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Development of a thermal physiological model to analyze the effect of local radiant heaters in electric vehicles †

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Abstract

In the global effort to reduce CO_2 emissions and mitigate climate change, there is significant interest in replacing internal combustion engine vehicles with electric vehicles. Furthermore, the use of radiant heaters rather than conventional air conditioning systems may reduce the energy consumption in electric vehicles. In this work, a thermal physiology model that includes the effect of local radiant heaters was developed to predict the temperature change in a human body in a cold or warm environment. The developed model indicated an increase in the mean skin temperature when radiant heaters were used in a cold environment. Local and overall thermal sensation and thermal comfort predicted from simulation showed an escalation in the sensation and comfort, thereby suggesting an improvement in passenger comfort with the addition of local radiant heaters. This study might contribute to effective energy saving strategies and passenger comfort in electric vehicles.

Keywords: Electric vehicle; Thermal physiology; Radiant heaters; View factor; Skin temperature

1. Introduction

There is significant interest in the use of electric vehicles (EVs) rather than internal combustion engine vehicles (ICEVs) to reduce CO_2 emissions and mitigate the effects of global warming [1]. Heating and air conditioning are essential subsystems in vehicles that maintain cabin comfort levels. Whereas ICEVs use waste heat from the engine to cool and heat the vehicle cabin, engine waste heat in EVs is insufficient and therefore additional electrical energy is necessary to power these systems, which can considerably impact driving mileage [2, 3]. In fact, air conditioning and heating account for 33 % of EV energy losses; additionally, 27 % is attributed to rolling resistance, 25 % to electric and mechanical losses, and 15 % to air resistance and other sources [3, 4]. Therefore, efficient design of these subsystems is essential for increasing the mileage range of EVs, especially the heating subsystem, which consumes more energy than does its cooling counterpart.

Radiant heaters placed on the wall of the vehicle cabin interior may offer a solution to reduce heating energy consumption. Since there is no need to heat the whole interior of the vehicle, the energy consumption is reduced and the passengers feel an increased heating effect due to radiation heat transfer characteristics. A radiant heater is expected to reduce the maximum energy consumption of the vehicle to 50 %. However, the radiant heater alone may not meet the heating demand of the vehicle, hence a combined infrared and convective heating system could be more appropriate [5].

The use of thermal comfort modeling of the vehicle cabin environment is essential in evaluating the effect of local radiant heating [6]. Several researchers have reported the development of thermal comfort models used to address local thermal sensation, each of which has advantages, limitations, and suitable application ranges [7]. Human thermoregulation modeling is a two-stage process that includes a physiological model to determine the temperature distribution in the human body and a psychological model to predict the thermal sensation and comfort, as detailed in Fig. 1. The physiological model is a controlled passive system and includes the physical human body and heat transfer phenomena in and around the human body [8]. Psychological modeling is a controlling active system that can predict regulatory responses, such as peripheral vasomotion, sweating, and shivering [9], and can calculate the temperature distribution throughout the body by applying heat transfer and energy balance to each body part.

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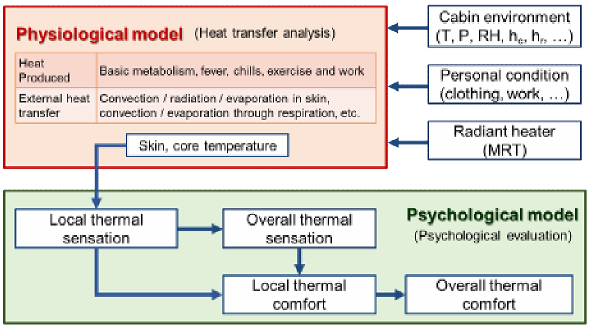


Fig. 1. The human thermoregulation modeling process.

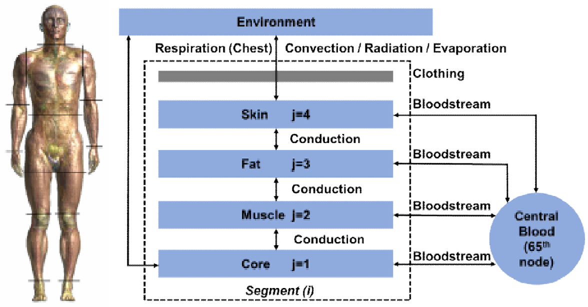


Fig. 2. Body segmentation based on Tanabe physiology model.

The psychological model is based on the feeling of temperature in the human body and is obtained by surveying an individual's preference for sensation and comfort and interpreting the response result and body temperature as a correlation or functional form. This is influenced by various body characteristics such as the sex, age, constitution, and race of the respondents, which also influences the scale, experiment proficiency, and experience of sensation and comfort.

Several models have been developed to estimate the physiological and psychological effects of heat or cold on the human body. One of the earliest physiological and psychological models were created by Gagge et al. [10] and Fanger [11], respectively. Gagge's physiological model considered the entire body as a cylindrical segment composed of a core and a skin layer. Fanger's psychological model was based on the evaluation of thermal comfort through a predicted mean vote and predicted percent dissatisfied. Both of these models have been widely used to assess the thermal comfort of occupants in buildings and were the basis for the ASHRAE Handbook. Later, Stolwijk [12] developed a multi-segment model in which the head modeled as a sphere and the body was divided into five cylinders. Each segment was further divided into four layers, including the core, muscle, fat, and skin. Stolwijk also presented a thermal model of the active system suitable for body temperature regulation in physiological models.

Based on the Stolwijk model, Tanabe further subdivided the body parts [13, 14]; this model was then further improved and is commonly referred to as the University of California Berkeley (UCB) model [15]. Alternatively, Fiala et al. [8] divided the body into 15 segments and identified the nodes in the circumferential direction in the cylindrical segments. Unlike the Stolwijk model, a thermal model for the active system was also developed separately [9]. Both the UCB and Fiala model are suitable because they involve a multi-segment model dividing the body into several parts to observe local heating effects caused by a radiation heater. A psychological model involving multiple segments was modeled effectively by Zhang [16-18]. Zhang had 109 subjects complete a questionnaire involving nine questions on thermal sensation and six questions on thermal comfort to which they responded in the range of −4 (very cold/very uncomfortable) to +4 (very hot/very uncomfortable), with 0 indicating neutral/comfortable.

This study aims at developing a thermal physiological model for the human body near to radiant heaters and analyzing the effect of local heating by the heaters. We developed the model by incorporating calculation of the mean radiant temperature into the UCB model for thermal comfort. The results of the model are presented in relation to the mean skin temperature. The effect of local radiant heating on human body is determined by predicting the local and overall thermal sensation and thermal comfort. Through this study, we realized that the UCB psychological model needs to be improved for considering the local radiant heater more suitably.

2. Materials and methods

An in-house developed MATLAB program was used to calculate the thermophysical characteristics of the human body based on the Tanabe model [14].

2.1 Thermophysical modeling

A model considering the influence of a radiator on human physiology was developed to predict the temperature distribution of the skin and core body temperature. As detailed in the Tanabe model, the body was divided into 16 segments: Head, chest, back, pelvis, and two each of the shoulders, arms, hands, thighs, legs, and feet. Each segment was then divided into four layers to create 64 nodes; including a single pool of blood flow brought the total number of nodes to 65. The body segmentation process used in the UCB physiological model is illustrated in Fig. 2. The governing equations for the calculation of temperature distribution are [14]:

Core layer:

$$C(i,1)\frac{dT(i,1)}{dt} = Q(i,1) - B(i,1) - D(i,1) - RES(i,1)\,. \quad (1)$$

Muscle layer:

$$C(i,2)\frac{dT(i,2)}{dt} = Q(i,2) - B(i,2) + D(i,1) - D(i,2)\,. \quad (2)$$

Fat layer:

$$C(i,3)\frac{dT(i,3)}{dt} = Q(i,3) - B(i,3) + D(i,2) - D(i,3)\,. \quad (3)$$

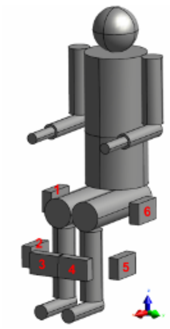


Fig. 3. 3D cylindrical segmented human model with local radiant heaters for view factor calculation.

Skin layer:

$$C(i,4)\frac{dT(i,4)}{dt}=Q(i,4)-B(i,4)+D(i,3)-Q_t(i,4)-E(i,4)\,. \quad (4)$$

Central blood:

$$C(65)\frac{dT(65)}{dt}=\sum_{i=1}^{16}\sum_{j=1}^{4}B(i,j) \quad (5)$$

where *C (i, j)* is the heat capacity of node *(i, j)* and *T (i, j)* is its temperature, *Q (i, j)* is the rate of heat production, *B(i, j)* is the heat exchanged between each node and the central blood compartment, *D (i, j)* is the heat transmitted by conduction to the neighboring layer within the same segment, *RES (i,* 1*)* is the heat loss by respiration, Q_t *(i,* 4*)* is the convective and radiant heat exchange rate between the skin's surface and environment, and *E (i,* 4*)* is the evaporative heat loss at the skin's surface.

Considering the interior space available in the car, six radiators 15 cm x 10 cm were placed around the body as shown in Fig. 3. Heaters 1 and 2 were placed 7 cm from the right thigh and right leg, heaters 3 and 4 were placed 9 cm from the front right and left leg, and heaters 5 and 6 were placed 8 cm from the left leg and thigh. The effect of the radiant heater was expressed in the human body heat transfer model through the mean radiant temperature (MRT). The MRT was defined as the uniform temperature in the virtual closed space where the human body could receive the same amount of radiant heat from the surroundings and was calculated as:

$$\overline{T_{i,r}^4}=T_1^4F_{i-1}+T_2^4F_{i-2}+\cdots+T_N^4F_{i-N} \quad (6)$$

where $\overline{T_{i,r}^4}$, T_N and F_{i-N} represent the mean radiation temperature, the N^{th} surface temperature, and the view factor between the i^{th} segment and the N^{th} surface, respectively, in the i^{th} segment. All surfaces were to be blackbodies and the indoor surface temperature was assumed uniform, except the radiation heater. The view factor, which refers to the ratio of the energy from one side of a space to the other and forms a certain geometric arrangement, was calculated between the individual radiator and each human segment using the simulation software COMSOL Multiphysics. The governing equation used for calculating the view factor was:

$$F_{1\to 2}=\frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}dA_2dA_1 \quad (7)$$

where A_1 and A_2 are two general surfaces, s is the distance, and θ_1 and θ_2 represent the angles between the surface normal and a ray between the two differential areas dA_1 and dA_2, respectively.

The determined average radiation temperature was then used instead of the external surface temperature in the skin and external radiative heat transfer calculations in the human physiology model.

2.2 Thermal sensation and thermal comfort modeling

The psychological effect of local radiant heaters was then determined based on the local and overall thermal sensation and thermal comfort, which were calculated using the UCB model [16-18]. The local and overall thermal sensation and thermal comfort were primarily determined using the average skin temperature from the thermal physiological model. Skin temperature change will alter the thermal sensation and thermal comfort characteristics.

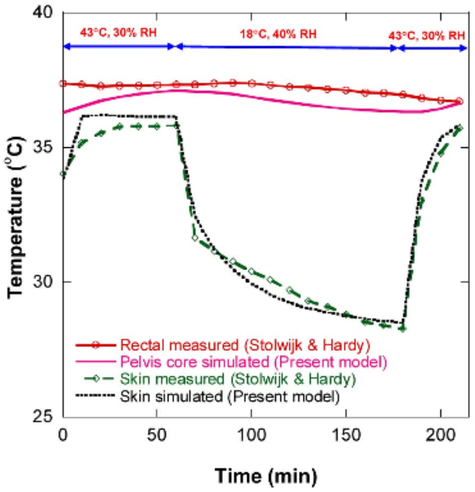
2.3 Simulation scenario

The time-dependent environmental conditions used included a surrounding temperature of between −5 °C and 25 °C with a relative humidity of 20 % for 1 hour. The initial temperature of all body segments were set as that of the UCB model. A surface temperature of 90 °C was set for all heaters used. The heater temperature of 90 °C is the maximum value under safety limit. Therefore, the presented results reflect the largest effects of heater temperature. Simulations were performed with and without the heaters to determine the effect of localized radiant heating.

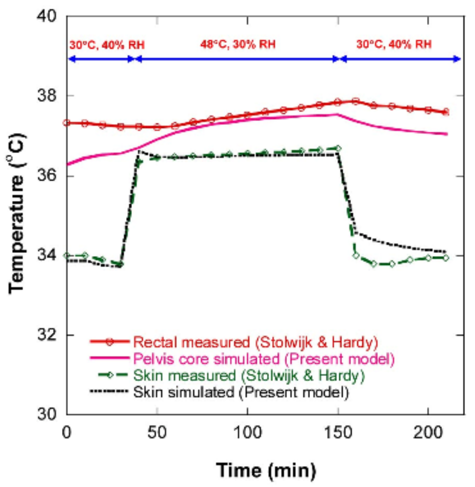
3. Results and discussion

3.1 Numerical validation

The developed model was validated by performing simulations results under similar environmental conditions as those used by Stolwijk and Hardy and comparing the results [19]; the results under two environmental conditions (cold and hot), which showed good agreement, are shown in Fig. 4. A total duration of 3.5 h was assumed for both simulation cases. For case 1, the temperature and relative humidity, respectively, were considered as 43 °C and 30 % for the first 1 h, 17 °C and 40 % for the next 2 hr, and 43 °C and 30 % for last 30 min, as depicted in Fig. 4(a). For case 2, they were considered as 30 °C and 40 % for the first 1 h, 48 °C and 30 % for the next 2 h, and 30 °C and 40 % for last 30 min, as shown in Fig. 4(b). In both cases, the pelvis core, skin, and rectal temperature

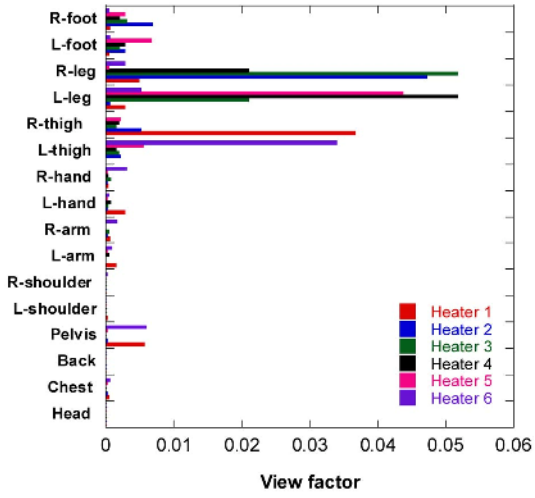


(a)

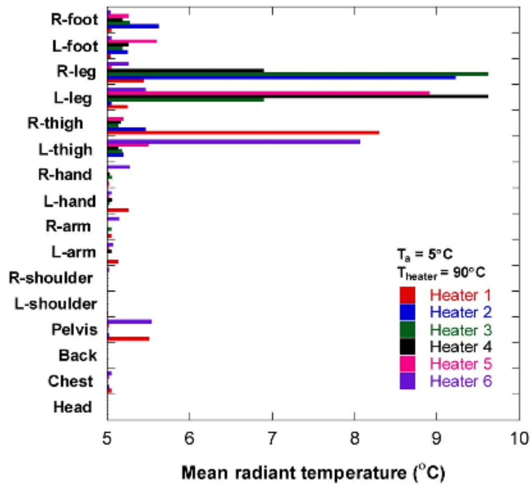


(b)

Fig. 4. Numerical validation of core and skin temperature with present and previous studies: (a) Case 1; (b) case 2.



(a)



(b)

Fig. 5. (a) View factor calculation of each body part; (b) MRT of each body part.

changes were predicted within 1 °C from previous results, thereby providing numerical validation.

3.2 Effect of local radiant heating

The view factor and corresponding MRT calculated as per the location of radiant heaters in Fig. 3 are presented in Figs. 5(a) and (b), respectively. A large variation in view factor was seen when heaters were placed near the leg and thigh regions. As shown in Fig. 5(a), high view factors were obtained for the leg and thigh regions, due to their proximity to the heaters. The heaters located in front of the leg (i.e., heaters 3 and 4) provided the highest view factor of around 0.05; the heaters located next to the leg (heaters 2 and 5) and the thigh (heaters 1 and 6) provided view factors of approximately 0.04 and 0.03, respectively, indicating that using a combination of heaters may improve overall skin temperature.

These calculated view factors were then used to calculate the MRT on individual body parts shown in Fig. 5(b). Setting the heater surface temperature to 90 °C increased the MRT on the left and right legs 6 °C above the surface room temperature of 5 °C due to heaters 2, 3, 4 and 5. Heaters 1 and 6 raised the average radiation temperature of the thigh to at least 9 °C. As the MRT rise was insignificant in body parts other than the legs and thigh regions, the local radiative heating effect of the radiator was confirmed. Thus, even when a heater is used, the average radiation temperature may be lower than the human body temperature, causing heat loss from the human body to the surrounding area. Since the radiator alone cannot heat the entire vehicle, a hypothetical scenario was designed in which a heat pump simultaneously operates so that the interior temperature gradually rises from −10 °C to 25 °C in one hour. MRT will also varies with the heater surface temperature and ambient conditions hence variation of these can also be considered.

The resulting change of the average skin temperature over

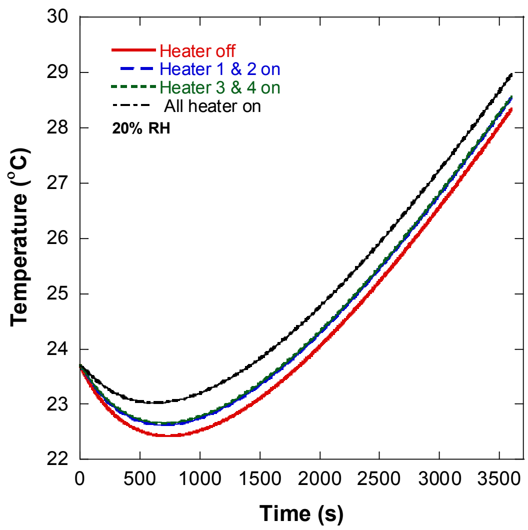


Fig. 6. Average change of skin temperature with different combinations of radiant heaters.

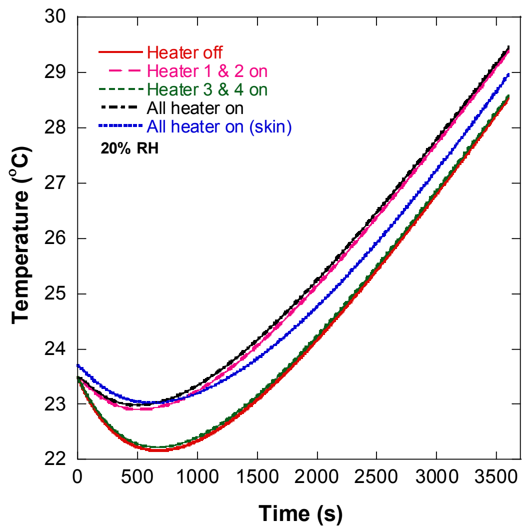


Fig. 7. The temperature increase at right thigh with different combinations of radiant heaters.

time is shown in Fig. 6. As the heating effect by the heat pump was initially weak in the −10 °C interior, the skin temperature decreased; as the room temperature rose it will affect the skin temperature. The skin temperature rose an average of 0.7 to 0.8 °C when all six heaters were in use. A similar effect was seen when only heaters 1, 2, 3 and 4 were in use. The radiant heater's local heating effect was concentrated in the legs and thigh region; a negligible effect was seen on the rest of the body, as shown in Fig. 5(b). The effect of the increase in average skin temperature was limited, as the weight of the skin of legs and thighs is about 1/3 of that of the whole body.

The resulting temperature change in the right thigh region is shown in Fig. 7. For closer inspection of the effects of heater placement, various combination of heaters were used: 1 and 2, 3 and 4 and 2 and 5. Heaters 1 and 2 provided a greater warming effect than 3 and 4, and the use of only heaters 1 and 2 provided a similar heating effect as when all heaters were used. The resulting temperature change in the right leg region when heaters 2 and 5 or 3 and 4 were used is shown in Fig. 8. The use of heaters 3 and 4, located at the front leg region, provided more warming than when 2 and 5 were used, but provided less warming than when all heaters were used. Figs. 7 and 8 also compares the average skin temperature increase with all heaters turned on in the thigh and leg regions. The temperature increase was found in between the other cases which shows there is an increase in whole body temperature when local radiant heaters are used.

A combination of heaters in the thigh/leg and front positions may therefore be more suitable for effective localized heating. Radiative heaters thus can increase the skin temperature more quickly. Heaters in use showed a maximum rise of about 1 °C in the thighs and 3.5 °C in the legs. Overall, using a radiant heater provided a direct rise in skin temperature without any fall period and allowed the leg skin temperature to reach 25 °C in approximately 20 minutes, which is a significantly very good time period in passenger vehicles. Hence, local radiant heaters can provide passengers an early comfort zone compared to conventional heating systems.

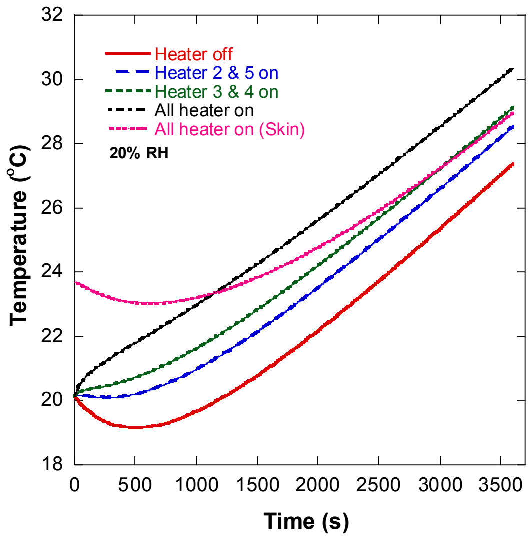


Fig. 8. The temperature increase at right leg with different combinations of radiant heaters.

The thermal sensation effect of passengers with and without local radiant heaters is shown in Fig. 9, where the local thermal sensation effect in Fig. 9(a) depicts increases in the leg and thigh region when the corresponding radiant heaters are in use, causing an increase in overall thermal sensation as displayed in Fig. 9(b). Similarly, the thermal comfort also increased when the radiators were turned on. A greater local thermal comfort increase was seen in the leg region than the thigh region, as illustrated in Fig. 9(c), which in turn improved the overall thermal comfort, as shown in Fig. 9(d). The higher local thermal sensation and comfort in the leg region was

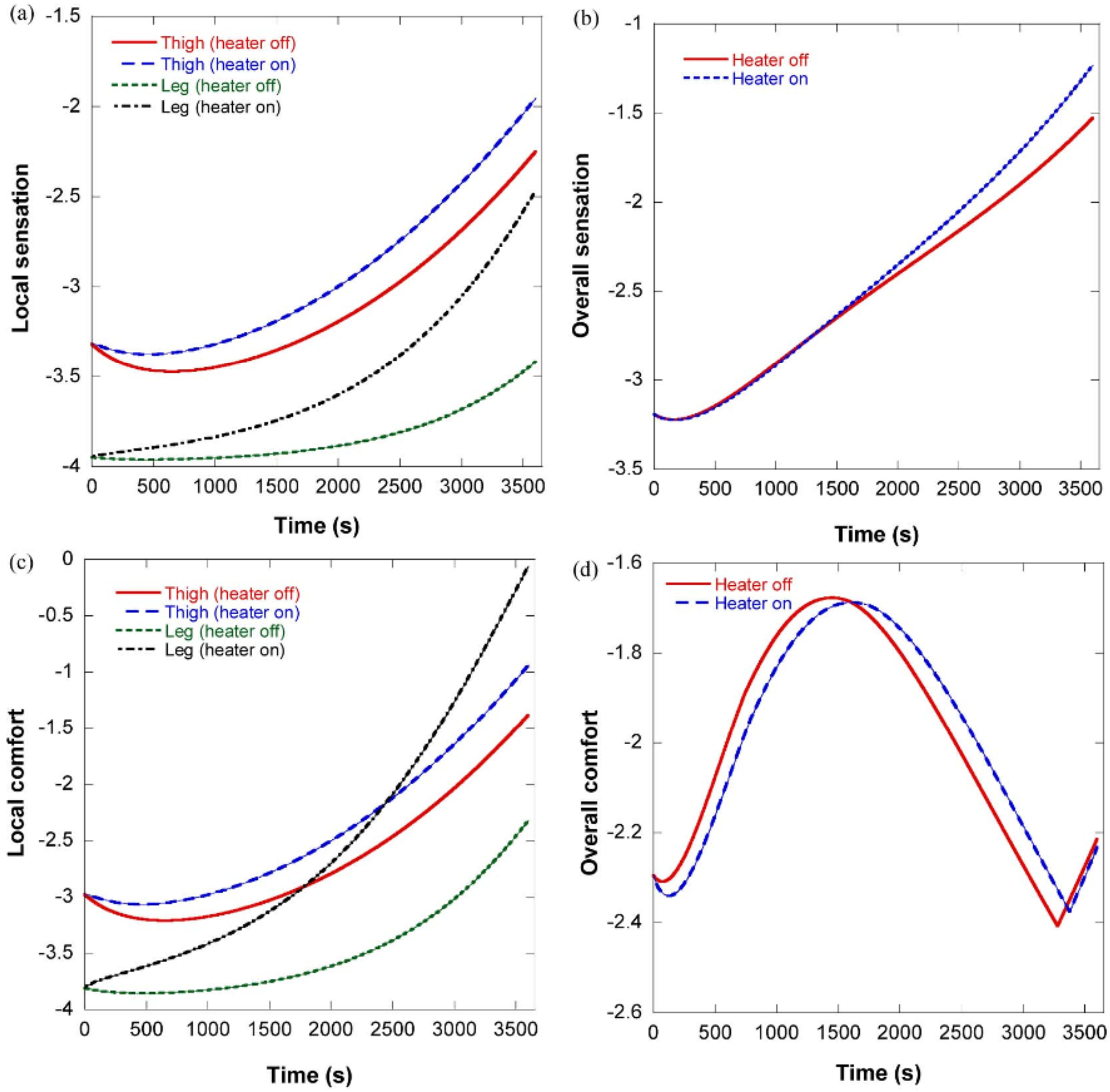


Fig. 9. Prediction of local and overall thermal sensation and thermal comfort: (a) Local thermal sensation in leg and thigh; (b) overall thermal sensation in the human body; (c) local thermal comfort in leg and thigh; (d) overall thermal comfort in the human body.

likely due to the multi number of heaters (2-5) surrounding the leg region. Even though an improvement in overall thermal comfort was obtained, the overall thermal comfort model showed an irregular trend. This inaccuracy may have been caused by the calculation method used in the thermal comfort model. Future work should therefore focus on to develop a thermal comfort model to provide more accurate estimation.

The thermal physiological modeling in this study showed that local radiant heaters can improve the thermal sensation and comfort in the human body. Although an improvement in overall thermal sensation and comfort was observed, a comfortable level was not reached in the scenario studied. Therefore, local radiant heaters may not be sufficient to provide adequate heating for passengers of EVs. Other researchers have indicated that using local heaters in the seats may efficiently improve thermal comfort while saving energy [20-23]. Combining local radiant heaters with seat heaters may provide an effective way to improve the thermal comfort for passengers, and will therefore be the subject of future work, along with further development of the psychological model. Overall, this work may contribute to the reduction of energy consumption in EVs.

4. Conclusions

A thermal physiology model that includes the effects of local radiant heaters was developed in this study. The accuracy of the calculations was confirmed by proving numerical validation by comparing with the previous available experimental data. View factor and MRT calculations showed the effect of individual radiant heaters for effective local heating. Calculations of the mean skin temperature indicated that the use of the heater showed an increase in temperature of skin when radiant heaters are turned on, thereby improving human thermal sensation and comfort. The combination of heaters at the different position also showed an enhancement in skin temperature thereby suggesting to use optimum combinations of heaters to improve the sensation and comfort level. Using radiant heaters allows for a direct rise in skin temperature without any fall period. Overall, the use of local radiant heaters improved the local and overall thermal sensation and comfort, indicating an improvement in human thermoregulation. The results of this study will contribute to predicting effective energy saving and passenger comfort in EVs.

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Nomenclature

C (i,j) : Heat capacity of node (*i,j*)
T (*i,j*) : Temperature
Q (*i,j*) : Rate of heat production
B (i,j) : Heat exchanged between each node and the central blood compartment
D(i,j) : Heat transmitted by conduction to the neighboring layer within the same segment
RES(i,1) : Heat loss by respiration
Q_t *(i, 4)* : Convective and radiant heat exchange rate between the skin's surface and environment
E (i, 4) : Evaporative heat loss at the skin's surface
MRT : Mean radiant temperature
T_N : Mean radiation temperature at N^{th} surface
$F_{i\text{-}N}$: View factor between the i^{th} segment and the N^{th} surface
A_1, A_2 : Two general surfaces
dA_1, dA_2 : Two differential areas
s : Distance
θ_1, θ_2 : Angles between the surface normal and a ray between the two differential areas

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