

Effects of vertical and horizontal heating panel on heat loss from human legs

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Abstract. In China's hot summer and cold winter zone, there are cold and humid in winter. If there is no heating measure, the human body will feel less comfortable in the cold environment. The traditional HVAC system consumes a lot of energy, and it is difficult to meet the thermal comfort needs of everyone. By creating a local thermal environment around the human body, the personalized heating system can significantly improve the thermal comfort level of the human body with lower energy consumption. In this paper, it is mainly analyzing the heating effect of the heating panel on the legs of the human body by theoretically analyzing the indoor temperature of 12 °C in the hot summer and cold winter zone. For the following two working conditions: the heating panel is placed vertically on the side of the human leg and the heating panel is placed horizontally under the feet. It is calculated that when the human body feels comfortable, the heat loss is about 45 W/m²~50 W/m². The conclusions are as follows: (1) When the heating panel is placed vertically on the side of the human leg, the thermal comfort needs are only met when the heating panel temperature is 70 °C and the distance between the heating panel and the leg is 5 cm or 10 cm. (2) When the heating panel is placed horizontally under the feet and the temperature of the heating panel is 70 °C, the local heat loss of the human body is less than 45W/m², and the human body feels slightly warmer.

1 Introduction

There are cold and humid in the winter of China's hot summer and cold winter zones. If there is no heating, the indoor temperature is usually lower. The average indoor temperature is about 10 °C. The human body is not comfortable due to the influence of the cold environment. It is a traditional and mature way to change the indoor thermal and humid environment by using the Heating Ventilation and Air Conditioning system. However, the HVAC system needs to maintain the temperature and humidity of the entire space to the setpoint, which is lower in energy efficiency and easily causes air pollution and the greenhouse effect ([1]). In addition, due to individual differences, the HVAC system is difficult to meet the thermal comfort needs of everyone ([2,3]), and 80% of people feel dissatisfied when using the HVAC system ([4]). *

In order to solve the above problems, researchers have developed a new system-personal comfort system (PCS), which achieves thermal comfort by individually controlling the microenvironment around each person. PCS systems can improve the thermal comfort of occupants and save energy. Choosing suitable PCSs for different buildings can save 4% to 60% of energy ([5,6]). Wang studied the variation characteristics of body heat loss under non-uniform and transient temperature, respectively([7,8]). Wang conducted an experimental study on the heat exchange between the typically exposed parts of the human body and the environment under different supply air temperatures, the supply air

volume, and airflow organization with the dummy in a comfortable state, and analyzed the range and ratio of convective heat exchange and radiation heat exchange ([9]).

Most of the studies on PCS systems focus on the overall thermal sensation and thermal comfort of the human body when using personalized heating equipment. Few studies analyze the effect of personalized heating equipment on the heat loss of local parts of the human body from the physiological response. This paper aims to theoretically analyze the influence of a single heating panel on the local heat loss of the legs of the human body through calculation. In the analysis process, a simple model with the heating plate and the human leg in different positions is established for calculation, including the heating plate being placed vertically on the side of the human leg, and the heating plate being placed horizontally under the feet.

2 Theoretical analysis process of human body heat loss

Considering the human body as a system, it generates heat through metabolism and also transfers energy with the outside world to maintain the balance of heat production and heat loss in the human body ([10,11]). When the human body is in thermal comfort, the heat balance equation in the human body is:

$$M-W-E-(\pm R)-(\pm C)=0 \quad (1)$$

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Among them, M is the metabolic rate, W is the mechanical work done by the human body (W/m^2), E is the total evaporative heat loss of the human body (W/m^2), R is the radiative heat loss (W/m^2) of the outer surface of the human body to the surrounding environment, C is the convective heat loss (W/m^2) of the outer surface of the human body to the surrounding air. Considering the calculated human body sitting in the winter indoors, the mechanical work W and the evaporative heat loss E are ignored, and only the convection and radiation heat loss (sensible heat loss) of the human body are considered in the calculation process, that is, when the human body is in a state of equilibrium: $M=R+C$.

R can be calculated by the formula (2) :

$$R = \varepsilon f_{cl} f_{eff} \sigma [(t_{cl} + 273)^4 - (\theta_{mrt} + 273)^4] \quad (2)$$

Among them, ε is the emissivity of the human body surface, $\varepsilon \approx 0.95$, f_{cl} is the area coefficient of human clothing, and f_{eff} is the effective radiation area factor (the ratio of the effective radiation area of the wearing body to the total external surface area), σ is the Stephen-Boltzmann constant, which is $5.67 \times 10^{-8} W/(m^2 \cdot K^4)$, t_{cl} is the outer surface temperature after the human body is dressed ($^{\circ}C$), θ_{mrt} is the average radiant temperature ($^{\circ}C$) of the surrounding environment.

C can be calculated by formula (3) :

$$C = f_{cl} h_c (t_{cl} - t_a) \quad (3)$$

Where: h_c is the convective heat transfer coefficient, $W/(m^2 \cdot ^{\circ}C)$, it can be calculated by the formula (4), t_a is the ambient temperature, $^{\circ}C$.

$$h_c = 2.38(T_{cl} - T_a)^{0.25} \quad (4)$$

However, the heating process of the heating panel will affect the heat loss of the human body. One part is the radiative heat transfer that the heating panel radiates directly to the surface of the human body, and the other part is that the heating panel affects the air around the human body so that the air has a certain temperature rise, and then affects the convective heat transfer of the human body.

The calculation of the heat transfer amount of radiation directly radiated from the heating panel to the human body is mainly calculated by the formula (5) ([12]) :

$$R_{cl,2} = \sigma [\varepsilon_{cl}(t_{cl} + 273)^4 - \varepsilon_2(t_2 + 273)^4] F_{cl,2} \quad (5)$$

ε_{cl} is the surface emissivity of human clothing, ε_2 is the heating panel emissivity; $F_{cl,2}$ is the angle coefficient between the heating panel and the body surface ([13]).

The radiative heat transfer of the heating panel to the human body can inhibit the external radiative heat loss of the human body. Therefore, the actual radiative heat loss R of the human body under the influence of the heating panel is the radiative heat loss of the human body minus the radiant heat transfer of the radiant panel to the human body, that is: $R_a = R - R_{cl,2}$.

The influence of the heating panel on the ambient temperature is first obtained through software simulation to obtain the effect of a single heating panel on the air temperature when placed indoors, and then the convective heat loss of the human body in this environment is calculated by formulas (3)~(4).

According to the heat balance relationship, the formula (6) :

$$t_{sk} = t_{sk} - I_{cl}(R + C) \quad (6)$$

t_{sk} is the surface temperature of human skin ($^{\circ}C$), I_{cl} is the thermal resistance of human clothing, ($m^2 \cdot K$)/ W .

The theoretical analysis idea is shown in Figure 1. The outer surface temperature and heat loss of the human body are calculated through convection, radiation calculation formula, and heat balance relationship.

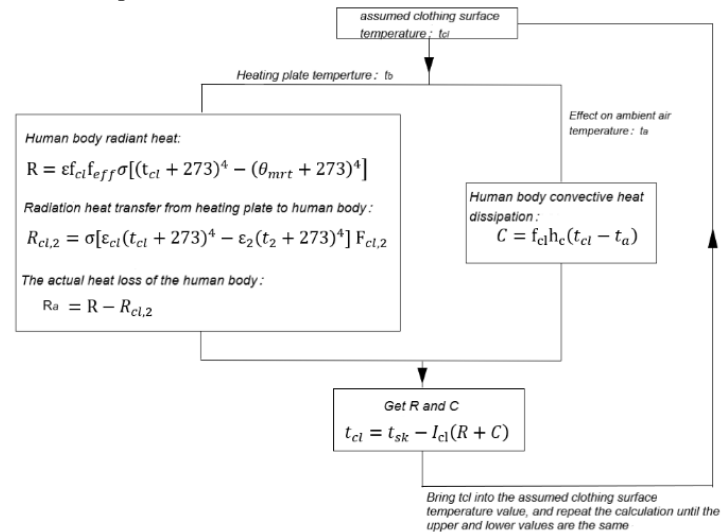


Fig. 1. Theoretical analysis flow chart.

3 Simulation

The feet, calves, and knees of the human body are simplified as human leg cuboids. The size is determined by querying the adult human body size in GB 10000-1988 ([14]).

When the heating panel is parallel to the leg, the influence on the leg is mainly directed to the lateral surface of the leg. As shown in Figure 2, the leg of the human body is approximated as a cuboid of 10 cm×10 cm×50 cm (length × width × height).

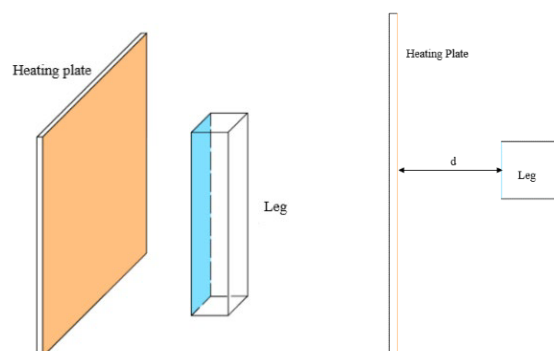


Fig. 2. Simplified schematic diagram of the heating panel placed vertically on the side of the human leg.

For the case where the heating panel is placed horizontally under the feet, as shown in Figure 3, it is regarded as two legs arranged side by side, which is simplified to a cuboid of 20 cm × 10 cm × 50 cm (length × width × height), and it is placed in the center of the

panel, the effect of the heating panel on the human body is mainly directed to the front and side of the legs.

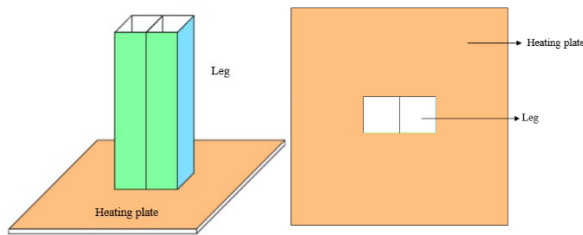


Fig. 3. Simplified schematic diagram of the heating panel placed horizontally under the feet.

Airpak is used to simulate the effect of placing a single heating panel in the room. And the Indoor zero equation model is chosen. The other parameters are set as shown in Table 1.

Table 1. Model parameters.

Name	Size(m)	Temperature(°C)
Room	6×3.4×3.4	12
Outside temperature	-	9
East Wall	6×3.4	11
South wall	3.4×3.4	11
West wall	6×3.4	11
North wall (Facade)	3.4×3.4	10
Ceiling	6×3.4	11
Floor	6×3.4	11
Parallel panel	0.6×0.6	-

According to the different positional relationships between the heating panel and the human body, the working conditions shown in Table.2~3 are set during the analysis.

Table 2. The working condition setting that the heating panel is placed vertically on the side of the human leg.

Working conditions	The ambient temperature(°C)	d (cm)	Heating panel temperature(°C)
1~3	12	5	40, 50, 70
4~6		10	40, 50, 70
7~9		15	40, 50, 70
10~12		20	40, 50, 70

Table 3. The working condition setting that the heating panel is placed horizontally under the feet.

Working conditions	The ambient temperature(°C)	Heating panel temperature(°C)
1	12	40
2		50
3		70

4 Results

4.1 Air temperature under the influence of the heating panel

The heat loss of the human body consists of two parts, convection, and radiation. The calculation of convection heat loss is related to the ambient temperature.

The temperature field under different heating panel temperatures when the simulated heating panel is parallel to the human leg is shown in Figure 4. The temperature gradient in the figure ranges from 12 °C to the set temperature of the heating panel. The calculation results of the air temperature at different distances in front of the heating panel at different temperatures are shown in Table 4. The temperature of the heating panel is slightly different at the same distance, but the overall difference is not large. Therefore, the temperature value at the center of the heating panel is selected for subsequent calculation.

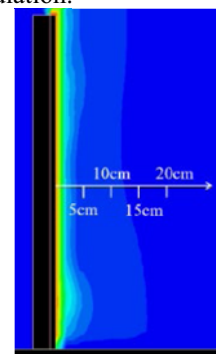


Fig. 4. The distribution of the temperature field when the heating panel is placed vertically.

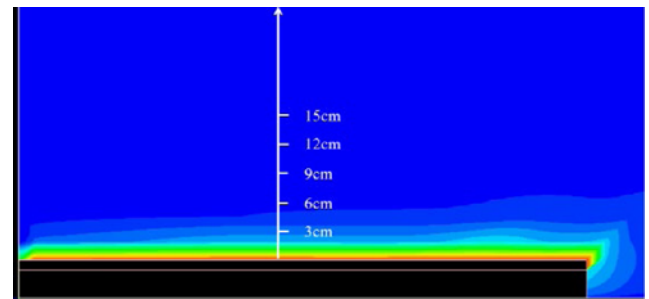


Fig. 5. The temperature field distribution diagram of the horizontal placement of the heating panel.

Table 4. The calculated temperature of the surrounding air when the heating panel is placed vertically.

d(cm)	Heating panel temperature(°C)		
	40	50	70
5	13.2	13.7	15.1
10	12.8	13.2	14.1
15	12.4	12.7	13.4
20	12.1	12.4	13.0

Table 5. The calculated temperature of the surrounding air with the heating panel placed horizontally.

d(cm)	Heating panel temperature(°C)		
	40	50	70
3	13.4	14.2	16.0
6	12.1	12.6	13.4
9	12.1	12.6	13.4
12	12.1	12.6	13.5
15	12.2	12.6	13.5

Figure 5 shows the simulation results of the temperature field at different heights of the heating panel placed horizontally under the feet. Table 5 shows the calculated temperature of the air at 3 cm, 6 cm, 9 cm, 12 cm, and 15 cm upwards from the heating panel, and also takes the temperature value at the center of the heating panel for subsequent calculation. When the heating panel is placed horizontally, the feet are in direct contact with the heating panel. It can be found from Table 5 that the temperature difference between 6 cm and 15 cm away from the heating panel is not significant, and the air distribution of the heating panel is only at 3 cm when the temperature is higher. Therefore, in the subsequent calculation of the heat loss of the legs, the legs are regarded as a whole, and d is taken as the air temperature value at 6 cm~15 cm.

4.2 Theoretical calculation of heat loss from the human body

First, it is essential to determine the heat loss in the comfortable state, which will be used as the criterion. When the ambient temperature is 21°C, the clothes are long-sleeved shirts, knitted sweaters (thin), jeans, socks, and sports shoes, the thermal resistance value is 0.6clo, and the calculated heat loss of the human body is 50.7 W/m². The ambient temperature is 23°C, and the clothes are selected from knitted sweaters (thin), jeans, socks, and sports shoes. The thermal resistance value is 0.51clo, and the heat loss is 45.8 W/m². At the ambient temperature of about 22°C, the average skin heat flow is about 48 W/m² ([15]). Therefore, in the subsequent comparison of the heat loss of the human body, this range is selected as the criterion for determining the comfort state. If it is higher than 50 W/m², it is determined to be colder; if it is lower than 45 W/m², it is considered to be warmer.

When the ambient temperature is 12°C, the heat loss of the legs is calculated to make the upper and lower clothing of the human body more uniform. The clothes conclude casual jacket, thin sweater, autumn clothes, thick long johns, jeans, socks, and sports shoes. The thermal resistance value is 1.18clo. And the skin temperature of the legs is 32.55°C. ([16]). When the heating panel is not used, the heat loss of human legs is 63.8 W/m². This does not meet the comfort needs. Thermal comfort can be improved by wearing more clothes. It is calculated that the thermal resistance of the clothing needs to reach 1.7clo when the heat loss is in the comfort zone, However, the method of increasing the thermal resistance of clothing in real life is not completely applicable. Therefore, the heating panel can be used to improve comfort. The results of the heat loss of the human body under the influence of the heating panel are shown in Tables 6~7.

When the heating panel is placed vertically, the calculation results of the heat loss of the legs are shown in Table 6. It can be found that the use of the heating panel can reduce a certain amount of external heat loss in the legs. It is more obvious that the restraining effect on the heat loss of legs with the increase of the set temperature. Thermal comfort cannot be satisfied when the heating panel is 40°C and 50°C. When the

temperature of the heating panel is increased to 70°C, and the distances are 5 cm or 10 cm for comfort, the heat loss is 46.1 W/m² and 50 W/m² respectively. However, in the actual situation, it is very dangerous for exposed parts such as the hand when the temperature of the heating plate is 70 °C, so attention should be paid to the practical application.

The heat loss of the legs under the influence of the horizontally placed heating panel is shown in Table 7. Because the foot is in direct contact with the heating panel, it has a greater impact on the thermal sensation of the legs. It can be seen from Table 7 that only when the temperature of the heating panel is 70°C, the heat loss is 37.7 W/m², which is less than 45 W/m². And the impact on the thermal comfort of the human body is slightly warmer. At the same time, the foot in direct contact with it will overheat due to the excessive temperature of the heating plate, Therefore, it is possible to isolate the foot from the heating plate by raising the foot. When the temperature of the heating panel is 50°C, the heat loss is 51.9 W/m², which is slightly larger than the heat loss in a comfortable state. It will make the human body comfortable through improve the microenvironment temperature of the human body by adding heat preservation outside the heating panel to reduce the external heat loss of the human body.

Table 6. Calculation results in heat loss of human legs.

Heating panel temperature(°C)	d(cm)	R _a (W/m ²)	C (W/m ²)	Total (W/m ²)
40	5	34.7	24.2	58.9
	10	35.5	25.1	60.6
	15	36.1	26.1	62.3
	20	36.3	26.9	63.2
50	5	35.8	19.5	55.4
	10	36.4	20.9	57.3
	15	37.1	22.4	59.5
	20	37.1	23.6	60.7
70	5	37.5	8.6	46.1
	10	38.7	11.4	50.0
	15	39.3	14.0	53.2
	20	39.2	16.3	55.5

* Bold data is the result of heat loss ≤ 50 W/m².

Table 7. Calculation results in heat loss of human legs.

Heating panel temperature(°C)	d(cm)	R _a (W/m ²)	C (W/m ²)	Total (W/m ²)
40	41.0	17.4	58.5	41.0
50	44.8	7.1	51.9	44.8
70	53.9	-16.2	37.7	53.9

* Bold data is the result of heat loss ≤ 50 W/m².

5 Conclusion

This paper analyses the influence of the heating panel on the local heat loss of the human body when the indoor temperature is 12°C through theoretical calculation. Combined with calculation and literature data, the heat loss of the human body is about 45 W/m²~50 W/m² in a comfortable state, which is used as an evaluation standard to analyze the use of heating plates.

When the heating panel is placed vertically on the side of the human leg, only the temperature of the

heating panel is 70°C and the distance is 5 cm or 10 cm can meet the comfort requirements.

When the heating panel is placed horizontally under the feet, only the heat loss of the heating panel is less than 45 W/m² under the working condition of 70°C. At this time, the temperature of the heating panel is relatively high, and the human body feels slightly warmer.

This paper roughly divides the heat loss in the comfort zone of the human body and conducts a simple calculation of the local heat loss of the human body. In the future research, it is indispensable that there should carry out relevant experiments to verify the effect of the heating plate on the local heat loss of human body, and study the relationship between human body partial heat dissipation and thermal sensation.

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