ELSEVIER

Applied Ergonomics 36 (2005) 301–312

APPLIED ERGONOMICS

www.elsevier.com/locate/apergo

An investigation of thermal comfort inside an automobile during the heating period

Omer Kaynakli, Muhsin Kilic*

Department of Mechanical Engineering, Faculty of Engineering and Architecture, Uludag University, 16059 Bursa, Turkey

Received 3 March 2004; accepted 6 January 2005

Abstract

This paper describes a combined theoretical and experimental study of thermal comfort during the heating period inside an automobile. To investigate the effects of thermal conditions on the human physiology and thermal comfort during the heating period, temperature, humidity and air velocity were measured at a number of points inside the automobile, so thermal conditions were accurately determined. The human body was divided into 16 sedentary segments, and the change of temperature was observed both experimentally and theoretically. During transient conditions of the heating period, heat and mass transfer between the human body and the interior environment of an automobile were simulated by a computational model, and predictions were compared with the measured data. It is shown that there is a good agreement between the model predictions and experimental results. By means of the present model, the effects of the fast transient conditions of the heating period on the sensible and latent heat transfer from the body, body segments skin temperatures and thermal sensation were investigated in detail.

Keywords: Automobile; Heating period; Thermal comfort; Thermal sensation

1. Introduction

The passenger compartment of an automobile is heated in the winter months by circulating hot engine coolant through a coolant-to-air heat exchanger that warms the compartment's air. The heating system is designed to operate in conjunction with the air ventilating system to provide the desired air temperature. With progressive reductions in engine size, stemming from considerations of fuel economy, and corresponding reductions in the heat available for the passenger heating system, there is interest in the development of more effective systems to ensure passengers thermal comfort even in extreme conditions by considering market situation. It is difficult to achieve and maintain passenger thermal comfort under extremely cold driving conditions. Some auxiliary heating or cooling apparatus may greatly reduce the time needed to attain thermal comfort. But, power requirements associated with this apparatus are substantial.

In the highly cold winter season, the heating period from the start up of the vehicle requires some time to reach steady-state conditions. During this period, conditions are highly nonuniform over the body of the occupant. The vehicle passenger experiences localized chilling due to contact with an initially cold seat or steering wheel, and nonuniform air velocities that vary depending on the location of the air registers and dashboard control settings. Thus, in addition to the air temperature, several other factors have a bearing on the thermal comfort of the passenger. Until the thermal comfort reached in the automobile compartment, the temperature and the humidity changes dramatically. Driver and passengers are greatly affected by these changes. This problem is needed to be solved with respect to human comfort, health and driving safety.

*Corresponding author. Tel.: +90 224 4429183; fax: +90 224 4428021.
E-mail address: mkilic@uludag.edu.tr (M. Kilic).

0003-6870/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apergo.2005.01.006

Nomenclature

A	surface area, m^2
c_p	specific heat, J/(kg K)
C	convective heat loss rate, W/m^2
CSIG	cold signal
E	evaporative heat loss rate, W/m^2
f	correction factor
h	heat transfer coefficient, $W/(m^2\,K)$
i	segment number
j	air or fabric layers number
k	conductive heat transfer coefficient, W/(m K)
L	thermal load, W/m^2
LR	Lewis ratio, °C/kPa
m	body mass, kg
$\dot{m}$	mass flow, $kg/(s\,m^2)$
M	rate of metabolic heat production, W/m^2
nl	number of layers covering segment
p	water vapor pressure, kPa
Q	heat transfer rate, W/m^2
r	outer radius of fabric layer
R	thermal or evaporative resistance, $(m^2\,K)/W$ or $(m^2\,kPa)/W$
RH	relative humidity
S	heat storage, W/m^2
t	time, s (unless specified in minutes)
T	temperature, °C
TS	thermal sensation
V	air velocity, m/s
w	skin wettedness
W	humidity ratio, kgH_2O/kg dry air
WSIG	warm signal
$\hat{W}$	external work accomplished, W/m^2
x	thickness, m

Greek letters

α	ratio of skin layer mass to total body mass
η	permeation efficiency

Subscripts

a	air, ambient
act	activity
al	air layer
b	body
bl	blood
cd	conduction
cl	clothing
cr	core
c	convection
dif	diffusion
e	evaporation
ex	exhaled
f	fabric
int	interface between outer clothing surface and a solid (such as the seat or back support)
o	operative
r	radiation
res	respiration
rsw	due to regulatory sweating
s	sensible
shiv	shiver
sk	skin
t	total

Consequently, there is substantial interest in the development of more efficient techniques for achieving and maintaining passenger thermal comfort in an automobile environment.

Human thermal comfort has been the subject of considerable previous study, and much of the available information was documented and codified in the literature (see ASHRAE, 1989; Parsons, 1993). Most of the studies have considered the thermal conditions are nearly uniform and steady over the entire body of occupant. Tanabe et al. (1994) investigated sensible heat loss from several parts of the human body by the use of a manikin. For each considered part of the body, total heat transfer coefficient and thermal resistance were found. Since their study was performed in constant temperature environment, it did not give any result about the thermal comfort conditions. The effects of thermal environment on the health, comfort and working efficiency of occupants was discussed separately 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 in that study. Kaynakli et al. (2003a) presented a numerical model of the heat and mass transfer between the human body and the environment. In their study, the required environmental and personal conditions for satisfaction of the people obtained under steady-state conditions, and total sensible and latent heat losses, skin temperature, wettedness, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) values were calculated via simulation. Kaynakli et al. (2003b) reported a study in which the human body is divided into 16 sedentary segments, a computational model of thermal interactions between each of the 16 body segments and the environment is developed. By the use of the model, skin wettedness and latent (sweating, diffusion) and sensible (conduction, convection, radiation) heat losses from