Modelling and Experimental Study on Electrically Heating Garment to Enhance Personal Thermal Comfort

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Abstract. Electrically heating garment (EHG) is an effective protection for human in cold environment. In this study, we analysed the principal agents of heat transfer in EHG, and established a theoretical model including heat conduction, natural convection and radiation. To verify the model, the numerical simulations and experiments were compared, and showed a temperature discrepancy smaller than 0.3°C, which was acceptable in engineering design. Using numerical simulation, it is convenient to optimize the design parameters of EHG in different thermal conditions. For instance, to maintain the average temperature of skin within 32-34°C when people are in low metabolic activities, the power of heating elements should range from 73.1-110.7 W/m² under high heating gear or 10.8-48.5 W/m² under low heating gear. The more importance is that the calculation allows easy predesign of EHG. The effect of the arrangements of heating elements was studied, herein, the results of six arrangement patterns were presented. It is found that the most effective arrangement can raise the average temperature of skin under heating elements about 0.4-1.2°C than other cases.

Keywords: Electrically heating garment; Personal thermal management; Thermal comfort.

1. Introduction

Cold environment discomforts people and lengthy exposure in cold environment probably causes episodic finger symptoms, respiratory symptoms, peripheral circulation symptoms, hypothermia, and repeated pain in the musculoskeletal system [1, 2]. Cloth protection is a traditional way to prevent heat loss from body in cold environment. However, some special vocations such as power grids disaster prevention require that the clothes not only can protect the body warm, but also should be light enough to guarantee normal work. Thus, clothes with ability of active heating is spawned. The active heating provides extra heat to the body instead of increasing the layers of garment, availing for less weight of clothing and less metabolism cost from clothes weight [3]. Electrical heating is an attractive heating method for its high heating efficiency and fast heating rates. Electrically heating garment (EHG), usually in style of coat or vest and driven by low-voltage direct current power, outperforms other heating products for flexibility, convenience and portability [4]. Generally, several heating elements supplied by portable battery are integrated in the EHG, and the heating elements fabricated by carbon fibers, graphene or wires are only tens of watts to ensure the safety of human [5, 6]. Recently sensors and
intelligent circuit are embedded to monitor the temperature and in turn to automatically regulate the power of the heating elements, which frees the users from frequent adjustments.

In the past decades, the effect of warming different parts of the body, such as hands, torso and foot, has been discussed [7-12]. Goldman et al. [13] reported that heating torso had ineffective impact on warming body. However, others argued with converse views. Rapaport et al. [14] concluded that hands comfort can be achieved by heating full body when body heat gain was greater than body heat loss. Brajkovic et al. [15] found that heating torso could increase average body skin temperature, finger thermal comfort and toe thermal comfort. Specifically, torso heating could warm fingers and toes at a comfortable temperature (22-25°C) for 2.5-3 hours during exposure to -15°C air with 2-hour 100 – 110 W heating power (with 0.366 m² heating area). Therefore, it is concluded that heating torso efficiently achieves thermal comfort, explaining vest type of EHG is widely commercially used.

Besides, studies on heating materials in garments are also conducted. It is found that graphene has promising electrical conductivity and thermal conductivity with less response time [16, 17]. Metallic nanowires (Ag, Cu, Ni compound etc.) have the capability of reflecting the radiation emitted by the human body, resulting in good thermal insulation [18, 19]. Although metal nanowires and graphene have great warming effect, materials preparation is yet complicated and expensive which in turn to limit their use within laboratory. On the contrary, carbon fiber is commercially used because of its easier manufacture process, high thermoelectric conversion efficiency, reliable tensile strength and durability [20]. Controlled by intelligent circuit, carbon fiber heating elements are divided into several pieces to uniformly and accurately warm the body, which results in wide use in business market.

With the great care for human health, the personal thermal management attracts an increasing attention. Although many studies have focused on the experimental warming effect and application of heating materials, the system performance and influencing factors of EHG is rarely studied. The numerical simulation is yet lack. However, numerical simulation is the most efficient method in engineering design for evaluating and optimizing the performance. Therefore, modeling and simulating the thermal transport of the EHG system is highly desired. It helps to investigate the impacting factors for EHG performance and human thermal comfort, in turn to guide the EHG manufacture and use suggestion.

In this work, the heat transfer model between human body, EHG and the external environment were established, and verified by experiments. The discrepancy between numerical simulation and the experiment was smaller than 0.3°C. Thermal resistance of EHG was calculated in different heat conductivities of the thermal insulation layer of EHG. Natural convection and radiative heat losses from EHG to environment were calculated and compared. An efficient arrangement of heating elements was suggested, which could raise the average temperature of skin under the heating elements (T₁) by 0.4-1.2°C compared with other arrangements. T₁ and the average temperature of the whole skin (T₂) were used as indicators to assess the heating performance of EHG. Linear dependence of the average temperature with respect to the environment temperature (noted as Tₐ), heating power of heating elements (noted as qₚ), metabolic heat flux of skin (noted as qₘ) were found. Based on temperature dependence, the optimal heating power under different cases were suggested to realize the thermal comfort for human body.

2. Thermal Transport Analysis of EHG

Human body has the ability to balance the body temperature in a normal range to avoid large fluctuation of the core temperature that is harmful to metabolism. The heat balance of the heat loss, heat production and the heat gain can be expressed as [12]:

\[ Q_{\text{body}} = (P + Q_{\text{m}}) - (Q_{\text{conv}} + Q_{\text{cond}} + Q_{\text{rad}} + Q_{\text{eva}} + Q_{\text{res}}) \]  

(1)

where \( Q_{\text{body}} \) is the heat storage of human body (W); \( P \) is the heat produced by extra heating elements (W); \( Q_{\text{m}} \) is the metabolic heat of human body (W); \( Q_{\text{conv}} \) is the conduction heat loss from the external surface of EHG to the environment (W), which can be neglected because of low heat conductivity of air (0.02617 W/(m·K)) and thermal insulation material (as low as 0.022 W/(m·K)) adopted by EHG; \( Q_{\text{rad}} \) is the heat loss by sweat evaporation (W), which can be neglected because sudation is limited by the low temperature in winter and little sweat can be absorbed by clothes; \( Q_{\text{evap}} \) is the heat loss of respiration (W), which can be neglected because respiration doesn’t affect the heat transfer process between EHG...
and environment and it is less than 5% of the total heat loss [21]; $Q_{\text{conv}}$ and $Q_{\text{rad}}$ are the heat loss by natural convection and radiation, respectively (W). When heat transfer among human body, clothes and environment reaches steady state, the heat released by human body and extra heat source equals to the heat released to environment, thus $Q_{\text{body}}=0$. Therefore, the heat balance equation can be simplified to:

$$P + Q_m = Q_{\text{conv}} + Q_{\text{rad}}$$

Figure 1. Network of heat transfer between skin, EHG and environment. Figure 1(a) shows the area with heating elements and Figure 1(b) shows the area without heating elements. In this figure, heat resistances, heat fluxes and temperatures in different parts are marked.

Based on the analysis above, a heat transfer network of a real EHG system is fabricated, as is shown in Figure 1. A thermal insulation layer with heating elements located in some areas of its inner surface composes EHG. The heat transfer network consists of two parts, and the first part contains heating elements while the another doesn’t. In the model, the inner cloth layer is not considered by hypothesizing clothing fitting skin snugly in actual situation, whereas the EHG is the outer cloth layer, which is direct exposure to air to tally with following experiments. It is assumed that there is no air gap in between the heating elements layer and the thermal insulation layer. And heating element is considered as a part of the internal surface of thermal insulation layer, so the thickness of heating element is neglected. Figure 1(a) shows the heat transfer across skin, EHG and environment with the existence of heating elements. Then system consists of skin, heating elements, insulation layer and environment, with the temperature labeled by $T_s$, $T_h$, $T_c$, $T_a$ (°C), respectively. Here, the thickness of heating elements is neglected. And it should be pointed out that $T_c$ represents the temperature of external surface of insulation layer. The heat supplied by heating elements transfers through two directions: (1) from heating elements to cold environment, including the thermal resistance of the thermal insulation layer ($R_c[°C/W]$), the natural convection thermal resistance ($R_{\text{conv}}[°C/W]$) and the radiation thermal resistance ($R_{\text{rad}}[°C/W]$). Here $q_h$ is the heating power of heating elements (W/m²) and $q_1$ is the heat flux from heating elements to the environment (W/m²). $q_{\text{rad}}$ and $q_{\text{conv}}$ represent the heat loss flux by natural convection and radiation respectively (W/m²). (2) from heating elements to skin. Considering the thinness and tightness of inner cloth, the temperature distribution of inner cloth and surface of skin is regarded as the same, thus there is only the thermal resistance due to the air ($R_s[°C/W]$) between heating elements and skin. Here $q_2$ is the heat flux released from heating elements to the human skin (W/m²). Figure 1(b) shows the heat transfer path across skin, EHG and environment without heating elements. $T_c'$ represents the temperature of the inner surface of EHG (°C). Different from Figure 1(a), heat transfers from human skin to environment passing through air shell and thermal insulation layer, and $q_m$ represents the metabolic heat flux from human skin (W/m²). And other symbols have the same meaning as in Figure 1(a).

The thermal transport analysis clarifies what kinds of heat transfer processes that need to be considered in the numerical simulation of EHG systems, including the heat conduction between skin and heating elements, the heat conduction between heating elements and thermal insulation layer, the natural convection and radiation between insulation layer and environment. In the following, the numerical
3. Numerical Simulation

Three-dimensional (3D) model for numerical simulation is established based on the theory model in Chapter 2 and it is shown in Figure 2. The heat transfer is considered between EHG and human torso and is overlooked for the four limbs parts which are considered as heat insulation surfaces. The establishment of torso model refers to Chinese national standard [22] for close to actual situation. The detailed parameters of torso model are listed in Table 1. A 10 mm layer cling to the manikin is generated to represent the EHG with a 1 mm air thin layer between skin and EHG. The heating elements are built by projecting rectangle with a length of 150 mm and a width of 70 mm on the inner surface of EHG. Five different areas are heated, located in lumbar, abdomen and upper back of body for thermal comfort consideration because heating these parts can significantly improve human’s thermal sensation in cold environment [23, 24]. The heating elements’ arrangement is shown in Figure 2.

| Table 1. The size of each part of human torso model. |
|-----------------------------------------------------|
| Part | Size (mm) |
|---|---|
| Bust | 970 |
| Waistline | 895 |
| Buttock circumference | 970 |
| Hight | 701 |
| Buttock width | 334 |
| Shoulder width | 403 |

| Table 2. The physical properties of materials used in the numerical simulation [25] |
|----------------------------------|
| Materials | Human body | Thermal Insulation layer |
|---|---|---|
| Density(ρ)/(kg/m^3) | 1098 | 20 |
| Heat capacity (Cp)/[J/(kg·K)] | 3088 | 1200 |
| Heat conductivity (k)/[W/(m·K)] | 0.475 | 0.022 |
| Emissivity (ε) | \ | 0.92 |

Figure 2. Diagrams of manikin model with human torso and EHG. (a)The human torso model (b) the sectional view of EHG model with five heating elements located in the lumbar (two), upper back (one) and the abdomen (two) of human torso. (c) The whole model established for our numerical simulation and the meshes distribution.

The numerical simulation was conducted using the 3D model above. The heat transfer processes of heat radiation, natural convection and conduction, as shown in Figure 1, are included in numerical simulation. Generally, thermal model of human torso can be equivalent to a cylinder because they have similar shapes [26]. The torso wrapped in EHG is considered as a cylinder with the height (H) of 0.7 m (the distance from neck to the waist of 3D model) and the diameter (D) of 0.3 m (dividing the volume of torso by height). The average heat transfer coefficient $h_{conv}$ [W/(m^2·°C)] of external surface of cylinder can be calculated as [27]:

$$h_{conv}=\text{Nu} \times \left(\frac{k}{H}\right) = \left(0.59R_a^{0.25} + 0.52 \frac{H}{D}\right) \times \left(\frac{k}{H}\right),$$  \hspace{1cm} (3)

where Nu is Nusselt number; $R_a$ is Rayleigh number measuring the intensity of buoyancy-drive flow;
k is the heat conductivity of air (W/(m·K)). $Ra$ is calculated as:

$$Ra = \frac{g \beta H^3 (T_e - T_a)}{\nu \alpha},$$  \hspace{1cm} (4)

where $\nu$ is the kinematic viscosity (N•s/m²); $\alpha$ is the thermal diffusion coefficient and $\beta$ is the coefficient of cubical expansion (1/°C). They are all the physical constants of air. $T_a$ is the temperature of the external surface of EHG (°C); $T_e$ is the temperature of environment (°C) and $g$ is the acceleration of gravity (m/s²). Both equation (3) and equation (4) are applied into natural convective heat transfer calculation. Radiative heat transfer coefficient is given below [28]:

$$h_{rad} = 5.67 \times 10^{-8} \times \varepsilon \times \left( \frac{(T_e + 273.15)^4 - (T_a + 273.15)^4}{T_e - T_a} \right),$$  \hspace{1cm} (5)

where $\varepsilon$ is the emissivity of outer fabric of EHG. The parameters of materials used in simulation are listed in Table 2. Some parameters, such as the power of heating elements, the heat conductivity of thermal insulation layer, metabolic heat flux and the temperature of environment, are changeable when they become research objects. To ensure the calculation accurate, tinier grids were meshed in the heating elements zone. Moreover, the grid independence was checked. The average temperature of the entire skin was calculated with the grids number of 240805, 589474, 718487, 1119781, 1968745, and 3118831. The results converge with discrepancy within 0.5% compared with the results of the maximum meshes. Therefore, the grid of 589474 was used in the numerical simulations herein.

4. Experiments

The experiment was conducted in a chamber with 6×9×3 m, and the environment temperature is consistent around 6°C, without wind. Two volunteers with body mass index (BMI) of 19.5 and 21.2 were hired to wear EHG for 3 times tests for each person. Volunteers were required to wear the same clothes. Before experiment, volunteers took same meals and then had a rest for 3 hours in our chamber until the skin’s temperature was stable to make sure that their metabolism was stable. EHG, made of 10 mm thick thermal insulation layer with heat conductivity ($\lambda$) of 0.022 W/(m·K), is shown as Figure 3(a). Heating elements, composed of carbon fiber electrical wires enveloped by fabric, are sewn on the inner surface of EHG and the arrangement of heating elements is shown in Figure 2 (b). The rated voltage of heating elements is 7.4 V and they have three working gears, namely low, middle and high gears. The heating power of three working gears is 2.9 W, 4.5 W and 4.8 W, respectively. Thermocouples, date collector and computer are used to record temperature and the measurement accuracy of thermocouples is ±0.1°C. The arrangement of thermocouples is displayed in Figure 3(b), and five thermocouples are placed on abdomen(two), upper back(one) and lumber(two) to measure the local skin temperature with every thermocouple being placed underneath the center point of heating element. $T_i$, $T_j$, $T_k$, $T_m$ and $T_n$ are the temperature values of the five thermocouples (°C). The sixth thermocouple was exposed to ambient to measure environment temperature, $T_a$[°C]. EHG was connected with portable mobile power with output voltage of 7.4 V. All the experiments were conducted by the same procedure, but the duration of each gear varies slightly due to manual switching, and the initial temperature of human skin is a little different. Nonetheless, the variation trend of the skin temperature in each experiment is quite similar. Therefore, we chose one experiment situation to do the simulation, and compare with the results. The experiment procedure diagram is shown in Figure 3(c). Volunteers with EHG kept sitting until metabolism and skin temperature became stable. Then, the low gear was turned on for 29.5 minutes, and was switched to middle gear for 27 minutes and followed by high gear for 35 minutes. Temperature data was recorded continuously by collector and computer during experiment.
5. Results and Discussion

5.1 Verification of the Heat Transfer Model

Numerical simulations and experiments are compared for verifying the reasonability of the simplification of heat transfer processes. Like the experiments, working durations of three gears are distributed as 29.5, 27 and 35 minutes and the total heating powers of three gears are set to be 2.9, 4.5 and 4.8 W which are measured in experiments. The metabolic heat flux ($q_m$) for different activities have been reported based on experiments conducted with adult subjects and has been widely used as standards [29-32]. After a long-time rest, for volunteers in sedentary state, the metabolic heat flux is 58 W/m², which is commonly used in the situations of a seated person at rest [12, 30]. The initial temperature of the simulation is set to be 35.1°C according to the experiment.

Figure 4 shows the comparison of the temperatures under heat element of simulation and experiment with different gears. In experiment,

$$T_1 = \frac{T_{T1} + T_j + T_k + T_m + T_n}{5},$$

where $T_{T1}$ is the environment temperature ($T_a$) between simulation and experiment at different gears. As figure shows, the difference between experiment and simulation is small.

Figure 3. (a) Schematic diagram of experiment with the EHG being designed as a jacket, (b) position of thermocouples, and (c) experiment procedures with every modes’ running time displayed.

Figure 4. Comparation of $T_1$ in the same environment temperature ($T_a$) between simulation and experiment at different gears. As figure shows, the difference between experiment and simulation is small.
and in simulation

\[ T_1 = \frac{\int_{S_1} T_i \, dS}{S_1}, \quad (7) \]

where \( S_1 \) represents heating elements area of the skin and \( T_i \) is the temperature of a dot on \( S_1 \). It can be seen that the environment temperature only fluctuates slightly around 6°C, in consistent with the simulation. Because of the temperature fluctuation of human skin, the experimental temperature distribution exists ups and downs as a function of time; thus, we average the temperature in each duration. The average temperature of the skin under heating elements (\( T_1 \)) rise from initial 35.1°C to 36.7°C when the low gear is turned on. Once switching to middle gear, \( T_1 \) rises to 37.9°C, while \( T_1 \) increases to 38.9°C at high gear. By contrast, temperature rises smoothly during every gear in simulation. In simulation, \( T_1 \) rise from initial 35.0°C to 36.5°C with the low gear on, and to 38.2°C and 39.2°C at middle and high gears, respectively. In the initial stage of simulation, \( T_1 \) has a large fluctuation since the iteration is not converged, which disappears as calculation moves forward. In both experiment and simulation, \( T_1 \) goes through a steep rise after turning up the heating gear and goes through a sharp decline after turning off the heating in EHG. The temperature-time curves of experiments and simulations are in reasonable agreement. Quantitatively speaking, the discrepancy of the average temperature of the skin in simulation and experiment at different gears is smaller than 0.3°C. Therefore, it is justified that the heat transfer model is fairly good to characterize the heat transfer situation of EHG systems.

5.2 Thermal Analysis of EHG

In this section, we mainly explore the heat loss of EHG and the total thermal resistance of EHG from inner surface of thermal insulation layer to environment, i.e., \( R_{\text{tot}}[^{\circ}C/W] \), which is highly dependent on the material of the thermal insulation layer. Thus, the relationship between thermal resistance and the heat conductivity of insulation layer is explored by simulation. From the heat transfer network (Figure 1(a)), \( R_{\text{tot}} \) can be expressed as:

\[ R_{\text{m}} = \frac{T_h - T_a}{q_1}, \quad (8) \]

where \( T_h \) and \( T_a \) are the temperatures of heating element and the environment, respectively, and \( q_1 \) is the heat flux from heating elements to environment. However, in Figure 1(b), \( R_{\text{tot}} \) can be expressed as:

\[ R_{\text{tot}} = \frac{T_c' - T_a}{q_m}, \quad (9) \]

where \( T_c' \) is the temperature of the inner surface of thermal insulation layer (°C) and \( q_m \) is the metabolic heat flux from human skin. So, the average total thermal resistance of EHG (°C/W) can be calculated as:

\[ R_{\text{tot}} = \frac{\int_{S_h} \frac{T_h - T_a}{q_1} \, dS + \int_{S_n} \frac{T_c' - T_a}{q_m} \, dS}{S_h + S_n}, \quad (10) \]

where \( S_h \) is the heating elements area on the inner surface of EHG and \( S_n \) represents the area where no heating elements exist. Figure 5 shows the relation between \( R_{\text{tot}} \) and the heat conductivity of the thermal insulation layer calculated by equation (10). Results display that \( R_{\text{tot}} \) increases with the decrease of heat conductivity of insulation layer, and the increase rate becomes slightly faster. Quantitatively speaking, \( R_{\text{tot}} \) increases from 0.420 to 0.670 K·m²/W when the heat conductivity of thermal insulation layer decreases from 0.034 to 0.018 W/(m·K). Since the thermal resistance has great effect in preventing heat waste of heating element to environment, it is necessary to adopt low heat conductivity material for EHG. Furthermore, the values of natural convection heat loss and the radiative heat loss are calculated under different environment temperature. According to Figure 1(a) and Figure 1(b), when calculating the heat loss by the two methods, calculating expressions can be given as:

\[ Q_{\text{conv}} = \int_{S_e} q_{\text{conv}} \, dS \quad (11) \]
\[
Q_{\text{rad}} = \int_{S_e} q_{\text{rad}} \, dS
\]

where \( S_e \) is the external surface of EHG. As is shown in Figure 6, the total heat production equals to total heat loss, which is about 37.9 W when \( \lambda \), \( q_m \) and \( q_b \) are set to be 0.025 W/(m·K), 58 W/m² and 40 W/m², respectively. What’s more, even though environment temperature varies, the proportion of radiative heat loss is always larger than that of natural convection heat loss. With heat radiation becoming dominant in the heat loss of EHG, an effective way of enhancing the warming capacity of EHG lies in applying low emissivity materials to the external surface of EHG.

\[Q_{\text{rad}} = \int_{S_e} q_{\text{rad}} \, dS\]  \tag{12}

5.3 Skin Temperature under Different Conditions

The average temperature of human skin is of great importance in the entire body comfort sensation [33] and is commonly used as a criterion for the appraisal of thermal comfort [34 – 36]. Many previous studies revealed that the relationship between average temperature of skin and thermal comfort sensation was linear [37 - 40]. Wang et al. [39] proposed the linear function (TSV=0.6108×T²-20.155, where TSV is the index reflecting the sensation and T² [°C] is the average temperature of skin) of thermal comfort sensation related to the average temperature of skin, from which we could calculate T² to be 33°C when neutral thermal comfort sensation was reached with TSV=0. And this result was confirmed by other studies [38,40]. Meanwhile, the temperature of the skin underneath heating elements should be also taken into consideration because improper heating power could cause local over-heating or over-cooling problems. Two temperature values are defined, which are vital indexes to estimate the thermal comfort: average temperature of the skin under heating elements (T₁) and average temperature of entire skin of torso (T₂) are calculated. T₁ can be calculated by equation (7) and T₂ are calculated from:

\[
T_2 = \frac{\iiint_{S_2} T dS}{S_2}, \tag{13}
\]

where \( S_2 \) represents the whole torso skin area; \( T_1 \) is the temperature of a dot on \( S_2 \) (°C).
Figure 7. Variation of $T_1$ and $T_2$ at different (a) heat conductivities of EHG, (b) heating power of heating elements, (c) environment temperatures, and (d) metabolic heat flux of human skin. And the linear relations between temperatures ($T_1$ and $T_2$) and $T_a$, $q_h$ and $q_m$ are found. The variation of $T_1$ and $T_2$ at different parameters of EHG are studied by control variate method. Figure 7 shows the $T_1$ and $T_2$ dependence on heat conductivity of thermal insulation layer ($\lambda$), environment temperature ($T_a$), the heating power of heating elements ($q_h$), metabolic heat flux of skin ($q_m$). It is found that $T_1$ and $T_2$ have nonlinear dependence on $\lambda$. As the decrease of $\lambda$, the increase rates of $T_1$ and $T_2$ are enlarged, in consistent with the increase of thermal conductivity between the heating elements and environment, as shown in Figure 5. $T_1$ or $T_2$ are linearly increased by $q_h$. When $q_h$ increases by 10 W/m$^2$, $T_1$ increases 1.3°C and $T_2$ increases 0.48°C. Although the high power can give high $T_1$ and $T_2$, it probably causes overheating and shorten the work duration. The linear dependence on $q_h$ would be used to design the selection of controlling gears of EHG. Figure 7(c) shows the trend of $T_1$ or $T_2$ when environment temperature is changed. $T_1$ and $T_2$ are also linearly increased with $T_a$ and $q_m$. The increase amplitudes of $T_1$ and $T_2$ are the same. When $T_a$ increases 10°C or $q_m$ increases 10 W/m$^2$, $T_1$ and $T_2$ increase about 9.5°C and 5.0°C, respectively. All the results show that skin temperatures ($T_1$ and $T_2$) are highly sensitive to $\lambda$, $q_h$, $T_a$ and $q_m$, so all these parameters should be considered when designing EHG. That’s to say, when several parameters are given, the others should be carefully decided.

Figure 8. The effect of $T_1$’s range and $T_2$’s range on the selection of the power of heating elements ($q_h$). (a) a person is in the state of resting (b) a person is in the state of mild activity. As is shown above, the linear relationship between $T_1$ or $T_2$ and $q_h$ has been confirmed. In cold environment and low metabolic intensities, skin temperatures reach a low point and EHG with good thermal insulation and suitable heating power is necessary. Here, a method for the quick design of EHG is proposed and a typical situation is studied when $\lambda$ and $T_a$ are set to be 0.022 W/(m·K) and -5°C. In
order to choose appropriate heating power \((q_h)\) for low activity intensities, we set \(q_h\) to be 58 W/m\(^2\) (corresponding with resting state) and 72 W/m\(^2\) \[33\], which means a person does light work with resting for two thirds of the time, respectively. When study the activity intensity of 58 W/m\(^2\), \(q_h\) is set to be 15, 35, 55, 75, 95 and 115 W/m\(^2\) to study the variation of \(T_1\) and \(T_2\). As Figure 8(a) shows, the linear fitted curve of \(T_1-q_h\) and \(T_2-q_h\) are given as:

\[
\begin{align*}
T_1 &= 0.1407q_h + 28.457 \quad (14) \\
T_2 &= 0.0532q_h + 28.112 \quad (15)
\end{align*}
\]

It is a fact that a person feels most comfortable when the average temperature of skin is 33°C \[38-40\]. Therefore, in this study, thermal comfortable scope of average temperature of skin is defined from 32°C to 34°C. Solving equation (14), the optimal \(q_h\) is found to range from 73.1 W/m\(^2\) to 110.7 W/m\(^2\). Furthermore, the temperature of skin under heating elements shouldn’t be so high, otherwise human may feel so hot. Therefore, we define the temperature of skin under heating elements lower than 42°C in this method for safety consideration. Equation (15) is solved and result shows that \(q_h\) should be lower than 96.3 W/m\(^2\). In conclusion, the heating flux of heating elements should range from 73.1 W/m\(^2\) to 96.3 W/m\(^2\) to maintain thermal comfort when human is in resting state. When human’s activity intensity reaches 72 W/m\(^2\), \(q_h\) is set to be 0, 5, 25, 45, 65 and 85 W/m\(^2\) to find another range of heating power for this situation. According to Figure 8(b), the linear fitted curve of \(T_1-q_h\) and \(T_1-q_h\) are given as:

\[
\begin{align*}
T_1 &= 0.1404q_h + 31.808 \quad (16) \\
T_2 &= 0.0530q_h + 31.429 \quad (17)
\end{align*}
\]

With defining average temperature of skin \((T_2)\) from 32°C to 34°C and the temperature of skin under heating elements \((T_1)\) lower than 42°C for safety consideration, we calculate the scope of the heating power of heating elements and that is 10.8 W/m\(^2\) to 48.5 W/m\(^2\). According to the analysis above, a kind of thermal comfortable EHG should have two gears with heating power of 10.8 W/m\(^2\) - 48.5 W/m\(^2\) for low gear and heating power of 73.1 W/m\(^2\) - 96.3 W/m\(^2\) for high gear to maintain thermal comfort in different situations. What’s more, this method for EHG design can be applied to other cases with different environment temperatures, different customer’s requirements and different cloth materials.

5.4 Effect of Arrangement of Heating Elements
The simulation allows convenient pre-research for performance of EHG under different design. Different arrangements of heating elements probability result in different skin temperature even though with the same heating power. Since the temperature of skin is linear dependence of heating power, an efficient arrangement leading to high skin temperature suggests low energy cost and long working time. Here, six sets of arrangement of heating element are studied, as shown in Figure 9. All of heating elements in the six cases are still located around some areas on human skin (chest, lumbar, upper back or abdomen), where overall thermal sensation can be improved by local heating \[23, 24\]. The parameters of \(\lambda\), \(T_s\), \(q_m\) and \(q_h\) are set to be 0.025 W/(m·K), 0°C, 58 W/m\(^2\) and 40 W/m\(^2\), respectively. The size of heating elements remains constant in six different arrangements. Figure 9 shows that type (b) has the highest \(T_1\), which is about 0.4°C larger than type (a) and nearly 1.2°C larger than other types. In conclusion, type (b) can result in the highest local temperature for satisfying the temperature requirement of the most demanding part of human body.
Figure 9. The sectional view about six arrangement methods of heating elements and the average temperature of the skin under heating elements. In every figure (a-f), The left one shows the back position of human torso and the right one shows the front position of human torso.

6. Conclusion

This study introduced a simple and practicable heat transfer model for EHG. From the theoretical analysis, the heat transfer process of human body, EHG and environment system were simplified, with the heat conduction between human body and EHG, natural convection between EHG and environment and radiation between EHG and environment necessarily considered. The heat transfer model was fairly accurate, verified by the comparison of numerical simulation and experiments, with the discrepancy of skin temperature smaller than 0.3°C. Thermal resistance of EHG and skin temperatures were selected as thermal indicators to assess the performance of EHG. According to calculation results, a nonlinear relationship exists between the total thermal resistance of EHG and the thermal conductivity of the thermal insulation layer of EHG. In addition, the effect of heat conductivity, heating power of heating elements, metabolic flux of human, and environment temperature on the average temperature of the skin under heating elements (T₁) and the average temperature of the whole skin (T₂) were investigated. What’s more, A method of searching for optimal heating power of heating elements was proposed based on the linear relationship between skin temperature and the heating power of heating elements. It was found that the power should range from 73.1 W/m² - 110.7 W/m² for high heating gear and 10.8 W/m² - 48.5 W/m² for low heating gear to make sure the comfortable skin temperature within 32-34°C, under different activities when environment temperature is -5°C. What’s more, the relationship between the arrangements of heating elements and T₁ was also explored. The T₁ was increased as many as 0.4-1.2°C after optimization of arrangements. According to specific environment and different usages, EHG can be customized by using this heat transfer model, which is helpful for the quick design of EHG. In conclusion, this work comprehensively considered all the influencing factors in EHG design by numerical simulation methods and can give useful introductions to the customization of EHG.

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