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Toward better estimation of HVAC Loads: integrating a detailed human thermal model into building simulation

Mohamad Rida[a], Nicolas Kelly[a]*

[a]*University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ, UK*

Abstract

The transient nature of the occupant heat load is not fully addressed and implemented in a building simulation tool. In this paper, the effect of using dynamic occupant heat loads in building simulation on energy building performance and occupant thermal comfort has been studied. A two-node thermoregulatory model was integrated into ESP-r. The predictions of the integrated two-node model were compared to two commonly used approaches in building simulation: gains modelled as a basic fixed profile and gains modelled using a polynomial function of temperature and relative humidity. The variation in occupant thermal load demonstrated appreciable differences on both cooling and dehumidification loads.

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Keywords: Dynamic occupant heat loads, Human thermal comfort, Occupant thermoregulation, Building simulation.

1. Introduction

Building simulation software is an important tool in assisting building designers to reduce the energy consumption in buildings and their environmental systems. However, the effectiveness of building simulation relies on good models and plausible data inputs. While during the design process occupant loads are often represented in building simulation

* Corresponding author. Tel.:+44-141-574-5083 ; fax: +0-000-000-0000 .
E-mail address: mohamad.rida@strath.ac.uk

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as a fixed schedule e.g. [1]. Whereas, the prediction of comfort using simulation tools becomes difficult in low-energy, well-insulated building designs, which are often lightweight and so temperature is sensitive to excitations such as occupant heat gains. To improve the prediction of thermal behaviour in building such as these, gains from occupants should be represented dynamically, recognising that human thermoregulatory physiology changes considerably as the surrounding environment thermal condition changes.

This paper presents a series of increasingly more complex human thermal models, integrated within the ESP-r building simulation tool and contrasts performance predictions with those emerging from simulations using less rigorous representations of occupant gains.

Nomenclature

T_{cr}, T_{sk}	Skin and core temperature.
C_{cr} , C_{sk}	Skin and core thermal capacitance of body.
M_{cr} and M_{sk}	Basal core and skin metabolic rate.
M_{Shiver}	Thermoregulatory shivering metabolic rate.
W	Mechanical work done by the body.
Q_{res}	Heat dissipated through respiration.
$Q_{cr\text{-}sk}$	Heat exchange between the core and skin through contact resistance.
$\dot{m}_{bl,sk}$	Skin blood flow
C_{bl}	Specific heat constant of blood.
hc	External convection heat transfer coefficient between the skin and the surroundings
hr	Radiation transfer coefficient
he	Evaporation coefficient deduced from hc by Lewis formula
T_{amb}	Surrounding air temperature,
$\bar{T}_{amb\_mrt}$	Mean radiant temperature,
P_{amb}	Ambient vapour pressure
P_{sk}	Skin vapour pressure
$\dot{m}_{sweat}$	Sweating rate
T_{sweat}	Sweating threshold temperature

1.1. Occupant Modelling

Human thermal models have been developed, improved and investigated for many years, with the first work emerging from in aerospace and military research [2]. Models can encompass interactions between the occupant and their thermal environment, perceptions of comfort and the interaction between the occupants and their physical environment [3]. Focusing on comfort, Fanger's PMV (1972) model was based on experiments done in uniform and steady-state thermal environments and is more suited to traditional commercial, air conditioned buildings. Humphreys and Nicol [4] concluded that the PMV method is only valid for prediction of thermal comfort under tightly controlled conditions. Many types of research showed the limitation of the PMV/PPD, especially when used in non-uniform and transient thermal environmental conditions [5] and other argued that PMV cannot take into consideration the differences between ages and genders [5,6]. More recently, de Dear et al. [7] Introduced the adaptive model where he argued that the person should not be studied as a passive recipient in a given thermal environment; instead, the individual should be simulated as an active agent interacting with their environment via multiple feedback loops. They also showed the difference in thermal comfort responses of a person in an air-conditioned environment vs. naturally ventilated building. The adaptive thermal is based on three different processes the behavioural adjustment, physiological acclimatisation and psychological habituation [7]. Research into the modelling of human thermoregulation and the interaction with thermal environments has a similarly long history. The thermoregulatory system defined as the physiological system responsible for maintaining the core temperature at a reasonable level by gaining or losing heat [8].

The majority of human thermal models are based on the work of Stolwijk [9] where the thermoregulatory system divided into two systems passive and active. The passive system is the heat exchange from the human body through its surrounding, it occurred by the different way of heat transfer, convection, evaporation and by conduction. There are three types of thermoregulatory responses which increase or decrease heat production and regulate heat loss from a person. The vasomotor, sudomotor and metabolic those called the active system [8,10].

Gagge's two-node model is broadly used to study the human body thermal response and to predict thermal sensation under transient environmental conditions. Gagge represents the human body as two concentric cylinders the first composed of skin and tissues layer and the second one of the skeleton, muscles and internal organs. His model based on the energy balance equations for the two-node, skin and core [11]. Zolfaghari et al. [12] based on the Gagge's model developed a simplified three nodal thermal sensation model. Where the human body was divided into three-lumped compartment: core, bare skin and clothed skin. Other researchers developed more detailed models with a higher number of nodes by dividing the human body into segments where each one constituted of a number of layers [8,9,10,13,14].

These models have been limited to study the human thermal comfort for a specific transient room thermal condition [15]. For more realistic predictions of occupant sensible and latent heat load inside buildings, a human thermal model of two nodes has been developed for ESP-r. The model is based on the Gagge model with improvement in skin blood flow and including clothing resistant.

2. Models and Implementation

The aim of this paper is to integrate a thermoregulatory model within the ESP-r building simulation tool and to compare the performance of this more detailed model to alternative, less rigorous approaches. A phased implementation was adopted, where the two-node thermoregulatory model was integrated into ESP-r and its predictions were compared to two commonly used approaches in building simulation: gains modelled as a fixed profile and gains modelled using a polynomial function of temperature and relative humidity.

2.1. Two-Node Model

The thermoregulatory model comprises a core and skin volume. Each of which can be subjected to an energy and mass balance. The model accounts for the variation in the occupant surrounding environmental condition (zone temperature and relative humidity), occupant activity rate and clothing level.
The energy balance equation used to calculate the body core temperature is as follows.

$$C_{cr}\frac{dT_{cr}}{dt} = M_{cr} + M_{shiv} - W - Q_{res} - Q_{cr\text{-}sk} + \dot{m}_{bl,sk}c_{bl}(T_{sk} - T_{cr}) \tag{1}$$

The equation to calculate the skin temperature is:

$$C_{sk}\frac{dT_{sk}}{dt} = Q_{cr-sk} - A_{sk}\left[h_c\left(T_{sk} - T_{amb}\right) + h_r\left(T_{sk} - \overline{T}amb_{mrt}\right) + h_e\left(P_{sk} - P_{amb}\right)\right] + \dot{m}_{bl,sk}c_p\left(T_{cr} - T_{sk}\right) \tag{2}$$

Skin blood flow $\dot{m}_{bl,sk}$ is variable and it depends on the body thermal state. The relation below defines the blood vessel constriction term from the cold thermal signal of the skin

$$Con = 0.5\times\left(T_{sk} - 33.7\right) \tag{3}$$

While the blood vessel dilation factor is calculated, using the equation below related to warm core thermal signal.

$$Dil = 3.43\times\left(T_{cr} - 36.8\right) \tag{4}$$

Skin blood is given by the relation addressed below taken from Foda et. al [16]

$$\dot{m}_{bl,sk} = \left(6.3 + 60\times Dil\right)/\left(1 + Con\right) \tag{5}$$

For the sweating rate, we adopted the correlation introduced by Smith [8] where sweating is sensitive to skin and core temperature.
First, the sweating threshold temperature is calculated from the correlation below

$$T_{sweat} = \begin{cases} 42.084 - 0.15833 T_{sk} & for\, T_{sk} < 33°C \\ 36.85 & for\ T_{sk} \geq 33°C \end{cases} \quad (6)$$

The sweat rate is given by a relationship of the difference between sweat threshold and core temperature.

$$\dot{m}_{sweat} = 45.8 + 739.4\left(T_{cr} - T_{sweat}\right) \qquad T_{cr} > T_{sweat} \quad (7)$$

The model has been integrated within the ESP-r. The user needs to specify the number of occupants (women, men and children) metabolic rate and clothing level; and after that, the model calculates the resulting heat and moisture gains. If a conventional ESP-r model is employed then these are injected to the air point of the zone where the occupant is situated.

2.2. Comparison Case

The predictions of the two-node model have been compared to two other approaches in order to gauge the impact of the more detailed modelling approach. The two approaches to modelling heat gains commonly used in building simulation are to represent heat and moisture loads as either 1) a time-varying profiles or 2) as a polynomial equation where the heat and moisture gains from an occupant are expressed as a function of the operative temperature and metabolic rate, as can be employed in tools such as EnergyPlus [17].

To facilitate this comparison, a polynomial-type model has been integrated into ESP-r. The polynomial was based on regression published data of sensible and latent heat loads from steady state data of ASHRAE [18] for some activity level and different room temperature, in addition to the data presented by Clark H. et al. [19] a study of heat loads released from occupants. The resulting 2nd order regression equations are for both sensible and latent heat load from the occupant of a large range of metabolic rate and operative temperature.

$$Sensible\, heat\, load = 198.42617 - 3.80901 T_{op} - 0.05419 T_{op}^2 - 0.42472 Met + 0.00171 Met^2$$
$$+0.01287 T_{op} Met - 0.00004 T_{op} Met^2 + 0.00002 Met T_{op}^2 - 3.8516 \times 10^{-7}\, Met^2 T_{op}^2 \quad (8)$$

$$Latent\, Heat\, load = 227.89011 - 14.95202 T_{op} + 0.24884 T_{op}^2 - 2.56734 Met + 0.00715 Met^2$$
$$+0.132 T_{op} Met - 0.00017 T_{op} Met^2 - 0.00107 Met T_{op}^2 \quad (9)$$

All three approaches have been applied to a test office (Figure 1) building. This comprises four main zones: a reception of 71 m^2 base area a general room of 77m^2 a conference room of 62m^2 and a manager's office of 13.5m^2. Figure 5 shows the model geometry.

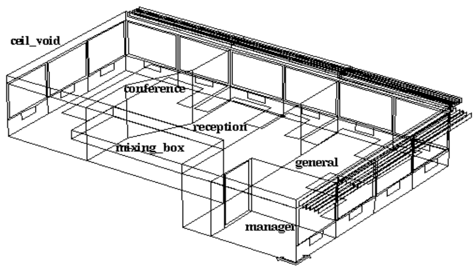

Figure 1 ESP-r Office Model

The construction data are shown in Table 1 and the occupancy schedule is shown in Table 2

Table 1: Selected constructions used in the model

Construction	U-value (W/m2K)
Ceiling	0.323
Floor	1.32
External wall	0.21
Double glazed window	2.243

For the occupant thermal model, clothing resistance is chosen to be 1 clo for all occupants.

Table 2 occupancy loads schedule for zone 'general'

Time (hrs)	No. of occupants	Sensible/Latent gain (W)	Metabolic rate (met)
0000-0700	0	0/0	0
0700-0800	1	100/60	1.54
0800-0900	3	300/180	1.54
0900-1200	5	500/300	1.54
1200-1400	3.25	325/195	1.54
1400-1700	5	500/300	1.54
1700-0000	0	0/0	0

The predictions of all three models were compared in a simulation of a typical summer week using climate data for London, UK.

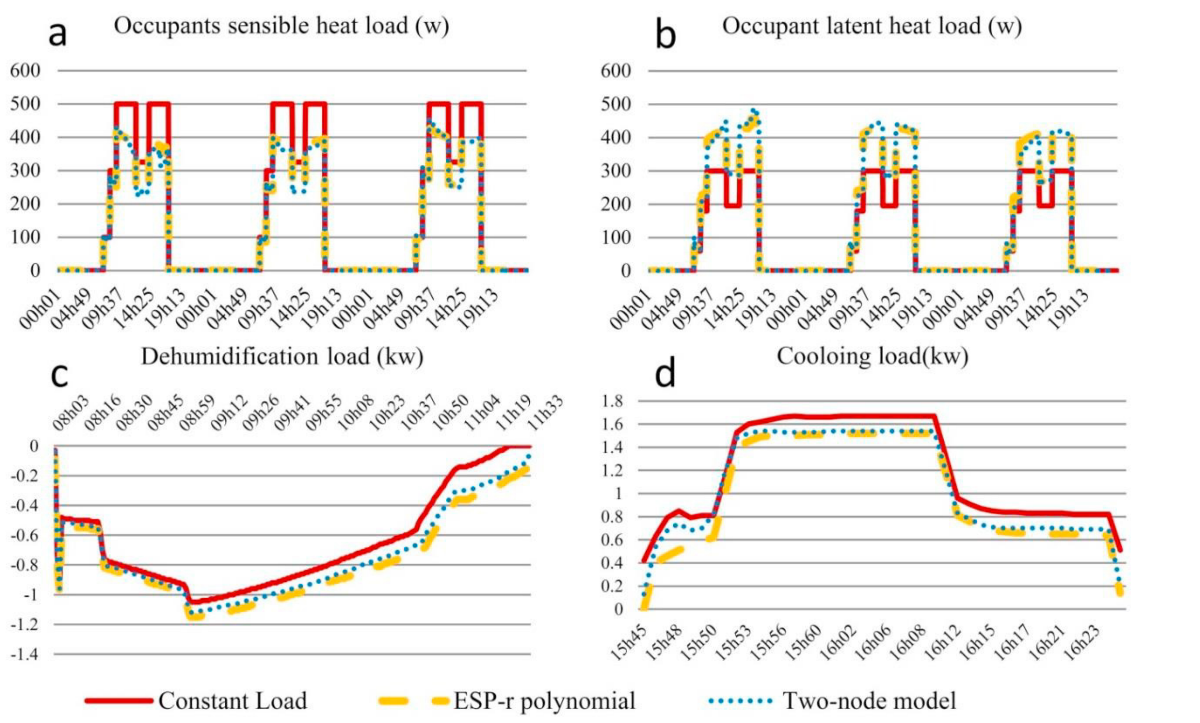

Figure 2 a,b, sensible and latent heat load from the different models c- Latent load – typical day (-ve implies dehumidification) d- Sensible cooling load – typical day.

Results in Figures 2 (a) and (b) show the input sensible and latent load from the occupants of the ‘General’ room of the model as derived from the various modelling approaches. The figures show that there are substantial differences between the dynamic polynomial or two-node models and the commonly used fixed value approach, with the sensible load over-predicted using fixed values and latent load under predicted in this case.

Figures 6 (c) and (d) show the latent cooling load and the sensible cooling load, when the air temperature of the general space is cooled to 25ºC and the RH restricted to 50%. Both show appreciable differences between the fixed and dynamic modelling approach, which could have an impact if the results were being used to select plant size.

Conclusion

The paper deals with the modelling of the thermal interactions between building occupants and their thermal environment. Different levels of modelling complexity are examined, looking at the different approaches to modelling occupants basic fixed profiles, functions of temperature and metabolic rate through to a dynamic multi-zone model. The two-node model has been integrated into the ESP-r building simulation tool. Subsequently, the impact of using fixed profiles contrasted against more dynamic models, demonstrating appreciable differences in a) the levels of internal sensible and latent gains and b) calculated cooling and dehumidification loads. However, further work will be conducted on developing and implementing a segmented detailed human thermal model within the CFD solver in ESP-r, to study local comfort.

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