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An investigation of thermal comfort inside a bus during heating period within a climatic chamber

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By this study, it was aimed to define a testing and calculation model for thermal comfort assessment of a bus HVAC design and to compare effects of changing parameters on passenger's thermal comfort. For this purpose, a combined theoretical and experimental work during heating period inside a coach was carried out. The bus was left under 20 °C for more than 7 h within a climatic chamber and all heat sources were started at the beginning of a standard test. To investigate effects of fast transient conditions on passengers' physiology and thermal comfort, temperatures, air humidity and air velocities were measured. Human body was considered as one complete piece composed of core and skin compartments and the Transient Energy Balance Model developed by Gagge et al. in 1971 was used to calculate changes in thermal parameters between passenger bodies and bus interior environment. Depending on the given initial and environmental conditions, the graphs of passengers Thermal Sensation and Thermal Discomfort Level were found. At the end, a general mathematical model supported with a related experimental procedure was developed for the use of automotive HVAC engineers and scientists working on thermal comfort as a human dimension.

1. Introduction

Thermal sensation and comfort models dealing with thermal interactions between human body and environment is an important topic to assure comfort state of both passengers and drivers inside vehicles. Thermal comfort studies started first for buildings and then afterwards continued also for vehicles. Human thermal comfort has been a subject in many previous studies and considerable amount of available information was documented and codified in the literature (ASHRAE, 1989; Parsons, 1993). Most of the studies have considered that the thermal conditions are nearly uniform and steady over entire body of occupant. However, less attention appears to be directed to comfort in vehicles, where thermal conditions are highly non-uniform and transient over body of occupant.

Gagge et al. (1971) investigated first physiological control mechanisms and thermal comfort (ASHRAE, 1997). Doherty and Arens (1988) worked on evaluation of physiological bases of thermal comfort models (ASHRAE, 1997). Parsons (1993) on the other hand worked on Human Thermal Environments (ASHRAE, 1989). He documented and codified information on Human Thermal Comfort. ASHRAE.TC 2.1 (1997) described all governing equations for thermal comfort and human physiology in the publishing of Physiology and Human Environment. The effects of thermal environment on health, comfort and working efficiency of occupants were separately discussed by Parsons (2000). The discussion was confined to the factors of heat and cold, vibration, noise, and light. Other environmental factors and combined effects were also briefly considered. Jones (2002) investigated further the capabilities and limitations of thermal models for use in thermal comfort models. In his study he compared several thermal sensation model outputs with measured data for a typical winter automobile warm-up condition and showed that the models differ widely in their predictions. Guan et al. (2003c) presented a literature review on current advances in thermal comfort modeling for both building and vehicle HVAC applications. Alahmer et al. (2012) reviewed Vehicular thermal comfort models comprehensively in their study. In addition to different experimental techniques used, a comprehensive review of different models developed to predict vehicular cabin's thermal comfort was provided. The manuscript discussed and analyzed each of the thermal indices that were typically used in assessing in-cabin conditions such as the Predicted Mean Value PMV index and the Predicted Percentage Dissatisfied PPD.

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Clothing insulation asymmetry and thermal comfort was studied by Olesen et al. (1988). McCullough et al. (1989) worked for preparation of a data base for determining evaporative resistance of clothing ASHRAE (1989). Insulation value, evaporative resistance and permeability index of 22 representative clothing ensembles with or without contribution of the air layer around clothed body were measured with a thermal manikin. These parameters were also measured for 39 component fabrics using a sweating hot plate apparatus. The predictions generated by the model were compared to values measured with a manikin. Tanabe et al. (1994) evaluated thermal environments by using a thermal manikin with controlled skin surface temperature. They investigated sensible heat loss from several parts of human body by use of a manikin. For each considered piece of the body, total heat transfer coefficient and thermal resistance were found. Since however their study was performed in a constant temperature environment, it did not give any result about thermal comfort conditions. Ogulata (2007) discussed theoretically basic physical principals of body's mechanism for heat transfer with environment and examined body's heat balance. Effects of clothes and various climatic conditions on thermal comfort were also investigated for different activities in this study.

Burch et al. (1991a,b) worked on an experimental study of passenger thermal comfort in an automobile under severe winter conditioning. Two different options for supplementary electrical heating such as low-power electric heating pads installed on seat and back support were studied experimentally and the results were reported. Changes of temperatures of interior and body parts contacted with solid surfaces were investigated during standard heating process in a very cold day (~−20 °C). During this period, effects of heat losses from the body by conduction, convection and radiation on thermal sensation (TS) were investigated. On the other hand, the heat losses from body segments and their skin temperatures were not considered during this study. The authors analyzed also passenger's thermal comfort in an automobile under severe winter conditioning in the same study.

Chakroun and Al-Fahed (1997) worked on Thermal comfort analysis inside a car. Their study of interest was temperature variation and thermal comfort inside a car parked under the sun during summer months in Kuwait. They considered effect of using different combinations of internal covering on PMV value inside the car. Lee and Yoon (1998) investigated effects of ventilation mode on the distribution of air temperature and velocity in a 1/10 scale vehicle interior model during heating period experimentally. In their experiments, three different ventilation modes (panel-vent, foot-vent and hybrid-vent) were tested at the same flow rate. Aroussi and Aghil (2000) studied characterization of flow field in a passenger car model. In their study, they tried to understand air flow behavior to improve climatic comfort within passenger vehicles. But, in the study, effects of air flow on human body were not mentioned and any result related to thermal comfort was not reached. Daanen et al. (2003) investigated driving performance in cold, warm, and thermo-neutral environments. They experimentally investigated effects of warm, cold and thermo-neutral environments on driving performance and concluded that driving performance was affected from cold and hot ambient conditions. Guan et al. (2003a) presented an experimental study to examine human thermal comfort under highly transient conditions in an automobile. They used an environmental chamber to simulate 16 typical winter and summer conditions. Thermal sensation modeling was discussed in their companion paper (Guan et al., 2003b). In their mathematical model, physiological and psychological factors were combined and environmental and personal parameters were used as inputs to determine the physiological responses. Alahmer et al. (2011) worked on analysis of vehicular cabins' thermal sensation and comfort state, under relative humidity and temperature control, using Berkeley and Fanger models. At the end, it was shown that controlling the relative humidity along with the dry bulb temperature (DBT) enables the cabin to reach comfort zone faster than sole control of the cabin (DBT), in both cooling and heating processes, i.e. summer and winter conditions, respectively.

Kaynakli et al. (2002) presented a computational model of heat and mass transfer between human and vehicle interior environment during heating and cooling periods. The model was based on the heat balance equation for human body combined with empirical equations defining sweat rate and mean skin temperature. Kaynakli et al. (2003a) again presented a numerical model of heat and mass transfer between human body and its environment. There, the required environmental and personal conditions for satisfaction of people obtained under steady-state conditions and total sensible and latent heat losses, skin temperature, skin wettedness, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) values were calculated by simulation. Kaynakli et al. (2003b) reported also a study in which human body is divided into 16 sedentary segments, a computational model of thermal interactions between each of 16 body segments and the environment was developed. By the use of the model, skin wettedness and latent (sweating, diffusion) and sensible (conduction, convection, radiation) heat losses from each body segment and whole body are calculated for both sitting and standing postures. Kaynakli et al. (2004) studied additionally thermal comfort during heating and cooling periods in an automobile. They presented a model of thermal interactions between a human body and interior environment of an automobile. The model was based on the heat balance equation for human body, combined with empirical equations defining sweat rate and mean skin temperature. Effects of both heating and cooling processes on thermal comfort inside the automobile were investigated. Kaynakli and Kilic (2005) investigated thermal comfort inside an automobile during heating period. The study presented an experimental work and a mathematical model of thermal interactions between a human and the interior environment of an automobile. Human body was divided into 16 sedentary segments, change of temperature was observed both theoretically and experimentally. The model was based on the heat balance equation for human body, combined with empirical equations defining sweat rate and mean skin temperature. Simulation was performed by use of transient conditions. Effects of heating process on thermal comfort, with respect to temperature, relative humidity and air velocity inside an automobile were investigated in this study. Test duration was 60 min in their study and initial temperature at the start of the test was 0 °C.

Kilic et al. (2006) studied determination of required body core temperature for thermal comfort with steady-state energy balance method. In this study, the fundamental equations given in the steady-state energy balance and the empirical relations expressing effects of the thermoregulatory control mechanisms of body were combined. Kilic and Akyol (2009) separately investigated environmental parameters affecting thermal comfort as air temperature, relative humidity, mean radiant temperature and air velocities on human body segments. In the study, effects of non-uniform and highly transient thermal comfort parameters were tested for two ventilation modes (panel vents, windshield and foot vents). With the prepared simulation model, thermal behavior, physiological reactions (skin temperatures) and thermal sensations of the driver were predicted. The model was justified with experimental data obtained from the literature. Gagge model was used for the analysis.

A direct thermal comfort investigation for a bus in general and for a coach in particular, as in the current study was not met in the