International Journal of Engineering and Technology, Vol. 15, No. 3, August 2023

Heating Performance and Energy-Efficiency Evaluation of a Personal Heating Device: Numerical Simulation and Experimental Validation

Qibin Li and Hong Liu*

***Abstract*—In southern China, where there is no district heating in residential buildings, the thermal comfort of indoor occupants cannot be guaranteed in winter due to the high energy consumption of whole-space heating. Foot Heating Pad (FHP), as a Personal Comfort System (PCS) device, enables occupants to improve thermal comfort with less cost. In this study, the effects of local heating by FHP on foot skin temperatures and thermal comfort were investigated, and the energy-efficiency performance of FHP was analyzed. A heat transfer model of human foot, which consists of four layers of body tissues, was established to simulate the foot temperatures under continuous and intermittent heating, and the numerical simulation of the model was accomplished using ANSYS. Besides, an FHP (36 W) based on Peltier heater was proposed and developed to heat the foot, and a climate chamber experiment involving 16 subjects was performed to collect subjects' thermal comfort votes at three ambient temperature conditions of 8 °C, 11 °C, and 14 °C. The simulation results show that the foot skin temperature was significantly enhanced, and the plantar skin temperature increased by seven Temperature (K). Besides, there was no significant difference in foot temperature distribution between intermittent heating and continuous heating. However, the experimental results indicated that continuous heating was more effective in enhancing subjects' thermal comfort and was able to ensure a neutral overall thermal sensation in a 14 °C environment. The Corrective Power (CP) of FHP was 7K and the Corrective Energy & Power (CEP) was 5.1W/K. This study is expected to provide guidance for the optimization design of PCS devices.**

***Index Terms*—Personal comfort system, foot heating, skin temperature, thermal comfort, energy-efficiency**

I. Introduction

Domestic heating devices such as air-source heat pumps and gas fireplaces have been widely used in the Hot Summer and Cold Winter (HSCW) zones of China, which is humid and rainy in winter. However, Liu *et al.* [1] conducted field measurements of indoor thermal environment in residential buildings in the HSCW zones, and the results showed that the average daily heating time was only 1.4 hours due to the high energy consumption, and the average indoor air temperature was only 12.7 °C, which was far below the lower limit of the winter comfort zone (20–24 °C) [2]. Cold indoor environment not only reduce occupants' thermal comfort, but also affect the productivity of home-workers [3]. Therefore, creating a comfortable indoor environment in residential buildings without district heating is becoming an increasing social concern.

In recent years, researchers have investigated Personalized Comfort Systems (PCS) that directly heat localized spaces/body parts with lower energy consumption, such as radiant heaters, heated seats, and foot/hand warmers [4]. Previous studies have shown that when the human body is in a non-thermally neutral environment, local thermal stimulation on the body can also affect the rest of the body at the same time [5], thus PCS can be used to improve the overall thermal comfort with localized thermal stimulation of the body. And it has been shown [6] that occupants' overall satisfaction with the indoor environment is also increased when using PCS. In addition, the proper use of PCS can also significantly reduce the energy consumption of Mechanical Heating Ventilation and Air Conditioning (HVAC) systems [7].

However, there are differences in the extent to which the thermal sensation of different body parts affects the overall thermal comfort. For example, cold discomfort in the extremity of the body (feet/hands) is a major factor contributing to overall discomfort [8]. Therefore, studies have investigated the effect of the heated part of PCS on thermal comfort. Liu *et al.* [9] collected local thermal comfort when seven body parts were heated separately in a 19 °C environment and found that the most significant improvement in thermal comfort was observed when the wrist was heated and conversely the least effective when the torso was heated. In addition, studies have investigated the effects of typical heating methods on thermal sensation (radiant, convective, and conductive heating). Wang *et al.* [10] found that contact heating was more comfortable and more economical than radiant heating. Besides, Shin *et al.* [11] verified the effect of graphene heating mats in intermittent versus continuous heating mode on thermal comfort and found that only continuous heating significantly improved the thermal psychological response. While Lopez *et al.* [12] applied static temperature and dynamic cyclic temperature modes separately to a wearable heated bracelet and found that cyclic heating better improved overall thermal sensation than continuous heating. Therefore, most studies on conductive foot heating have been conducted in climate chambers, making it difficult to clearly reveal the processes of foot heat transfer. Besides, the effects of local intermittent heating on human thermal responses have not been fully studied.

This study aimed to evaluate the heating performance and energy efficiency of a foot heating pad. For those objectives, an FHP that can dynamically adjust the heating temperature was developed and the impact of intermittent and continuous heating on human thermal response was analyzed. Firstly, a

Manuscript received April 3, 2023; revised June 15, 2023; accepted July 3, 2023.

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DOI: 10.7763/IJET.2023.V15.1229

heat transfer model of human foot was established, and the change process of foot temperature was simulated. Secondly, the developed foot heating pad was used to heat the subjects under the typical HSCW winter environment, and the subjects' thermal comfort votes were collected. Lastly, the energy-saving performance of FHP was analyzed. The conclusions obtained in this study are expected to provide guidance for the optimization design of PCS devices.

II. Methods

A. Numerical Simulation

In this study, 3D simulations of heat transfer in the foot were performed using ANSYS Workbench. A simplified model of the human foot structure was created in 3DS MAX as shown in Fig. 1. The foot tissues were divided into four layers, consisting of skin, fat, muscle, and bone layer, as shown in Fig. 1(a). The transverse and longitudinal sections of the foot were shown in Fig. 1(b) and Fig. 1(c), and the foot size is 25 cm × 10 cm × 8 cm [13]. Considering the complexity of the actual heat transfer, the model is simplified in this study and the following assumptions are made. Firstly, only heat transfer between the layers of tissues was considered and mass transfer was neglected. Secondly, the air gap inside the fabric layer was neglected. Lastly, only convective heat transfer was considered between the fabric layer and the air, radiative heat transfer was neglected.

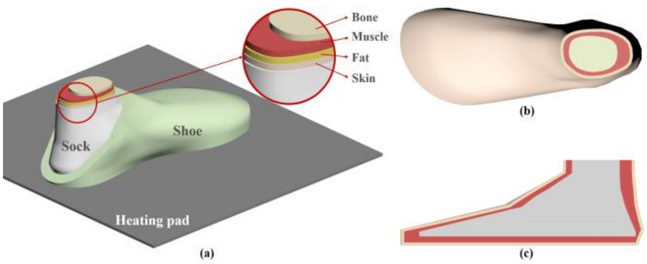

Fig. 1. (a) Geometry diagram of the multi-layers foot model with heating pad, (b) Horizontal cross-section of the foot model, (c) Vertical cross-section of the foot model.

B. Mathematical Model

The most widely used in the field of biological heat transfer is the classical biological heat transfer equation proposed by Penes [14] in 1948. The equation is simple and universal, and its general form is:

$$\rho c(\partial T/\partial t)= \nabla(k\nabla T)+ \rho_b c_b w_b(T_a-T)+ q_m \tag{1}$$

where ρ, c, T, t, and k is tissue density, tissue specific heat, tissue temperature, time, and tissue thermal conductivity, respectively. While ρ_b, c_b, w_b, T_a, and q_m is blood density, specific heat of blood, blood perfusion rate (mL/(s) mL), arterial blood temperature, and metabolic heat production (W/m^3), respectively. The first item on the right of the equation is the net heat introduced by the tissue, the second item is the heat brought into the tissue by blood perfusion, and the third item is the heat generated by tissue metabolism.

C. Boundary and Initial Conditions

The topmost ankle section is connected with the lower leg and can be regarded as an adiabatic surface. Its Neumann boundary condition can be described as:

$$-\lambda(\partial T/\partial n)=0 \tag{2}$$

where, n is the outer normal direction of the heat exchange surface. Since 44 ℃ is the thermal pain threshold of the human body [15], 41 ℃ was selected as the average surface temperature of the foot heating in this study. The control group was No Heating (NH) and its surface temperature was T_{NH}=20 ℃. For the Constant Heating (CH) mode, its surface temperature was taken as T_{CH}=41 ℃. For the High Frequency Intermittent Heating (HH) mode, the heating surface was set to fluctuate between 40 ℃ and 42 ℃ in a cycle of 1min, and its temperature was expressed in $T_{HH}(t)$. For the Low Frequency Intermittent Heating (LH) mode, set the heating surface to fluctuated between 39 ℃ and 43 ℃ in a cycle of 4min, and its temperature was expressed in $T_{LH}(t)$. For the above two intermittent heating surfaces of the foot, the Dirichlet boundary condition can be described as:

$$T_{HH}(t)=41+2/\pi\cdot\sin^{-1}\sin(\pi/30\cdot t-\pi/2) \tag{3}$$

$$T_{LH}(t)=41+4/\pi\cdot\sin^{-1}\sin(\pi/120\cdot t-\pi/2) \tag{4}$$

The surface of the fabric exposed to the indoor environment exchanges heat with the surrounding air through natural convection, and its Robin boundary conditions can be described as:

$$-\lambda(\partial T/\partial n)=h_{air}(T-T_{air}) \tag{5}$$

where, h_{air}=10 W·m^{-2}·K^{-1} is convective heat transfer coefficient, and T_{air} is air temperature. When the indoor temperature was 14 ℃, the local heating had obvious effect on the overall thermal sensation [16]. In addition, the indoor temperature of residential buildings is less than 10 ℃ during the coldest month [17]. Therefore, the upper limit of ambient temperature was determined as 14 ℃, and the lower limit was determined as 8 ℃ in this study.

The starting time of simulation corresponds to the time when the human body begins to heat after 30 mins of cold exposure. However, the foot temperature of people who have been exposed to cold environment for a long time is relatively low, thus the initial foot temperature under the three air temperatures in this study was 27 ℃, 28.5 ℃ and 30 ℃, respectively.

D. Thermophysical Parameters

Typical biological tissue thermophysical parameters [18] are shown in Table I. Besides, q_m is 684 W·m^{-3}, w_b is 5×10^{-4} mL·s^{-1}·mL^{-3}, and T_a is 37 ℃ [19]. The thermophysical parameters of fabric layers were selected according to the typical values [20].

TABLE I: Thermal Properties and Parameters Used in the Model

Layers	Density (kg·m^{-3})	Specific heat (J·kg^{-1}·K^{-1})	Thermal conductivity (W·m^{-1}·K^{-1})	Thickness (mm)
Skin	1109	3391	0.37	1.4
Fat	911	2348	0.21	1
Muscle	1090	3421	0.49	8
Bone	1178	2274	0.31	—
Sock	350	1210	0.03	1
Shoe	350	1210	0.03	10

E. Mesh and Solution

The foot model was discretized by a hybrid mesh combining structured and unstructured meshes, and adaptive sizing with a resolution of 5 was used. The computational mesh is shown in Fig. 2, where the minimum mesh size is 1 mm, the total number of mesh cells is 1.26 million. The finite element method was applied to the energy differential Eq. (1), the solution type was set to transient heat transfer, and the time step was set to 30 s. The temperature variations of the representative points (point I, point S) on instep and the sole of the foot were set in the solution results for one hour.

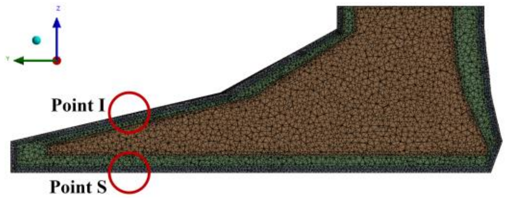

Fig. 2. Meshed geometry of the vertical cross-section of the foot model.

F. *Climate Chamber Experiment*

In this study, a climate chamber experiment was carried out in January 2022 at Chongqing. The dimensions of the climatic chamber were shown in Fig. 3(a) and Fig. 3(d). The room temperature and relative humidity were measured and recorded by a temperature and humidity recorder (HOBO, UX100-011) with ranges of −20 °C to 70 °C (±0.21 °C) and 1% to 95% (±2%), respectively. The structure of the heating pad is shown in Fig. 3(b), with dimensions of 60 cm × 30 cm × 2 cm, and from top to bottom are a thin copper plate for heat conduction, a thermistor for measuring the temperature of the copper plate, a polyurethane gasket isolating the thermistor from the heating element, a Peltier heating element, and thermally conductive silicone grease applied between the Peltier element and the thin copper plate. The FHP can heat the foot with low energy consumption by converting the input electrical energy into heat energy and transferring it to the copper plate. the temperature of the heating surface of the FHP (39 °C to 43 °C) was regulated by a PID control system as shown in Fig. 3(c) to achieve intermittent heating of the heating pad with an input power of 36 W.

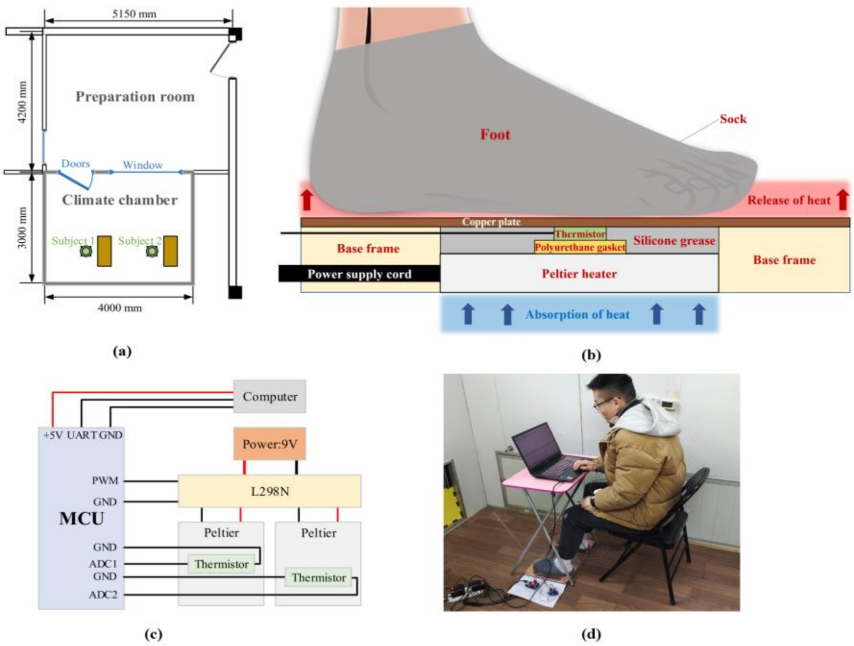

Fig. 3. Experimental platform and equipment.

Sixteen college students (eight males and eight females) were recruited as subjects in this study. All subjects lived in Chongqing within the last year, had no history of rhinitis, dry skin syndrome, or other cardiovascular diseases. All subjects wore typical winter clothing of the HSCW zone, including long-sleeved shirts, sweaters, thick jackets, thick straight pants, thick socks and uniformly provided cotton slippers, and were not allowed to change clothes during the experiment. The average clothing insulation was calculated to be 1.3clo according to ASHRAE 55 standard [21]. Other basic characteristics of the subjects were shown in Table II.

TABLE II: CHARACTERISTICS OF SUBJECTS

Gender	Sample size	Height (cm)	Weight (kg)	BMI	Age
Female	8	162 ± 5	51 ± 9	19.2 ± 3.1	23.1 ± 1.1
Male	8	172 ± 4	59 ± 9	20.2 ± 2.5	23.4 ± 1.6
Total	16	166 ± 11	55 ± 10	19.7 ± 2.5	23.3 ± 1.7

The designed and measured air temperature and relative humidity of the climate chamber were shown in Table III. Subjects were asked to arrive at the thermally neutral preparation room 30 min before entering the climate chamber to eliminate the effects of previous thermal experiences. Since this experiment simulates a home office scenario, subjects will sit quietly in their seats and will be allowed to use their cell phones, tablets, or computers for regular office activities, but will not be allowed to communicate with each other.

TABLE III: DESIGNED AND MEASURED AIR PARAMETERS (MEAN ± SD)

Designed parameters		Measured parameters	
Air temperature (°C)	Relative humidity (%)	Air temperature (°C)	Relative humidity (%)
8	60	8.1 ± 0.3	59.2 ± 2.6
11	60	11.3 ± 0.2	57.1 ± 3.3
14	60	14.3 ± 0.2	58.7 ± 2.8

The formal test started after the subjects entered the climate chamber, and each set of experimental conditions lasted 90 min and was divided into two phases. In the first phase, subjects were exposed to the unheated environment for 30 min, and then in the second phase, the foot heating pad was turned on and the surface temperature was adjusted to a preset value, and the subjects were exposed to the partially heated environment for 60 min until the end of the experiment. During this period, subjects filled out thermal comfort questionnaires at 10-min intervals to describe their level of thermal comfort at that moment. The overall thermal comfort was evaluated using a six-point break scale [22] ranging from −3 (very uncomfortable) to −2 (uncomfortable), −1 (slightly uncomfortable), +1 (slightly comfortable), +2 (comfortable) to +3 (very comfortable).

III. Results

A. Simulated Skin Temperature

The temperature distributions of the longitudinal section of the foot at two typical heating time points (30 min, 60 min) are shown in Fig. 4 (a) and Fig. 4 (b), respectively, where the red area represents the high temperature, and the green area represents the low temperature. The temperature distribution of NH control group shows that the longer the exposure time in the cold environment, the lower the temperature of the foot. The highest temperature was found in the core region of the foot, which is dominated by the skeletal layer, while the lowest temperature was found in the sole region, including the toes and heel. The difference between the CH experimental group and the NH control group showed that sole heating had a significant effect on the temperature distribution, increasing the temperature not only in the directly heated sole region, but also in the unheated instep region. However, there was no significant difference in the temperature of the heel region not covered by the slippers with or without heating. The comparison of CH experimental group with HH experimental group and LH experimental group illustrated that there was no significant effect of intermittent heating and continuous heating on the temperature change and distribution of the foot under the condition of maintaining the same average heating temperature of the heating surface, which indicated that there was no difference in the effect of different heating modes on the temperature of the foot in various cold environments.

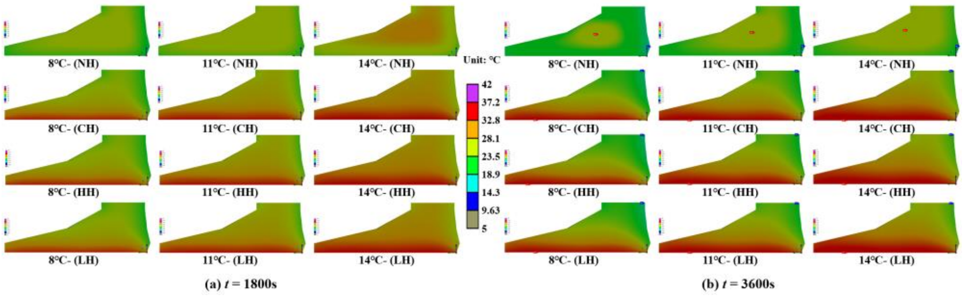

Fig. 4. Vertical cross-sectional temperature contours of the foot model (a) *t*=1800s (Middle of the heating), (b) *t*=3600s (End of the heating).

Fig. 5 shows the temperature-time curve of point I & S. The temperature of the sole increased to above 36.0 ℃ under foot heating, and the temperature rise before and after heating exceeded 7K. When not heated, the foot temperature continued to drop below 22.4 ℃, and the temperature drop exceeded 5K. In addition, although the instep is not directly heated, its temperature can be increased by more than 2K before and after heating. Compared with constant heating, the skin temperature change trend of the soles and dorsum of the feet during intermittent heating is roughly the same. The skin temperature of the soles of feet in direct contact with the heating surface fluctuates and rises during intermittent heating, and its frequency and amplitude are consistent with the temperature fluctuation characteristics of the heating surface. However, the change of skin temperature of the instep far away from the heating surface has nothing to do with the heating mode and shows a gentle rising trend (the temperature difference under each heating mode is less than 0.1K). It is noteworthy that for the instep not directly heated, the skin temperature differs from that of the sole in that it continues to rise after the onset of heating, but first experiences a short (10min) decline to a minimum and then begins to rise gradually.

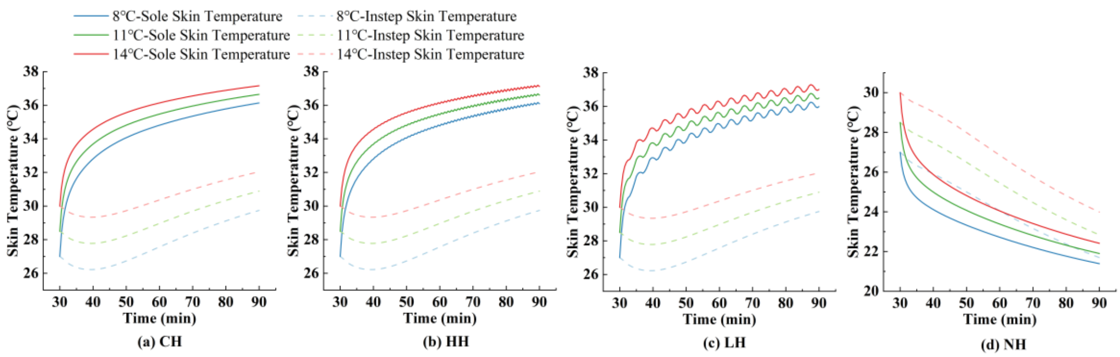

Fig. 5. Vertical cross-sectional temperature contours of the foot model (a) *t* = 1800s (Middle of the heating), (b) *t* = 3600s (End of the heating).

B. Thermal Sensation Votes

Fig. 6 displays the subjects' thermal sensation votes ($TSV_{overall}$). The results show that the $TSV_{overall}$ decreased over time in the cold environment at 8 °C, regardless of whether the subjects were heated or not, with the largest decrease in the absence of heating. In contrast, in the 11 °C and 14 °C environments, the $TSV_{overall}$ decreased only in NH, and increased in both intermittent and continuous heating. Comparing the results of each group at 90 min, it was found that the subjects' $TSV_{overall}$ was significantly improved by all heating modes compared to NH scenario, and the $TSV_{overall}$ was improved by 0.4, 0.5, and 0.6 at 8 °C, 11 °C, and 14 °C, respectively. There were also differences in the effects of different heating modes on the subjects' $TSV_{overall}$. The $TSV_{overall}$ in the CH group was −1.3 and 0.2 at 8 °C and 14 °C, respectively, which were significantly larger than the $TSV_{overall}$ in the intermittent heating groups. Local heating applied to the feet of the subjects improved this phenomenon, where continuous heating was more effective than intermittent heating in improving subjects' thermal sensation votes.

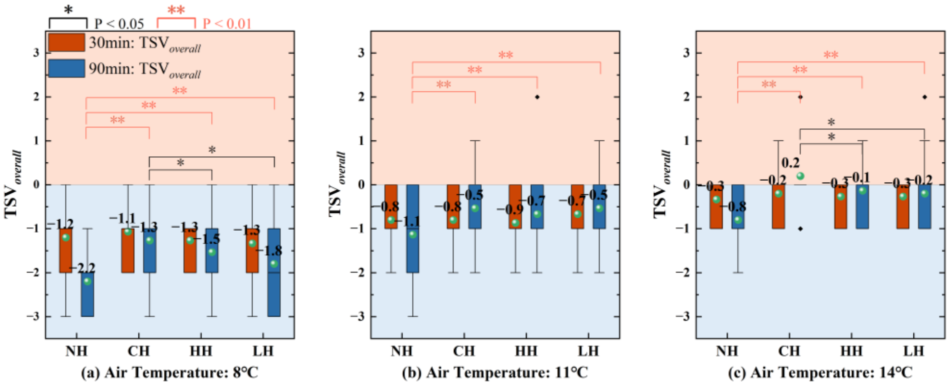

Fig. 6. Overall thermal sensation votes under four heating modes.

IV. Discussions

A. Heating Performance of Foot Heating Pad

From Fig. 4, it can be found that the foot temperatures in the intermittent and continuous heating modes were essentially equal. However, it does not mean that there is no difference in heating performance between the two heating modes, since Fig. 6 indicates that the subjects have higher TSV in the case of continuous heating. The simulation of foot temperature in this paper is a simplified heat transfer model based on the heat balance equation, but the thermal regulation of human tissues is more complex. Therefore, it is possible that the actual foot skin temperature is higher with continuous heating, resulting in a higher heat sensation poll for the subjects. Foot tissue temperature is mainly controlled by vasoconstriction and diastole as well as evaporation of sweat [23], and during intermittent heating, the degree of vasodilation may be affected because the heating temperature also decreases intermittently, resulting in a smaller blood perfusion rate during intermittent heating than during continuous heating, which ultimately reduces the skin temperature in the intermittent heating mode.

B. CP and CEP of Foot Heating Pad

The thermal comfort and energy consumption effectiveness of FHP was evaluated by Corrective Power (CP) [24] and Corrective Energy & Power (CEP) [25]. CP is the equivalent compensation temperature with PCS compared to without PCS at neutral thermal sensation. CEP is the ratio of a PCS's heating power to its CP. Since the indoor temperature corresponding to the neutral thermal sensation without heating is 21 °C [26], and the neutral indoor temperature in this study is 14 °C, the CP of FHP is 7K. In addition, since the heating power of FHP is 36 W, the CEP of FHP is calculated as 5.1 W/K.

Compared with previous studies on energy efficiency analysis of PCS, the FHP in this study exhibited a lower CEP, which implies a good energy efficiency. Heating the soles of the feet by direct contact effectively avoids heat dissipation into the surrounding environment, and the thermal resistance between the heating surface and the heated area is relatively low, so the FHP developed in this study can bring about a significant increase in the thermal comfort of the subjects with little energy consumption, thus providing an economically feasible solution for winter heating in HSCW areas.

C. Limitations

The simulation model used in this study simplifies the actual heat transfer situation and ignores the sweating process of the foot after heating and the corresponding evaporation of sweat, while changes in the humidity of the foot not only affect the distribution of foot temperature, but also may reduce the thermal comfort of the subjects. The effect of sweating situation on thermal comfort when the foot temperature is too high can be further studied in the future.

V. Conclusion

In this study, an economical and energy-saving foot heating pad had been developed, and numerical simulation method was applied to verify the heat transfer process during foot heating, and its heating performance and energy efficiency had been studied through climate chamber experiments. The main conclusions were as follows:

1) In the simulation of foot heat transfer model, the temperature of the sole will increase to above 36.0 °C, and the temperature of the instep can be increased by

more than 2K before and after local heating.

2) Continuous foot heating was more effective than intermittent heating in improving subjects' thermal sensation. However, heating the foot at 8 °C and 11 °C was not effective in meeting subjects' thermal comfort needs. Only heating the foot in an environment above 14 °C ensured that the overall thermal sensation of the subject was neutral.
3) The foot heating pad developed in this paper had an input power of 36 W. Compared with whole-space heating systems, the foot heating pad had an excellent energy-saving performance, with a Corrective Power of 7K and a Corrective Energy & Power of 5.1 W/K.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Qibin Li and Hong Liu concuted the research; Qibin Li analyzed the data and wrote the paper; all authors had approved the final version.

Funding

This research was financially supported by the 111 Project from the Ministry of Education of the People's Republic of China (Grant No. B13041).

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