, across various heating power levels. The figure showed that as heating power increased, the surface temperature of the heated film rose accordingly. Because the bottom heating film was in direct contact with the feet, heat conduction occurred from the feet to the bottom heating film, resulting in the bottom heating film temperature consistently being higher than the side heating film temperature. Additionally, the temperature of the enclosed system remained consistently higher than that of the semi-closed system, with the temperature difference increasing as power increased. The maximum temperature difference, 6.875 ℃, occurred at a heating power of 75 W for the side heating film.

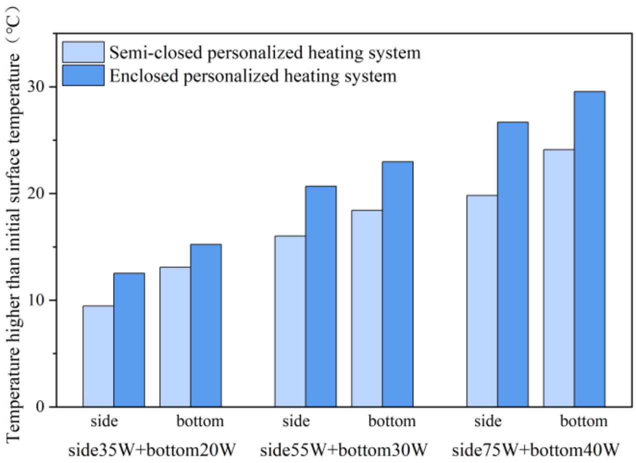

Figure 6. The surface temperature of the heated film higher than that of the initial no-heating condition under different heating powers.

Figure 7 reveals that temperatures at points Ta-1, Ta-2, and Ta-3 are elevated above the indoor air temperature under various operating conditions. The figure showed that the air temperature at Ta-1 was the highest, as Ta-1 was located above the heating box, where heated air rose and accumulated. In both the closed and semi-closed systems, the air temperature within the thermal micro-environments increased with higher heating power. However, the figure also revealed that the increase in air temperature was more pronounced in the closed localized heating system, with the gap between the two systems widening as heating power rose. When the heating power reached Side 75 W + Bottom 40 W, the air temperature above the indoor air temperature in the closed localized heating system was more than double that of the semi-closed system.

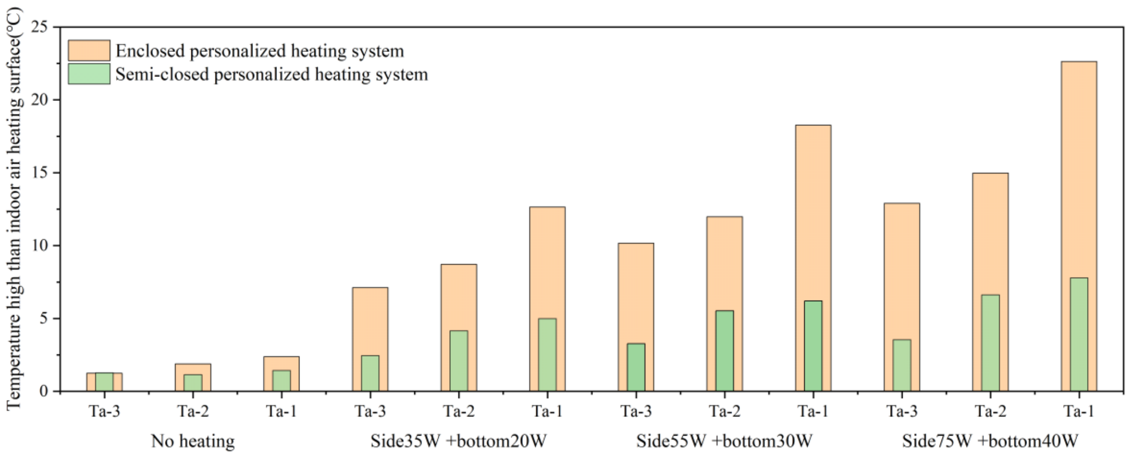

Figure 7. The air temperature inside the box (Ta-1, Ta-2) and under the seat (Ta-3) higher than the indoor ambient temperature (12 °C).

Table 5 shows that the average temperature of the heating box walls was calculated from the averages of Tb-1, Tb-2, Td-1, and Td-2. The average temperature of the heating box walls followed a similar trend to the air temperature and heating film temperature, increasing as heating power rose. This temperature was consistently higher in the enclosed system, with the gap between it and the semi-closed system widening as heating power increased.

Table 5. The average temperature of the inner wall under the heated box and seat higher than the indoor air temperature under different working conditions.

Working condition		**No heating**	**Side 35 W + Bottom 20 W**	**Side 55 W + Bottom 30 W**	**Side 75 W + Bottom 40 W**
The average temperature of the walls of the heating box	Semi-closed system	2.32	7.18	10.00	11.60
	Enclosed system	3.31	12.50	16.63	20.20

Local skin temperatures in the lower body of the human body were measured through experiments, including the sole (Tsole), leg (Tleg), and thigh (Tthigh), as shown in **Figure 8**. The figure showed that skin temperature increased with higher heating power, with a more pronounced rise in the enclosed system. This increase became more substantial as heating power rose, especially for the leg area, where the skin temperature reached 34.53 °C at a heating power of Side 75 W + Bottom 40 W—an increase of 6.19 °C compared to the semi-closed system.

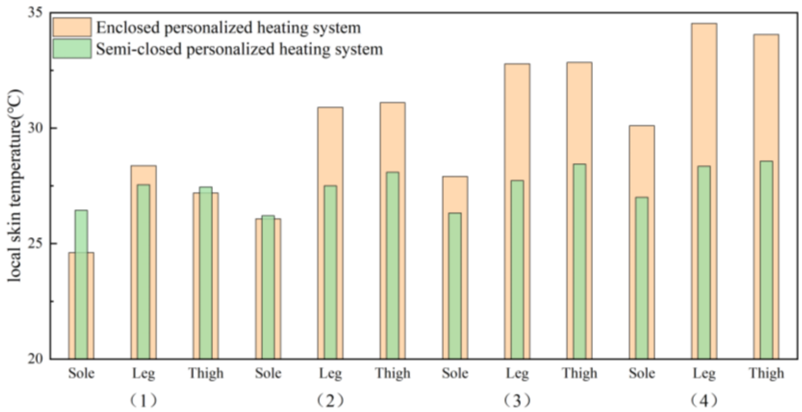

Figure 8. Local skin temperature of the lower body of the human body.

(1) No heating; (2) Side 35 W + Bottom 20 W; (3) Side 55 W + Bottom 30 W; (4) Side 75 W + Bottom 40 W.

3.2. The effect of enclosed system at room temperature of 10 °C

Table 6. Heating film surface temperature at an indoor temperature of 10 °C.

Working conditions	**Bottom heating film temperature (°C)**	**Rear wall heating film temperature (°C)**	**Left wall heating film temperature (°C)**	**Average temperature of side heating film (°C)**
Unheated	11.9	12.1	12.4	12.3
Side 35 W + Bottom 20 W	28.9	27.4	27.8	27.6
Side 55 W + Bottom 30 W	36.2	34.3	34.8	34.6
Side 75 W + Bottom 40 W	42.1	40.5	41.2	40.9

To investigate the heating performance of this enclosed system on the lower body at lower indoor temperatures, further temperature measurement experiments and analyses are required at indoor temperatures of 10 °C and 8 °C. At an indoor temperature of 10 °C, the surface temperatures of the heating film are detailed in **Table 6**.

As demonstrated in **Table 7**, with the increase in heating power, the wall average temperatures of the heated box and the underside of the seat significantly increased. The heated box wall's average temperature rose more rapidly than that of the wall beneath the seat.

Table 7. The average temperatures of the wall of heated box and the side wall under the seat higher than the indoor ambient temperature (about 10 °C).

Working condition	**No heating**	**Side 35 W + Bottom 20 W**	**Side 55 W + Bottom 30 W**	**Side 75 W + Bottom 40 W**
The average temperature of the walls of the heating box	2.70	12.38	16.64	20.66

Figure 9 illustrates the comparison of air temperatures at different positions inside the box (Ta-1, Ta-2, Ta-3), which were higher than the indoor air temperature. As power increased, the air temperature rose, with Ta-1 having the highest and fastest increase, reaching a maximum of 33.68 °C.

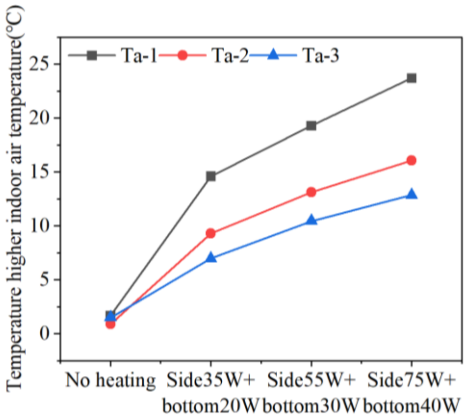

Figure 9. The air temperature inside the box when the indoor temperature was about 10 °C.

Figure 10 illustrated the changes in local skin temperatures across different heating powers. The results of Mauchly's test for sphericity indicated that the assumption of sphericity was met ($p = 1.00 > 0.05$), confirming that the data satisfied the sphericity requirement for ANOVA. The two-factor repeated measures ANOVA showed that different working conditions approached a significant effect on skin temperature response ($F = 4.58$, $p = 0.0539$), while there was a significant difference in skin temperature response across different body regions ($F = 5.85$, $p = 0.039$). **Tables 8** and **9** present the post-hoc test results for the main effects. As shown in the tables, under the higher heating condition (Side 75 W + Bottom 40 W), temperature was significantly higher than under the lower heating power conditions (Side 35 W + Bottom 20 W and Side 55 W + Bottom 30 W). No significant temperature differences were observed between other conditions. Under the same heating condition, the thigh's temperature response was significantly higher than that of the leg. However, the temperature difference between the sole and the other regions (leg and thigh) did not reach the level of significance. **Figure 11** depicts the local and overall thermal sensation of the human body when the indoor temperature was approximately 10 °C. Participants completed a thermal sensation survey every 10 min during each condition, with each condition lasting 40 min, resulting in four completions. The figure showed that as heating power increased, the TSV value also rose. Under certain conditions, the thermal sensation in the thigh was higher than the overall body sensation.

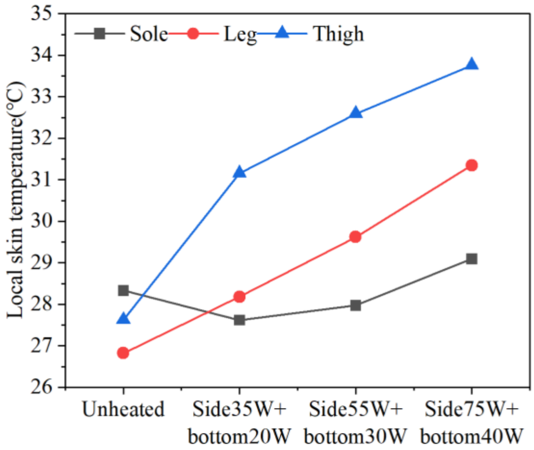

Figure 10. Local skin temperature of the lower body of the human body when the indoor temperature was about 10 °C.

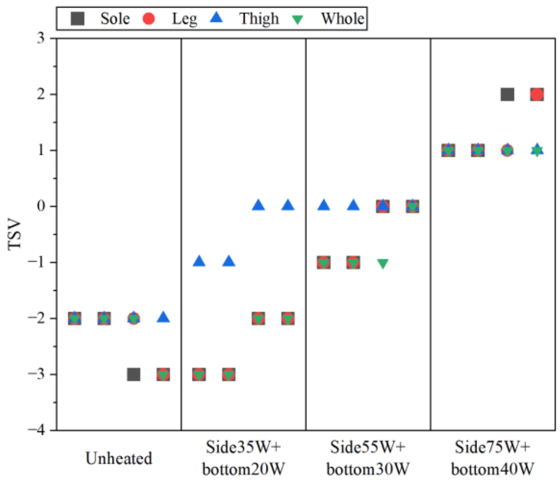

Figure 11. Local and overall thermal sensation of the human body when the indoor temperature was about 10 °C.

Table 8. Post-hoc test results for working condition main effect.

Heating Condition Comparison	*t*-value	*p*-value
Unheated vs. Side 35 W + Bottom 20 W	−1.14	0.373
Unheated vs. Side 55 W + Bottom 30 W	−1.60	0.251
Unheated vs. Side 75 W + Bottom 40 W	−2.39	0.139
Side 35 W + Bottom 20 W vs. Side 55 W + Bottom 30 W	−2.98	0.097
Side 35 W + Bottom 20 W vs. Side 75 W + Bottom 40 W	−4.85	0.040*
Side 55 W + Bottom 30 W vs. Side 75 W + Bottom 40 W	−6.93	0.020*

* indicates a statistically significant difference ($p < 0.05$).

Table 9. Post-hoc test results for body part main effect.

Body Part Comparison	*t*-value	*p*-value
Sole vs. Leg	−0.89	0.437
Sole vs. Thigh	−2.38	0.097
Leg vs. Thigh	−4.47	0.021*

* indicates a statistically significant difference ($p < 0.05$).

3.3. The effect of enclosed system at room temperature of 8 °C

Table 10 demonstrates that when the indoor temperature was 8 °C, the surface temperatures of both the side and bottom heating films exhibited similar values across three different working conditions. Compared to the data in **Table 6**, where the indoor temperature was 10 °C, there was a slight decrease in the surface temperatures of the heating films. **Table 11** reveals that the average temperatures of the heated box's wall were higher than the indoor air temperature.

Table 10. Surface temperature of heating film when indoor temperature was 8 °C.

Working conditions	Bottom heating film temperature (°C)	Rear wall heating film temperature (°C)	Left wall heating film temperature (°C)	Average temperature of side heating film (°C)
Unheated	10.8	10.3	10.4	10.4
Side 35 W + Bottom 20 W	28.1	25.6	26.0	25.8
Side 55 W + Bottom 30 W	34.1	31.7	32.1	31.9
Side 75 W + Bottom 40 W	40.8	37.7	38.4	38.0

Table 11. The average temperature of the wall of heated box and the lower side wall of the seat higher than the indoor ambient temperature (about 8 °C).

Working conditions	No heating	Side 35 W + Bottom 20 W	Side 55 W + Bottom 30 W	Side 75 W + Bottom 40 W
The average temperature of the walls of the heating box	3.68	13.74	17.20	20.85

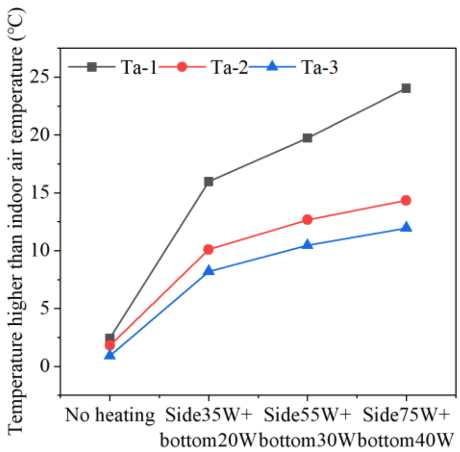

Figure 12. The air temperature inside the box when the indoor temperature was about 8 °C.

Figure 12 displays the internal air temperatures (Ta-1, Ta-2) within the heated box and the air temperature under the seat (Ta-3), all of which were higher than the indoor air temperature. When the heating was off, the three air temperatures were roughly the same. After turning on the heating, the temperature of Ta-1 rose rapidly, becoming significantly higher than Ta-2 and Ta-3, with Ta-2 slightly higher than Ta-3.

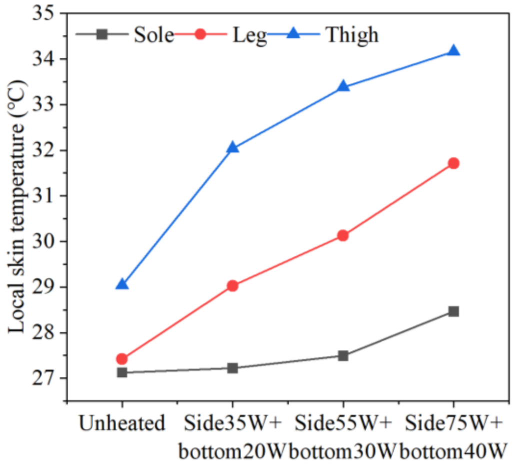

Figure 13. Local skin temperature of the lower body of the human body when the indoor temperature was about 8 °C.

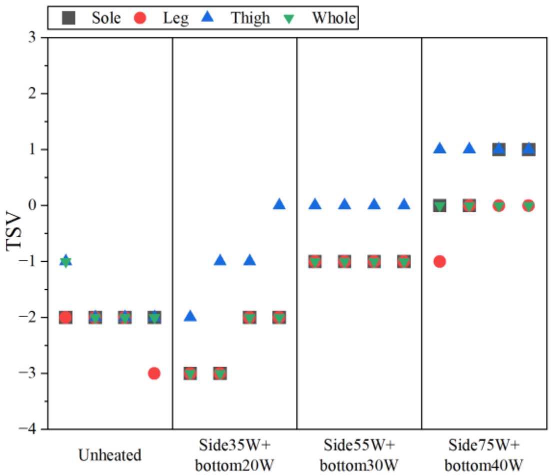

Figure 14. Local and overall thermal sensation of the human body at an indoor temperature of approximately 8 °C.

Figure 13 illustrates the temperature changes in the lower body's skin at an indoor temperature of 8 °C.The results of Mauchly's test for sphericity indicated that the assumption of sphericity was met (p = 1.00 > 0.05), confirming that the data satisfied the sphericity requirement for ANOVA. The two-factor repeated measures ANOVA showed that different working conditions had a near-significant effect on skin temperature response (F = 7.46, p = 0.0189), and there was a significant difference in skin temperature response across different body regions (F = 22.82, p = 0.0016). **Tables 12** and **13** present the post-hoc test results for the main effects. As shown in the tables, under the higher heating condition (Side 75 W + Bottom 40 W), the temperature was significantly higher than under lower heating power conditions (Side 35 W + Bottom 20 W and Side 55 W + Bottom 30 W). The temperature of the thigh was significantly higher than that of the sole and leg. **Figure 14** depicts the local and overall thermal sensation of the human body when the indoor temperature was approximately 8 ℃. As the heating power increased, the TSV value also rose. However, compared to the 10 ℃ room temperature condition, the heating effect was less pronounced in the last two conditions. Despite this, during the middle two conditions, the thermal sensation in the thigh remained higher than the overall thermal sensation.

Table 12. Post-hoc test results for heating condition main effect.

Heating Condition Comparison	***t*-value**	***p*-value**
Unheated vs. Side 35 W + Bottom 20 W	−1.87	0.202
Unheated vs. Side 55 W + Bottom 30 W	−2.14	0.165
Unheated vs. Side 75 W + Bottom 40 W	−3.13	0.089
Side 35 W + Bottom 20 W vs. Side 55 W + Bottom 30 W	−2.78	0.108
Side 35 W + Bottom 20 W vs. Side 75 W + Bottom 40 W	−4.80	0.041*
Side 55 W + Bottom 30 W vs. Side 75 W + Bottom 40 W	−4.55	0.045*

* indicates a statistically significant difference ($p < 0.05$).

Table 13. Post-hoc test results for body part main effect.

Body Part Comparison	***t*-value**	***p*-value**
Sole vs. Leg	−3.13	0.052
Sole vs. Thigh	−4.98	0.016*
Leg vs. Thigh	−7.07	0.006*

* indicates a statistically significant difference ($p < 0.05$).

4. Discussions

4.1. The enclosed system had a noticeably stronger heating effect on the thermal micro-environments compared to the semi-closed system

Table 4 indicate that the initial ambient temperature in the laboratory was similar under both the semi-closed and enclosed systems. The temperature difference on the heating film surface inside the heating box was approximately 1 ℃, suggesting that the blanket's coverage reduced heat loss. **Figures 6** and **7** show that after the heating was turned on, the heating power gradually increased, and the temperatures of the heating films on the sides and bottom also rose. Although the heating power of the side films was higher than that of the bottom, their surface temperatures were consistently 5 ℃ lower. This discrepancy was due to the bottom heating films not only generating their heat but also being in direct contact with the sole, allowing heat from the human body to transfer to them through conduction, thereby raising their surface temperatures.

The internal air temperatures, Ta-1 being higher and Ta-3 lower, indicated that the heated air rose, causing warmer air to accumulate at the top. The enclosed system also prevented heat loss through gaps between the table and the person, significantly reducing heat loss. Under the enclosed system, the internal air temperature was much higher; with the heating power set to 75W on the sides and 40W at the bottom, the maximum temperature of Ta-1 reached 22.63 ℃, which was 14.8 ℃ higher than under the semi-closed system. These results clearly demonstrate that under the same heating conditions, the enclosed system significantly enhanced the heating effect of the air inside the enclosure.

4.2. The enclosed system provided a significantly stronger heating effect on the human body compared to the semi-closed system

Because the wall temperature of the enclose system and the film surface temperature are both higher than those of the semi-closed system, the air temperature inside the enclosed system is also higher. This results in greater heat convection and radiation to the human skin, thereby increasing skin temperature. **Table 5** shows that under the semi-closed system, the skin temperature of the soles first decreased and then increased. However, under the enclosed system, the temperature of the soles gradually increased. Initially, the skin temperature of the soles under the enclosed system was 1.8 °C lower than under the semi-closed system. Eventually, when the heating film's power reached 75W on the sides and 40W at the bottom, the skin temperature of the soles under the enclosed system was 3.10 °C higher than that under the semi-closed system. This occurred because, under the enclosed system, the ground temperature was lower, resulting in a lower initial temperature of the soles. With the increase in heating power, the heating effect of the enclosed system became more pronounced, thereby raising the skin temperature of the soles. The skin temperatures of the sole, leg, and thigh all increased progressively with the power of the heating films. At 75W on the side and 40W on the bottom, the temperatures reached 30.10 °C for the sole, 34.53 °C for the leg, and 34.05 °C for the thigh, showing improvements of 3.10 °C, 6.18 °C, and 5.48 °C, respectively.

4.3. The effect of enclosed system on thermal sensation on lower body at low temperatures (10 °C, 8 °C)

As shown in **Figures 11** and **14**, when the indoor temperature was 10 °C, thermal comfort was achieved in the final 10 min under the condition of Side 55W + Bottom 30W. At an indoor temperature of 8 °C, under the same condition, only the thigh reached thermal comfort. The leg and sole reached thermal neutrality and comfort at a heating power of 75W on the side and 40W on the bottom. The thigh's thermal sensation adjusted more noticeably, achieving a comfortable and thermally neutral state with just 35W on the side and 20W on the bottom.

Based on the results of the two-factor repeated measures analysis, the following observations were made: At an ambient temperature of 10 °C, the effects of different heating conditions on skin temperature approached significance. At 8 °C, the effects of different heating conditions on skin temperature were significant. In both cases, higher heating power had a more pronounced impact on skin temperature. Under the same heating conditions, the temperature differences among different body parts were significant. At 10 °C, the temperature response of the thigh was significantly higher than that of leg. At 8 °C, the thigh's temperature response was significantly higher than both leg and sole. As heating power increased, the differences in temperature responses among body parts became increasingly significant, particularly in the thigh, where the response to higher heating power was more pronounced. These findings indicate that different body parts exhibit varying sensitivities to temperature, with the thigh demonstrating a notably higher response under high power conditions.

In the final heating stage, the sensation improved to slightly warm, suggesting a human preference for warmer conditions in colder environments. The overall thermal sensation closely aligned with the leg and sole's changes, indicating that the body's overall comfort level is largely influenced by its most uncomfortable parts [28,29].

4.4. The energy consumption of enclosed system

Previous studies have shown that the enclosed localized heating system provides superior heating effectiveness and insulation performance. However, the energy consumption of this system has not yet been thoroughly discussed. Some researchers have already proposed energy consumption metrics specifically for PCS. When the room temperature was 10 °C, the value of CP was 14K. The subjects achieved a neutral thermal sensation within an enclosed system with a system power of 55W on the sides and 30W on the bottom, resulting in a CEP of 6.07 W/K. When the room temperature decreased to 8 °C, the value of CP rose to 16K. At this lower temperature, the subjects maintained a neutral thermal sensation in the heating system with a power of 75W on the sides and 40W on the bottom, giving a CEP of 7.19 W/K.

At room temperatures of 8 °C and 10 °C, the CEP values for the enclosed system were 6.07 W/K and 7.19 W/K, respectively. These values are lower compared to those of other semi-closed systems, indicating lower energy consumption. Moreover, the ambient temperatures discussed in this paper are lower than those in most studies on semi-closed systems, which typically feature ambient temperatures above 12 °C. [26,27,30,31] Although the CEP of these semi-closed systems is lower than that in our study, it remains unknown whether these systems can provide thermal comfort in environments with temperatures below 12 °C.

4.5. Limitations

This study analyzed the impact of personalized heating devices on skin temperature, heat flux, and thermal sensation by selecting only eight subjects, resulting in a small sample size. Future studies should increase the sample size to obtain more comprehensive data on local thermal sensations, skin temperatures, and heat flux. Additionally, the thermal sensation model in this study considered only the skin temperatures of three parts of the lower body. Future research should include testing the skin temperatures of more body parts.

5. Conclusions

In this study, a new enclosed system was introduced. The study compared the heating performance of semi-enclosed and enclosed systems, examined the enhanced thermal sensation provided by the enclosed system at lower indoor temperatures, and analyzed its energy-saving effects. Key findings include:

1) Due to the lower heat loss of the enclosed system compared to the semi-closed system, the thermal micro-environment temperature was higher. When the enclosed system was activated, the increase in air temperature inside the heating box was significantly higher than that of the semi-closed system, reaching up to

twice as much. Additionally, the surface temperature of the heating film in the enclosed system was higher than that in the semi-closed system, with a maximum temperature difference of 6.875 °C. Consequently, the enclosed system led to a substantial increase in the skin temperature of the lower body, with a maximum rise of 6.19 °C.

2) Given the elevated thermal micro-environment temperature provided by the enclosed system, participants maintained thermal neutrality even as indoor temperatures fell to 8 °C and 10 °C. At an indoor temperature of 10 °C, when the heating power reached Side 55W + Bottom 30W, the Thermal Sensation Vote (TSV) essentially reached 0, thus achieving thermal neutrality. When the room temperature was 8 °C, at a heating power of Side 75W + Bottom 40W, the TSV essentially reached 0.
3) The response of skin temperature to different working conditions approached a significant level ($F = 4.58$, $p = 0.0539$), while the response among different body parts showed a significant difference ($F = 5.85$, $p = 0.039$). As heating power increased, the temperature response differences between body parts became more pronounced, particularly in the thigh region, which exhibited a significantly stronger response to higher heating power. This indicates that body parts vary in their sensitivity to temperature, with the thigh showing a notably greater response under high-power heating conditions. Under identical personalized heating conditions, the thighs were the first to reach thermal comfort. In environments with lower room temperatures, the overall sensation of warmth corresponded with the least comfortable parts.
4) At a room temperature of 8 °C, the CEP of the enclosed system used by the subjects was 6.07 W/K. At a room temperature of 10 °C, the CEP was 7.19 W/K. Compared to semi-closed systems, this enclosed system is more energy-efficient.

This study provided a basis for the practical application of personalized heating in buildings, demonstrating that fully enclosed heating systems are better suited to meet heating demands under low ambient temperatures compared to open or semi-enclosed systems. Additionally, the superior energy efficiency of fully enclosed localized heating systems offers a promising direction for research on energy-saving strategies in building environments.

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