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Experimental and theoretical investigation of the effect of radiation heat flux on human thermal comfort

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ABSTRACT

In this study, the effect of radiation heat flux from lighting lamps on human thermal comfort was investigated by both experimental and theoretical approaches. The experiments were carried out in an air-conditioned laboratory room in both the summer and autumn seasons. To determine the thermal response of a human body exposed to radiation heat flux from lighting lamps, a simulation model based on the Gagge model with some modifications was developed, and the effect of radiation heat flux from lighting lamps on human thermal comfort was investigated under transient conditions. The human body was separated into 16 sedentary segments, and the change in temperature was observed both experimentally and theoretically. During transient conditions, heat and mass transfer between the human body and the interior environment of a climate chamber were simulated using a computational model, and predictions were compared to the measured data. It is observed that there is a good agreement between the model predictions and experimental results.

1. Introduction

Lighting lamps play a significant role in increasing indoor air temperatures in shopping centers. Excessive use of lighting lamps for increasing the esthetic ambience of shopping centers affects the thermal comfort of customers and inmates. It has an especially adverse effect on the productivity of working personnel.

There have been many previous studies on thermal comfort. Atmaca and Yigit [1] investigated relative humidity effects on skin temperature and skin wettedness for different operative temperatures via simulation. In the simulation, the Gagge 2-node model was used with some significant modifications. The strength of the Gagge model is that, as a 2-node, lumped model, it is less complex than the Stolwijk or Wissler models. Therefore, the Gagge model is easier to use. However, this limits the amount of information it can provide with any given simulation and restricts the model to applications with uniform environmental conditions. Another shortcoming of the Gagge model is found in the control equations. There is considerable variation of the constants of these equations from one publication to another. This leads to questions as to why such variations appear, how these constants are determined, and whether one value should be used as opposed to another. However, simulation results appear insensitive to these constants values [2]. Atmaca et al. [3] examined the local differences between body segments caused by high radiant temperature to analyze the interior surface temperatures for different wall and ceiling constructions, taking into account their effect on thermal comfort by modifying the Gagge 2-node model. Zolfaghari and Maerefat [4] developed a model that accurately predicts thermal sensations of the bare, as well as the clothed, parts of the body. The prediction results are in good agreement with experimental and analytical results. Dongmei et al. [5] modified the Gagge's two-node model to develop a four-node thermoregulation model for a sleeping person. Tanabe et al. [6] developed a numerical method to predict the effective radiative area and the projected area of a human body in any posture. Tanabe et al. [7] improved the 65-node thermoregulation model based on the Stolwijk model. Pala and Oz [8] investigated thermal comfort of a bus HVAC design to compare the effects of changing parameters on the passenger's thermal comfort. Kaynakli and Kilic [9] described a combined theoretical and experimental study of thermal comfort during the heating period inside an automobile. Kaynakli et al. [10] studied a theoretical model of thermal interactions between a human and an interior environment using steady state conditions. Alfano et al. [11] studied mean radiant temperature measurement methodologies combined with a comparative analysis of metrological performances and practical principles. Liu et al. [12] investigated calculation methods for mean skin temperature based on experimental data. Kalmár and Kalmár [13] investigated the effect of the room geometry on the mean radiant temperature. Barna and Banhidi [14] examined the combined

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Nomenclature

A	surface area, m^2
A_D	DuBois surface area, m^2
C	convective heat transfer, W/m^2
C_{res}	sensible heat loss due to respiration, W/m^2
$c_{p,b}$	constant pressure specific heat of body tissue, kJ/kg K
$c_{p,bl}$	constant pressure specific heat of blood, kJ/kg K
$[CSIG]_{cr}$	cold signal from the core, dimensionless
$[CSIG]_{sk}$	cold signal from the skin, dimensionless
$(C+R)_t$	total sensible heat transfer, W/m^2
$E_{\max}$	maximum possible evaporative heat loss, W/m^2
E_{res}	evaporative heat loss due to respiration, W/m^2
E_{rsw}	evaporative heat loss due to regulatory sweating, W/m^2
E_{sk}	total evaporative heat loss from skin, W/m^2
h_c	convection heat transfer coefficient, W/m^2 K
h_{fg}	heat of vaporization of water, kJ/kg
h_r	radiation heat transfer coefficient, W/m^{2}K
i	body segment number, dimensionless
j	air or fabric layers number, dimensionless
k	thermal conductivity of the air, mm W/m^2 °C
K	effective conductance between core and skin, W/m^2 K
l	body height, m
LR	Lewis ratio, °C/kPa
M	total rate of body heat production, W/m^2
M_{met}	metabolic heat production, W/m^2
M_{shiv}	shivering heat production, W/m^2
m	body mass, kg
m_{bl}	blood circulation between core and skin, kg/m^2 s
m_{rsw}	rate of regulatory sweat generation, kg/m^2 s
nl	number of layers covering segment, dimensionless
P_a	water vapor pressure in ambient air, kPa
$P_{sk,s}$	water vapor pressure saturated at skin temperature, kPa
$Q_{cr,sk}$	heat flow from core to skin, W/m^2
$Q_{r,sk}$	radiation heat flux from lighting lamps to skin, W/m^2
R	radiative heat transfer, W/m^2
r	radius, m
R_a	thermal resistance of outer air layer, m^2 °C/W
R_{al}	thermal resistance of air layer, m^2 °C/W
$R_{e,a}$	evaporative resistance of outer air layer, m^2 kPa/W
$R_{e,a}$	evaporative resistance of air layer, m^2 kPa/W
$R_{e,f}$	evaporative resistance of fabrics, m^2 kPa/W
$R_{e,t}$	total evaporative resistance, m^2 kPa/W
R_f	thermal resistance of fabrics, m^2 °C/W
R_t	total thermal resistance, m^2 °C/W
S_{cr}	heat storage in core compartment, W/m^2
S_{sk}	heat storage in skin compartment, W/m^2
X	air layer thickness, mm
t_a	ambient air temperature, °C
$t_{b,m}$	average of the body temperature, °C
t_{cr}	core temperature, °C
$t_{cr,m}$	mean core temperature, °C
t_o	operative temperature, °C
t_r	mean radiant temperature, °C
t_{sk}	skin temperature, °C
$t_{sk,m}$	mean skin temperature, °C
w	skin wettedness, dimensionless
W	external work accomplished, W/m^2
w_{rsw}	required to evaporate regulatory sweat, dimensionless
$[WSIG]_b$	warm signal from the body, dimensionless
$[WSIG]_{cr}$	warm signal from the core, dimensionless
$[WSIG]_{sk}$	warm signal from the skin, dimensionless
α	fraction of total body mass concentrated in skin compartment, dimensionless
θ	time, s

influence of the radiant temperature asymmetry and warm floors in a climate chamber.

Previous thermal comfort studies related to radiation have only examined the asymmetric radiation effects of different wall temperatures on human thermal comfort. Lighting lamp affects on human thermal comfort have not been investigated for indoor environment conditions. In the present study, a simulation model based on the Gagge model [15–17] with some modifications was developed, and the effect of the radiation heat flux on thermal comfort, with respect to lighting lamps inside the climate chamber, was investigated. The details of the mathematical model are presented, and the predictions obtained by the model are compared with the experimental results in order to validate the model.

2. Mathematical modeling

This simulation is based on the Gagge 2-node model but includes some modifications. The simulation applies the Gagge 2-node model to individual body segments rather than to the whole body. The human body is divided into 16 cylindrical segments [18,19] representing the head, hands, arms, etc. Each of these segments consists of two body layers (core and skin) and a clothing layer. The DuBois surface area, weights and neutral core temperatures of the 16 body parts are shown in Table 1. The letter "i" (1–16) represents the body segment number in the following equations, and the body segment names can be found in Table 1. The neutral skin temperatures of the body segments obtained from the experimental studies are shown in Table 2. In this model, the heat storage equations for the core and skin layers can be expressed as follows:

$$S_{cr}(i,\theta) = M - W - [C_{res}(i,\theta) + E_{res}(i,\theta)] - Q_{cr,sk}(i,\theta) \quad (1)$$

$$S_{sk}(i,\theta) = Q_{cr,sk}(i,\theta) - [C(i,\theta) + R(i,\theta) + E_{sk}(i,\theta)] \quad (2)$$

Table 1
The neutral core temperatures, DuBois surface areas, and weights of the body segments [7].

i	Body segments	Neutral core temperature (°C)	DuBois surface area (m^2)	Weight (kg)	Height (m)
1	Left foot	35.1	0.056	0.480	
2	Right foot	35.1	0.056	0.480	
3	Left leg	35.6	0.112	3.343	
4	Right leg	35.6	0.112	3.343	
5	Left thigh	35.8	0.209	7.013	
6	Right thigh	35.8	0.209	7.013	
7	Pelvis	36.3	0.221	17.57	
8	Head	36.9	0.140	4.020	
9	Left hand	35.4	0.050	0.335	
10	Right hand	35.4	0.050	0.335	
11	Left arm	35.5	0.063	1.373	
12	Right arm	35.5	0.063	1.373	
13	Left shoulder	35.8	0.096	2.163	
14	Right shoulder	35.8	0.096	2.163	
15	Chest	36.5	0.175	12.40	
16	Back	36.5	0.161	11.03	
	Whole body		1.87	74	1.72