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ORIGINAL ARTICLE

Tracking Hand And Facial Skin Temperatures In An Automobile By Using Ir-Thermography During Heating Period

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ABSTRACT

The purpose of this study is to track hand and facial skin temperatures by IR-thermography under transient heating period in an automobile. Hands and face are the only unclothed parts of the body during heating period and they are much more affected by temperature variations in transient conditions, therefore heat losses from these parts are important and cause local discomfort. In order to capture infrared thermograph of these body parts, an infrared thermal camera which has a spectral range between 7.5 to 13 μm was used. Besides IR-thermographic results the thermal interactions between hand and face are simulated. In the simulation Gagge-2 node model was used. The simulation results are compared with the available data in the literature to verify the model. The results were in good agreement and can give a good prediction of temperature distribution and thermal discomfort of hand and face. Instant conductive, convective and radiative heat losses from hands and face were calculated for transient conditions. The obtained results can be used to improve thermal comfort models in automobiles as well as in other volumes under transient conditions.

Keywords: Thermal comfort, IR-thermography, Simulation

1. INTRODUCTION

Thermal conditions in an automobile cabin can rapidly change during transient heating or cooling periods. Rapidly changing thermal conditions affect the passengers driving performance. Previous studies show that at least %90 of the causes of accidents can be tracked back to driver impairment [1]. For this reason, the mental condition of the driver has been increasingly considered as being influenced by the thermal conditions occurring in the vehicle compartment [2]. Automobile HVAC systems mainly control the ambient temperature of the passenger compartment but driver and the passengers can receive local air flow. Researches show that local airflow affects the thermal comfort of subjects [3-6].

Measuring temperature with infrared thermography is a non-invasive or non-destructive technique in the stream field. Infrared thermography has been widely used for military security, forestry, medicine, mechanical and electrical systems maintenance, search and rescue, and building maintenance to determine temperature distribution of solid surfaces since two decades. To read an object's temperature via a thermograph a researcher has to know emissivity of the surface, ambient temperature, relative humidity, distance from object to camera and the wavelength of radiation that emitted from the object. Minkina and Dudzik [7] represented a study about infrared thermography errors and uncertainties. Choi et al. [8] studied the reliability of formulas for calculating mean skin temperature that measured by infrared thermography. There are only few studies in literature regarding infrared thermography usage for the temperature measurements or thermal comfort in the automobile cabin. The first infrared thermographic study in automobile was made by Carignano and Pipplone [9]. In their study, defrosting phenomena was investigated on windscreen industrial vehicles by computer aided thermographic analysis. Burch et al. [10], reviewed infrared thermography for automotive climate control analysis and gave also a different method for measuring ambient air temperature

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by using with a thin layered fiberglass screen mounted perpendicular to the air stream. Korukçu and Kilic [11], used IR-thermography to determine instant surface temperature distribution and facial skin temperatures of the driver inside an automobile cabin during transient heating and cooling periods. They also investigated different air velocity levels that are provided by the vents.

Thermal comfort studies mainly focus on the interactions between human and the surrounding ambient air. There are different mathematical models for estimating thermal sensation, skin temperature of body parts or thermal discomfort that using heat and mass transfer from human body. The most common mathematical models for thermal comfort studies are Fanger's Steady State Energy Balance Model [12] and Two Node Transient Energy Balance Model [13]. Stolwijk developed a 25 node model of thermoregulation [14] and Tanabe et al. [15] developed the 65-node thermoregulation model based on the Stolwijk model.

There are several studies for indoor environment but thermal comfort studies for automobiles are restricted in real ambient conditions. Most of the researches were investigated either in climatic chambers or with CFD models. There is no thermal comfort model for automobiles therefore previous thermal comfort models are used to predict the thermal behavior of occupants inside the passenger compartments. Kaynakli et al. [16] presented a computational model of heat and mass transfer between a human and the vehicle interior environment during heating and cooling periods. Their model was based on the heat balance equation for human body, combined with empirical equations defining the sweat rate and mean skin temperature. Kaynakli and Kilic [17] also investigated the thermal comfort inside an automobile during the heating period and compared their simulation model and showed that the data obtained from their experimental studies were in good agreement with their simulation model.

In this study, instant facial and hand skin temperatures of the driver were tracked by using an infrared camera during a 15 min transient heating period in an automobile and the results were compared with Gagge 2-Node Model simulation which assumes the body as two concentric cylinders. The differences between the experimental data and the simulation results were discussed.

2. METHODOLOGY

2.1. Experimental Setup

The experiments were carried out in a FIAT Albea 2005 parked outside. Only the plane vents were operated. The data were collected during the winter months of January and February of 2008 and there are three healthy male subjects chosen. The mean (SD) characteristics of the participants were as follows: age = 25 (2.64) yr, height = 176 (10) cm, weight = 79.67 (15.5) kg and body mass index = 25.61 (2.42) kg/m². Before the experiments, the subjects were briefed about aim of the study, procedure of the experiments etc.

The air velocity and the ambient conditions such temperature and humidity measurements were made by a Testo 350 M/XL 454 probe in every 10 seconds. The hand and facial skin temperatures were measured and recorded by Flir ThermaCam SC640 infrared camera, which has a 8 mm thick FOV 32° lens and 640 x 840 pixels resolution in every 10 seconds. Accuracy and the measuring range of the equipments were presented in Table 1.

Table 1.Accuracy of the equipments

Parameter	Interval	Tolerance
Air velocity	0 m/s – 10 m/s	± 0.04 m/s
Relative Humidity	0 % – 100 %	± 0.1 %
Temperature	- 20°C – 70°C	± 0.4 °C
Globe Temperature	0°C – 80°C	± 1 °C

To determine value of experimental measurement error, uncertainty analysis was calculated according to Moffat [18], average uncertainty in experimental results was found within ± %7.

Thermal resistances of naked body parts were taken 0 clo (1 clo=0.155 m²K/W) and level of metabolic activity was taken 1 met (58.2 W/m²) for a sedentary person [19]. All of the subjects stayed 15 minutes in the car.

To measure the hand and facial skin temperatures of the driver, infrared camera placed in front of the right passenger seat and focused on driver's face. In every 10 seconds the temperature measurements were taken. From the Figure 1, the position of the infrared camera can be seen. While measuring temperatures with infrared camera, ambient conditions of the automobile cabin such temperature, relative humidity, globe temperature and air velocity values were also measured and recorded in every 10 seconds.

Figure 1. Position of the infrared camera for hand and facial skin temperature measurements.

2.2. Simulation

In the simulation the hands and the face is modeled as two concentric cylinders in which the inner cylinder represents the body part's core (skeleton, muscles, internal organs), and the outer cylinder represents the skin layer. The body generates heat, and this heat has to be rejected from body to the environment via conduction, convection, radiation and evaporation. Transient energy balance means that the rate of heat storage is equal to the differences of heat gain and the heat loss. In this thermal model heat balance equations are written for two compartments as follows:

$$S_{cr} = M - W - (Q_{c,res} + Q_{e,res}) - Q_{cr,sk} \quad (1)$$

$$S_{sk} = Q_{cr,sk} - (Q_{cd} + Q_{cv} + Q_{rd} + Q_{e,sk}) \quad (2)$$

where M is the rate of metabolic heat production, W is the rate of mechanical work accomplished by the muscles, $Q_{c,res}$ and $Q_{e,res}$ are the convective heat losses from respiration, $Q_{cr,sk}$ is the rate of heat transport from core to skin, $Q_{e,sk}$ is the evaporative heat loss from the skin. Q_{cd}, Q_{cv}, Q_{rd} are the conductive, convective and radiative heat losses from skin respectively. The heat storage rates for the compartments can be written separately in terms of thermal capacity and time rate of change of temperature in the compartments:

$$dT_{cr} / dt = S_{cr} A_D / \left((1-\alpha) m c_{p,b}\right) \quad (3)$$

$$dT_{sk} / dt = S_{sk} A_D / \left(\alpha m c_{p,b}\right) \quad (4)$$

Where α is the fraction of body mass concentrated in skin compartment, A_D is the DuBois surface area, m is the body mass, $c_{p,b}$ is the specific heat of body (3.49 kj/kgK), T_{cr} is the temperature of the core and T_{sk} is the temperature of the skin compartment.

Total convective and radiative heat transfer rates can be calculated as

$$Q_{cv} + Q_{rd} = \frac{(T_{sk} - T_o)}{R_{cl} + \dfrac{1}{f_{cl}(h_c + h_r)}} \quad (5)$$

Where R_{cl} is the thermal resistance of clothes, f_{cl} is the ratio of clothed area to DuBois area, h_c and h_r are the convective and radiative heat transfer coefficients. Operative temperature (T_o) is calculated as

$$T_o = \frac{h_c T_a + h_r \overline{T}_r}{h_c + h_r} \quad (6)$$

radiative heat transfer coefficient (h_r) was taken 4.7 W/m²°C and convective heat transfer coefficient (h_c) was taken as

$$h_c = 8.3 V^{0.6} \quad (7)$$

To obtain the mean radiant temperature ($\overline{T}_r$), a globe thermometer was placed on the right passenger seat. Mean radiant temperature is defined as the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with the occupant as the actual enclosure. Mean radiant temperature can be calculated for a standard globe thermometer

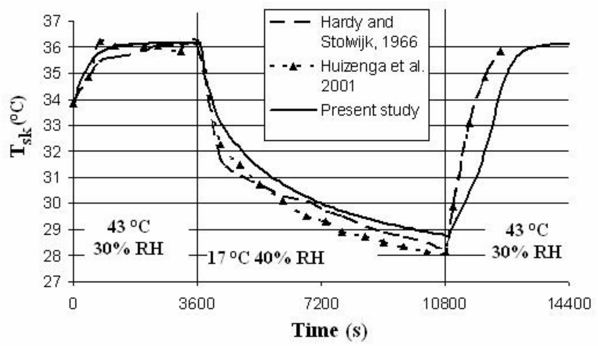
$$\overline{T}_r = \left[(T_g + 273)^4 + 2.5 \times 10^8 \times V^{0.6} \times (T_g - T_a)\right]^{1/4} - 273 \quad (8)$$

Where T_g is the temperature of the globe thermometer, V is the air velocity at the level of the globe thermometer and T_a is the ambient temperature around the globe [20].

Other equations for determining sensible and latent heat losses can be found from the previous studies that regarding thermal interactions between human body and the surrounding environment [21, 22].

2.3. Validation

In order to verify the simulation model, the results from the experimental data and the simulation were compared with other experimental and simulated results. Hardy and Stolwijk [23] exposed the subjects to a step change from 43 °C at 30% RH to 17 °C at 40% RH. Mean skin temperatures of the subjects for various time steps were given in that study. Stolwijk and Hardy [14] exposed the subjects to upward step change from 30 °C at 40% RH to 48 °C at 30% RH and presented mean skin temperatures of the subjects. Huizenga et al. [24] presented the simulation results obtained from the Berkeley comfort model based on the Stolwijk model for similar environmental conditions with the mentioned experimental studies, and compared the results with the measured data. Raven and Horvath [25] exposed the subjects to a downward step change from 28 °C at 45% RH to 4.7 °C at 70% RH, in still air. Skin temperatures on segments were presented in that study. In this study simulation results are compared with the experimental and simulated data which are explained above in Figure 2. It can be seen that compared results are in good agreement with slight differences that are taken from the previous researches.



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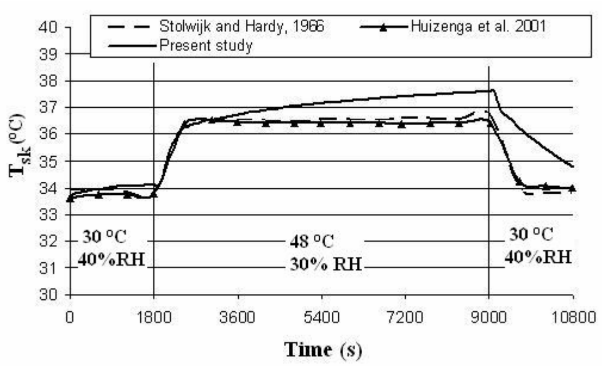

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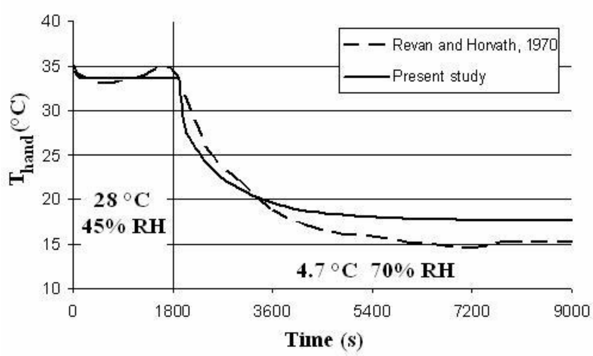

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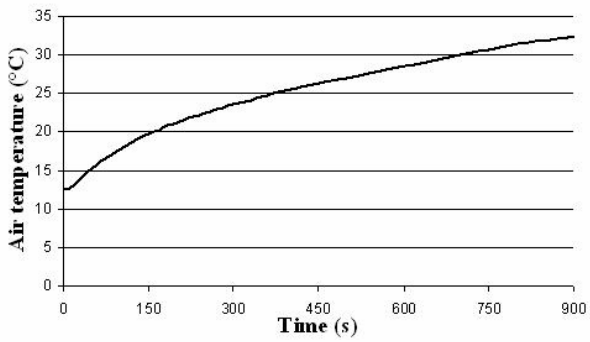
Figure. 2. Comparison of the present study with the results taken from the literature: (a) and (b) Mean skin temperatures, (c) skin temperature on the hand.

3. RESULTS

3.1. Ambient conditions

Experimental results were obtained at 10 °C outside temperature and %58 relative humidity for 15 min heating period. Variations of cabin conditions were represented in Figure 3. As air temperature increases with the time relative humidity decreases. With increasing temperature of the air solid surfaces are also heated and the mean radiant temperature changes. The rate of the mean radiant temperature inside the cabin was also presented.



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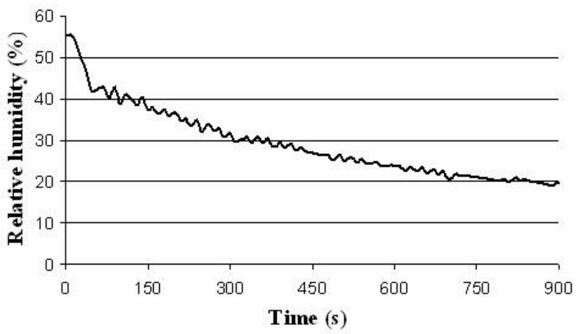

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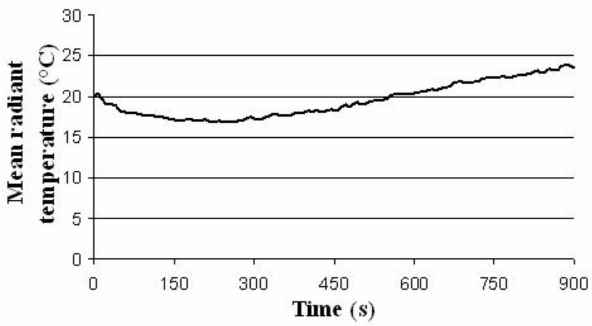

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Figure. 3. Variations of cabin conditions with time: (a) air temperature, (b) relative humidity and (c) mean radiant temperature.

3.2. Thermographs

In order to capture the thermographs of driver's face and hands, infrared camera was mounted on a tripod and placed in front of the right passenger's seat. Infrared camera was focused on the face and the hands of the driver and took pictures in every 10 seconds. At the same time air condition parameters such temperature, relative humidity, mean radiant temperature and air velocity were measured and recorded in every 10 seconds. Instant values of ambient parameters, emissivity and the distance from object to camera were assigned to the software of infrared camera. The uncertainties and errors caused by these parameters are investigated by Minkina and Dudzik [7]. Thermographs were also validated by thermocouple measurements, Korukçu and Kilic [11]. In Figure 4 thermographs of the driver's face and hands were presented. As seen from the thermographs facial and hand skin temperatures increases with time, moreover, temperature of solid surfaces, steering wheel and clothes of the driver also increases. With increasing time the colour of the surfaces becomes lighter indicating the increase of the surface temperatures.

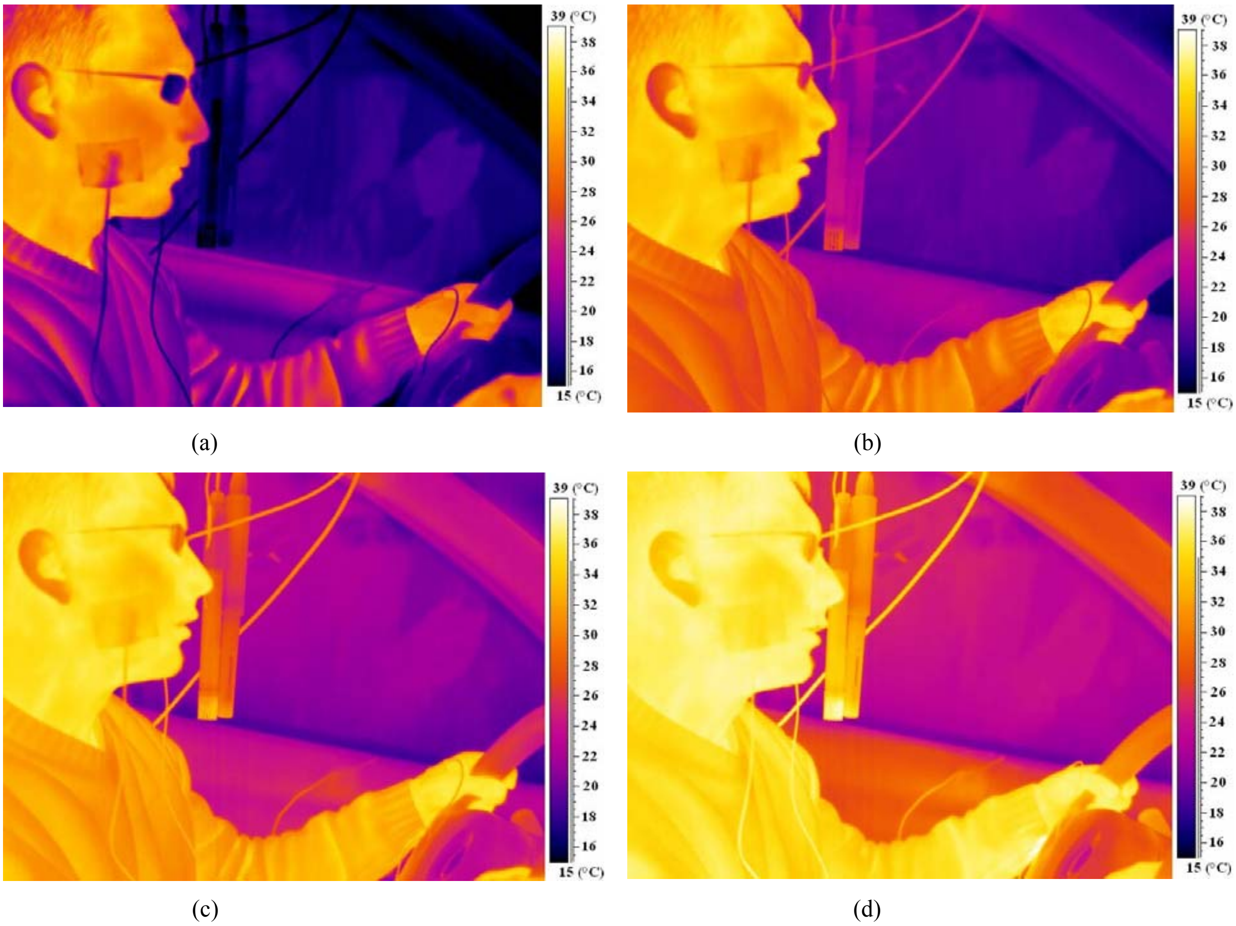


Figure. 4. Thermographs of the driver's face and hands during heating period: (a) t = 0 min, (b) t = 5 min, (c) t = 10 min and (d) t = 15 min.

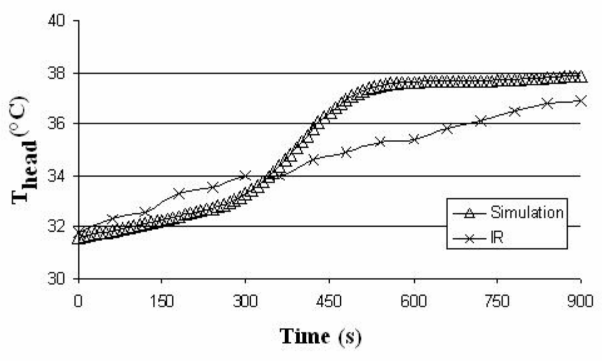
3.3. Comparisons of the experimental and simulation results

Experimental hand and facial skin temperatures were compared with simulation results. The skin temperatures were measured and simulated for head, right and left hands. DuBois area, mass and the measured local air velocity values for each segment is presented in Table 2.

Table 2. DuBois area, mass and the measured local air velocity values for each segment.

Body segment	Air velocity (m/s)	Mass (kg)	DuBois area (m^2)
Head	0.15	5.18	0.18
Right hand	0.15	0.38	0.05
Left hand	1.25	0.38	0.05

In Figure 5, experimental and simulation results for head, right and left hand temperatures were represented. As seen from Figure 5, the experimental and the simulation results are in good agreement. There is no thermal comfort model for the automobile occupants therefore there are slight differences with the simulation and experimental results. In the simulation convection and radiative heat transfer coefficients are assumed as constant values but it is known that these parameters are not steady in transient conditions. Also, ambient conditions such air temperature, relative humidity and mean radiant temperature values in the model that taken were assumed steady but these values are varying with time and the change of these parameters with time were assigned as functions into the simulation.



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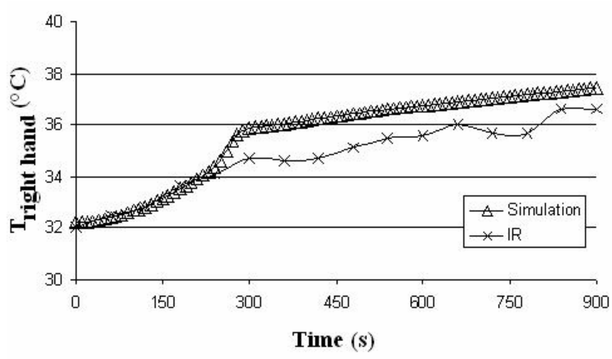

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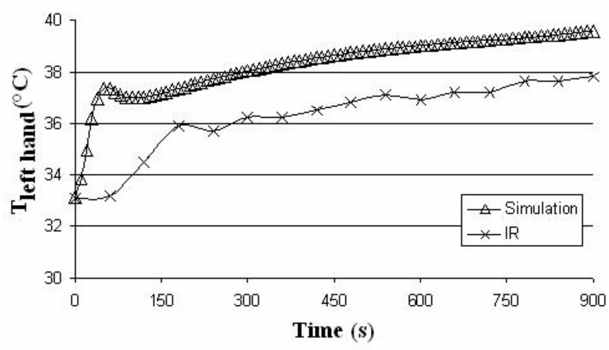

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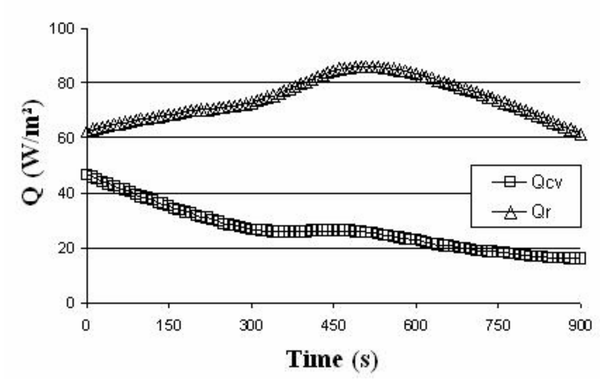
Figure. 5. Comparisons of experimental and simulation results: (a) Head, (b) right hand and (c) left hand temperatures.

3.4. Heat losses

Conductive, convective and radiative heat losses were also calculated with the simulation model and represented in Figure 6. As seen from the Figure 6, convective heat losses from head and hands are decreasing with time because temperature of these body parts is increasing during the heating period. Conductive heat losses of hands are also decreasing with time due to the temperature increase of these parts during the experiment. Conductive heat loss of the head was not calculated because head does not contact to any cold part of the automobile cabin. Radiative heat losses for head and right hand are increasing in the first half of the experiment and then they tend to decrease to their initial values. Radiative heat loss of the left hand is increasing in the beginning and then stays steady during the experiment.



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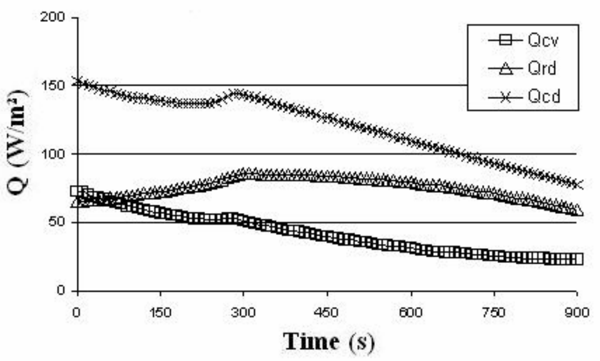

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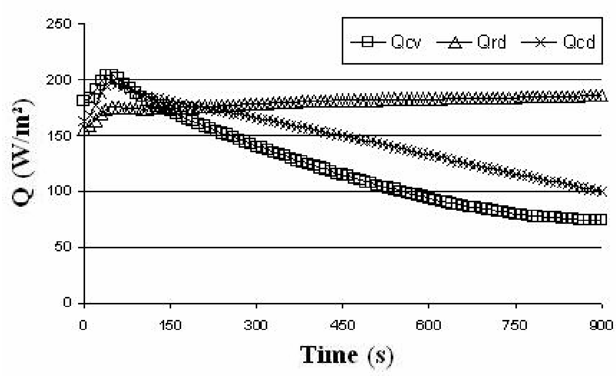

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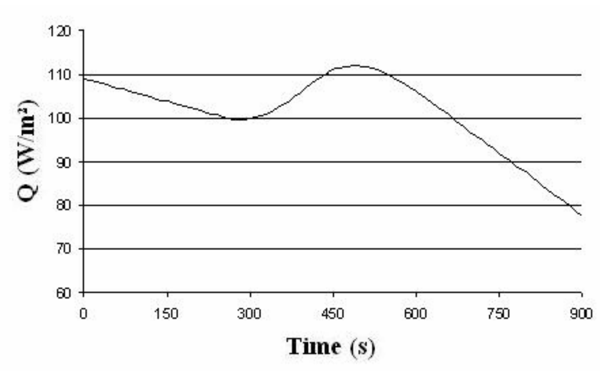
Figure.6. Conductive, convective and radiative heat losses from the simulation results: (a) Head, (b) right hand and (c) left hand.

Total heat losses for head, right and left hand were represented in Figure 7. Total heat loss value of the head fluctuated between 100-110 W/m² from the beginning to the half of the experiment and then it started to decrease. Total heat loss value of the right hand fluctuated between 280-290 W/m² in the beginning of the experiment and then started to decrease. In the first minutes of the experiment total heat loss of the left hand rapidly increased from 500 W/m² up to 575 W/m² then it started to decrease.



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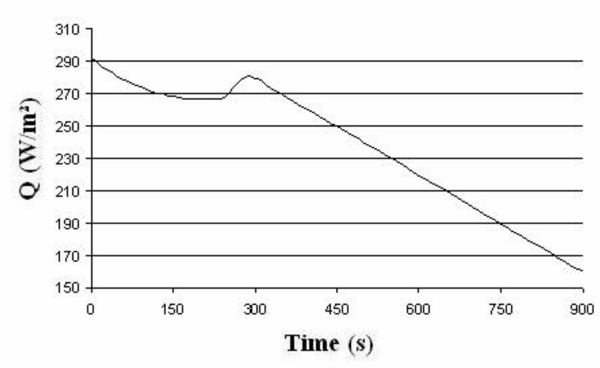

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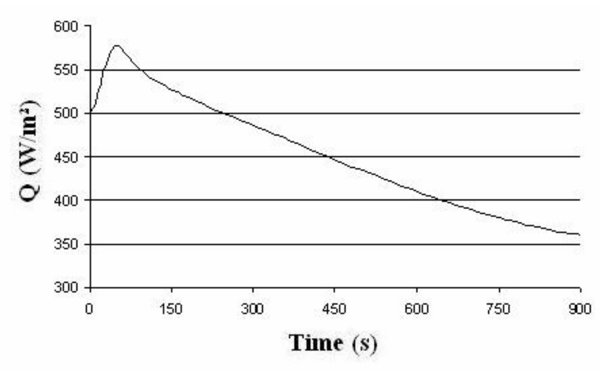

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Figure. 7. Total heat losses from the simulation results: (a) Head, (b) right hand and (c) left hand.

By multiplying total heat losses with DuBois surface area of each part we can obtain the exact amount of heat loss from these parts. Figure 8 represents the comparisons of total heat losses from head, right and left hand.

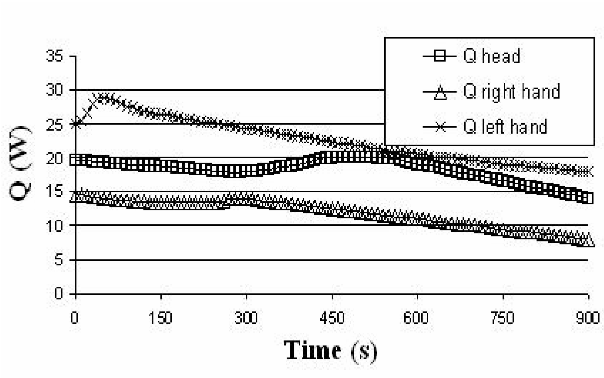

Figure 8. Comparisons of total heat losses from head, right and left hand.

As seen from the Figure 8 instant total heat loss value of left hand is much more than that of head and right hand. Due to the relatively high air velocity values and proximity to cold surfaces left hand lost more heat than that of other parts.

4. CONCLUSION

Hands and face are the only unclothed parts of the body of a driver inside the automobile cabin during winter conditions. Although the other parts of the body are in desired temperature conditions, the naked parts of the body exposed to relatively lower temperatures and causes local thermal discomfort. In this study, hand and facial skin temperatures were tracked by an infrared camera and the results were compared with a simulation model that calculates heat and mass transfer between the human and the surrounding ambient. Transient ambient conditions were taken as input to the model to predict the skin temperatures. Besides skin temperature measurements, conductive, convective and radiative heat losses were also calculated.

Due to the fact that there are rapid transient conditions, it is concluded that the results are in good agreement and give a prediction of the experimental results. As a result of this study, thermal comfort models in non-uniform conditions and HVAC systems for automobiles would be improved and the results can be used to validate CFD studies in similar researches.

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NOMENCLATURE

A_D DuBois surface area, *m²*

$c_{p,b}$ specific heat of body, 3.49 *kj/kgK*

f_{cl} clothing area factor, A_{cl}/A_D

h_c convective heat transfer coefficient, *W/m²K*

h_r radiative heat transfer coefficient, *W/m²K*

M rate of metabolic heat production, *W/m²*

m body mass, *kg*

Q_{cd} conductive heat loss, *W/m²*

Q_{cv} convective heat loss, *W/m²*

Q_{rd} radiative heat loss, *W/m²*

$Q_{e,res}$ evaporative heat loss from respiration, *W/m²*

$Q_{c,res}$ convective heat loss from respiration, *W/m²*

$Q_{e,sk}$ evaporative heat loss from the skin, *W/m²*

$Q_{cr,sk}$ rate of heat transport from core to skin, *W/m²*

R_{cl} thermal resistance of clothing ensemble, *m²°C/W*

S_{cr} heat storage in core compartment, *W/m²*

S_{sk} heat storage in skin compartment, *W/m²*

T_a ambient air temperature, *°C*

T_{cr} core temperature, *°C*

T_g globe temperature, *°C*

T_o operative temperature, *°C*

$\overline{T}_r$ mean radiant temperature, *°C*

T_{sk} skin temperature, *°C*

t time, *s*

V air velocity, *m/s*

W rate of mechanical work, *W/m²*

α fraction of body mass concentrated in skin compartment, dimensionless

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