Available online at www.sciencedirect.com
ScienceDirect
Building and Environment 42 (2007) 3210–3220
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

Effects of radiant temperature on thermal comfort

Ibrahim Atmaca*, Omer Kaynakli, Abdulvahap Yigit

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

Received 13 October 2004; received in revised form 11 July 2006; accepted 21 August 2006

Abstract

The aim of this paper is to investigate the local differences between body segments caused by high radiant temperature, and to analyze the interior surface temperatures for different wall and ceiling constructions with their effect on thermal comfort. For the segment-wise thermal interactions between human body and its surrounding, simulations have been conducted by appropriately modifying Gagge 2-node model to multi-segment case to demonstrate the local differences. Simulation results are found to be in good agreement with experimental and simulation results reported in the literature. To calculate the interior surface temperatures of the wall and ceiling, the sol–air temperature approach is used for convenience. It is shown in the paper that the body segments close the relatively hot surfaces are more affected than others and interior surface temperatures of un-insulated walls and ceilings exposed to a strong solar radiation reach high levels, all of which cause thermal discomfort for the occupants in buildings.

Keywords: Thermal comfort; Radiant temperature; Solar radiation; Simulation

1. Introduction

The good building design characteristics, including both the engineering and non engineering disciplines, might be summarized as follows [1]:

- meets the purpose and needs of the building's owners/managers and occupants,
- meets the requirements of health, safety and environmental impact as prescribed by codes and recommended by consensus standards,
- achieves good indoor environment quality which in turn encompasses high quality in the following dimensions: *thermal comfort*, indoor air quality, acoustical comfort, visual comfort,
- creates the intended emotional impact on the building's occupants and beholders.

Thermal comfort is defined as "that condition of the mind in which satisfaction is expressed with the thermal environment" [2]. Six primary factors identified to most affect the thermal comfort are air temperature, humidity, air velocity, *mean radiant temperature*, clothing level and metabolic rate. The mean radiant temperature is a significant factor, especially in buildings whose envelopes were exposed to a strong solar radiation, that conventional indoor temperature and humidity control cannot guarantee indoor comfort. Cold walls or windows may cause a person to feel cold even though the surrounding air may be at a comfortable level. Likewise warm surfaces may cause a person to feel warmer than the surrounding air temperature would indicate. The building envelopes are the main factors of building energy efficiency and human thermal comfort, as they represent a skin of the building's body. The building whose envelopes include suitable insulation has little internal heat gains and outside gains from solar radiation, and in such a situation, the interior surface temperature of the building walls helps in defending from outside environmental conditions. In buildings where envelopes are un-insulated, the interior surface temperature of the building walls is affected from the outside environmental conditions, especially the solar radiation. Therefore, the interior surface temperatures of these walls rapidly increase.

*Corresponding author. Tel.: +90 224 4428179; fax: +90 224 4428021.
E-mail address: atmaca@uludag.edu.tr (I. Atmaca).

0360-1323/$ - see front matter
doi:10.1016/j.buildenv.2006.08.009

Nomenclature

A	surface area, m^2
C	convective heat loss from skin, W/m^2
c_p	constant pressure specific heat, kJ/kgK
E	evaporative heat loss, W/m^2
F	view factor, dimensionless
h	heat transfer coefficient, W/m^{2}K
i	segment number
I	solar radiation, W/m^2
j	surface number
L	thermal load (W/m^2)
m	body segment mass, kg
M	rate of metabolic heat production, W/m^2
PMV	predicted mean vote index, dimensionless
q	heat flow, W
Q	heat flow rate, W/m^2
RH	relative humidity, dimensionless
S	heat storage, W/m^2
T	temperature, °C
W	external work (W/m^2)
α	absorptance of the surface and fraction of body mass concentrated in skin compartment, dimensionless
ΔR	radiation exchange, W/m^2
ε	emmitance of the surface, dimensionless
θ	time, s
$\sum R_{\mathrm{I}}$	thermal resistance of the wall or ceiling excluding the outside air film resistance, m^2 K/W
$\sum R_{\mathrm{II}}$	thermal resistance of the wall or ceiling excluding the inside and outside air film resistances, m^2 K/W

Subscripts

a	air or ambient
cr	core
cr,sk	from core to skin
e	sol–air
int	interior surface
N	surface number
o	outside
p	person
r	radiation
res	respiration
s	exterior surface
sk	skin

Recently, several studies dealing with thermal comfort, especially radiant temperature have been carried out by researchers. Detailed radiation properties for a thermal manikin were predicted numerically by Sorensen [3]. In the study, the view factors between individual body segments and between the body segments and the outer surfaces were determined and it was pointed out that radiation between individual body segments is important. Similarly, Sakoi et al. [4] proposed a method for estimating the view factor that can be used in place of diagrams for large- and medium-scale spaces. Experimental study dealing with radiant temperature effects on thermal comfort with Predicted Mean Vote (PMV) scale was performed by Yang and Su [5]. Olesen and Parsons [6] described existing ISO standards and current activity concerned with thermal comfort including draught, vertical air temperature difference, floor temperature and radiant asymmetry which cause mostly local thermal discomfort. Holz et al. [7] dealt with energy performance simulation programme accompanied by comfort indications such as mean radiant temperature and air velocity. Butera [8] described the factors which affect thermal comfort conditions in detail and also summarized heat and mass transfer equations between body and environment. In addition, the change of PMV indices with operative temperature at various activity levels, air velocity and clothing were given. Kaynakli et al. [9] investigated the human thermal comfort for sitting and standing posture under steady-state conditions and Kaynakli and Kilic [10] examined the effects of clothing and air velocity on thermal comfort under transient conditions. But in these studies, the mean radiant temperature was assumed to be equal with ambient air temperature. In order to improve the present understanding of the human thermal comfort and HVAC system, further investigations still have to be carried out. On the other hand, Yumrutas et al. [11] developed an analytical solution method for the estimation of space heat gain and interior surface temperatures of buildings, but the effect of surface temperature on human thermal comfort has not been taken into consideration.

In this study, the effects of radiant temperature on the human thermal comfort are investigated. This paper comprises two purposes. One of them is to investigate the local differences between the body segments caused by high radiant temperature. For this aim, thermal interactions between human body and its environment are simulated to predict skin temperature of the individual body segments. In the simulation, PMV index is also calculated to discuss thermal comfort or discomfort. This simulation is based on Gagge 2-node model but includes some significant modifications over the Gagge 2-node model. The simulation is to apply the Gagge 2-node model to individual body segments rather than to the whole body. The human body is described by 16 cylindrical segments representing the head, hands, arms, etc. The required data for each of the body segments such as neutral temperatures of the core and skin layers, surface areas, and weights are taken from the existing literature. Using this simulation, time-dependent sensible and latent heat losses are obtained to determine PMV index. Time-dependent skin temperatures are also