MODELING HUMAN RADIATION EXCHANGE IN OUTDOOR URBAN ENVIRONMENTS

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Abstract

Results from the radiation components of five existing human thermal exchange models (COMFA, MENEX, PET, OUT_SET* and Burt models) for outdoor areas along with the 6 directional method and a new model employing projected area factors ($f_p$) and effective radiation area factors ($f_{eff}$) determined from a sample of contemporary Caucasian adults in Canada were compared.

Most differences between models came from absorbed solar radiation because of differences in $f_p$ and $f_{eff}$. Some models do not directly employ $f_{eff}$ and/or $f_{eff}$ values of directly-exposed-to-hemispherical-sources-of-diffuse radiation. The ranges between models for absorbed solar, net longwave and total net-radiation were 146, 41 and 186 Wm$^{-2}$, respectively. These differences between models can be significant in total human thermal exchange.

Keywords

Human body area factor · Radiation · Outdoor area

1. INTRODUCTION

A number of human thermal exchange models have been developed which include all important modes of energy exchange. Some of those capable of use in outdoor urban environments are the Burt model (Burt 1979 and Burt modified by Tuller 1990), COMFA (COMfort FormulA; Brown and Gillespie 1986, Kenny et al. 2008), MENEX (Man-ENvironment heat Exchange; Blazejczyk 1994, 2004), PET (Physiological Equivalent Temperature, Höppe 1993) and OUT-SET* (Pickup and de Dear 2000).

Urban outdoor environments have a very important and different climatic variable compared with indoor environments, solar radiation. Insolation effectively raises the apparent temperature nearly 14°C under calm conditions and 7°C in a strong wind (Steadman 1971). Each increase of direct beam solar radiation of around 200 Wm$^{-2}$ increases PMV (Predicted Mean Vote, Fanger 1972) by one sensation scale unit (Hodder and Parsons 2007).

In this study, results from the radiation components of five existing human thermal exchange models (COMFA, MENEX, PET, OUT_SET* and Burt models) along with the 6 directional method (VDI 1998) and a new model (Park and Tuller model) employing recently derived average body area factors of standing and walking postures determined from a sample of normal- and over-weight Caucasian adults in Canada were compared. Emphasis is on the effect of differences in human body area factors.

2. MATERIALS AND METHODS

Total absorbed radiation on the human body surface ($Q$) is the sum of absorbed solar radiation ($R$) and net longwave radiation ($L$) on the surface: $Q = R + L$ (Wm$^{-2}$).

To compare the models simply, the effect of clothing was not included. The albedoes of a body surface ($\alpha_b$), objects in the sky hemisphere ($\alpha_o$) and ground ($\alpha_g$) and emissivity ($\epsilon_b$) of the body surface were set to 0.3, 0.2, 0.3 and 0.97, respectively. These values were used in many previous modeling studies. Incoming direct beam ($K_b$), diffuse beam ($K_d$), reflected ($K_r$) by vertical objects (buildings, trees and other structures) in the sky hemisphere ($K_{ov}$) and by the ground ($K_{rg}$), solar radiation, and longwave radiation coming from objects (buildings, trees and other structures) in the sky hemisphere ($L_{ov}$) and ground ($L_g$) before being absorbed by the human body surface were set to constant, observed values and were directly used in all radiation models. Gagge et al. (1969) found skin temperatures ($T_{sk}$) was between 27 °C and 36.5 °C in steady state conditions. Differences in effective radiation area factors ($f_{area}$) on human longwave radiation are very insensitive to skin temperature. A $T_{sk}$ of 31 °C was employed in this study.

To compare the existing radiation models, clear summer data collected at 3 times at 13 measurement sites were used: in the morning (7:30~9:00 A.M.), at noon (11:30~1:00 P.M.) and in the afternoon (3:30~5:00 P.M.) (Fig. 1). The research site was Winegard Walk at the University of Guelph, Guelph, Ontario, Canada. The latitude and longitude of the site are 43°32’N 80°14’W. The average ground elevation is 345 m ASL. For this study, only the data observed at sunny locations were used: 4 locations (No. 1, 8, 9, 11) in the morning, all locations at noon, and 8 locations (No. 1, 3, 5, 8, 9, 10, 11, 13) in the afternoon. Solar and longwave radiation flux density data were collected from six directions (up- and downward and the four cardinal directions) with a Kipp & Zonen CNR1 Net-Radiometer. For more detail, see Park (2003).

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The quantities of absorbed solar and net longwave radiation on the body surface area were compared among the models. The differences among them would be caused by their adopted different concepts of body shapes which resulted in various body area factors. They also use different formulas to estimate sky emissivities ($e_{sky}$) in longwave radiation algorithms. The important body area factors are the effective radiation area factor ($f_{eff}$) and projected area factor ($f_p$). Body shape and posture control the area exposed to direct beam solar radiation (projected area, $A_p$) and the proportion of the total body surface area exposed to the surrounding radiant environment rather than to other body parts (effective radiation area, $A_{eff}$). $f_p$ is $A_p / A_{eff}$ and is used in the calculation of absorbed direct beam solar radiation. $f_{eff}$ is $A_{eff} / A_D$ (where $A_D$ is the total body surface area) and is employed to estimate all solar and longwave exchanges. In this study, converted projected area factors ($f_p^*$ = $f_p$ × $f_{eff}$) were used in computing absorbed $K_b$ because the OUT_SET*, COMFA, Burt and MENEX models used $f_p$ directly in their formulas.

**Park and Tuller model**

$$R = \left( f_p \cdot f_{eff} \cdot \frac{K_b}{\sin \theta} \right) \left( 1 + \frac{1}{2} f_{eff} \left[ K_b \psi_{sky} + (K_b t + K_a (1 - \psi_{sky})) \alpha_2 + (K_b t + K_a \psi_{sky} + K_{ro}) \alpha_0 \right] \right) (1 - \alpha_b)$$

$$L = \frac{1}{2} f_{eff} e_b e_{sky} \sigma (T_a + 273)^4 \psi_{sky} + e_0 \sigma (T_a + 273)^4 (1 - \psi_{sky}) + e_0 \sigma (T_a + 273)^4 \left[ 1 - e_{sky} \sigma (T_a + 273)^4 - f_{eff} e_b \sigma (273 + T_b)^4 \right] \frac{1}{2} f_{eff} e_b \sigma (273 + T_b)^4$$

where $\theta$ is solar altitude, $t$ is transmissivity and $\psi_{sky}$ is the sky view factor.

The average directionless $f_p$ of standing and walking postures can be calculated with a formula, $f_p = 3.34E - 07 \theta^3 - 6.60E - 05 \theta^2 + 8.42E - 04 \theta + 0.297$. The formula estimates measured $f_p$ within 0.002. The average value of $f_{eff}$ for standing and walking postures from a sample of Caucasian male and female adults in Canada, 0.836, was used. $f_{eff}$ can be obtained from $f_p \times f_{eff}$. The radiation formulas of the other models can be found in the literature. Key variables for the comparison in this study are $f_p$ and $f_{eff}$ in absorbed solar radiation and $f_{eff}$ and $e_{sky}$ in net longwave radiation. The various $f_p$ and $f_{eff}$ values used in the models are listed in Table 1.

**Table 1. The various $f_p$ and $f_{eff}$ values used in the models$^1$**

<table>
<thead>
<tr>
<th>Model</th>
<th>$f_{eff}$</th>
<th>$f_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td>0.725</td>
<td>$f_p = 3.81E - 07 \theta^3 - 6.55E - 05 \theta^2 + 3.02E - 04 \theta + 0.308$</td>
</tr>
<tr>
<td>OUT_SET*</td>
<td>0.75</td>
<td>$f_p = (0.42 \cos \theta + 0.043 \sin \theta)$</td>
</tr>
<tr>
<td>COMFA</td>
<td>0.78</td>
<td>$f_p^* = \frac{1}{\tan \theta}$</td>
</tr>
<tr>
<td>Burt</td>
<td>0.725</td>
<td>$f_p^* = 4.278 \exp(-0.0512 \theta)$ if $\theta \leq 5^\circ$, $f_p^* = 1.45^{(-0.51 + 0.36 \theta)}$ if $\theta &gt; 5^\circ$, $f_p^* = \frac{2634}{\theta} - 0.329$</td>
</tr>
<tr>
<td>MENEX</td>
<td>No use</td>
<td>$f_p = 3.34E - 07 \theta^3 - 6.60E - 05 \theta^2 + 8.42E - 04 \theta + 0.297$</td>
</tr>
</tbody>
</table>

$^1$ $f_p^* \times f_{eff}$. The OUT_SET*, COMFA, Burt and MENEX models used $f_p$ directly in their formulas.
3. RESULTS AND DISCUSSION

\( f_p \) is important in estimating human direct beam solar radiation. The greatest differences between models occur at low solar altitudes, up to 0.3 at \( \theta = 20^\circ \) (Fig. 2). They are in the range of about 0.12 - 0.14 between \( \theta = 60^\circ \) and \( 80^\circ \). Effects in urban modeling applications would depend on the urban morphology. They would be greater in more open landscapes where people on the ground are exposed to the low angle sun but be much less of a factor in low sky view factor environments where direct beam solar radiation will only reach the ground at high solar altitudes. \( f_p \) in three of the models, COMFA, PET and Park & Tuller, are relatively close and follow the same general trend through the entire range of solar altitudes.

All 5 radiation estimation models and one experimental model, the 6 directional method, were compared in absorbed solar, net longwave and total net radiation (Fig. 3).

There was a large range in computed human absorbed solar radiation between models at times and locations (150 - 175 Wm\(^{-2}\)) (Fig. 3a). Model results fall into two groups in the morning and afternoon when solar altitudes were lowest. The PET, Park & Tuller, COMFA and 6-direction method model results comprise the low-value group. Human absorbed solar radiation computed via the OUT_SET*, MENEX, and Burt models were about 100 Wm\(^{-2}\) greater than the lower-value group. The Burt model joined the lower-value group at noon.

Morning and afternoon differences in absorbed solar radiation reflect the lower solar altitude differences in \( f_p \) values (Figs. 2 and 3a). Absorbed diffuse beam and solar radiation reflected from the surroundings computed via the MENEX model were higher than those from other models (Fig. 3d). Employed \( f_{eff} \) values also create some differences between the models (Table 1 and Fig. 3a).

Maximum time & location differences in net longwave radiation were less than 39 Wm\(^{-2}\) (Fig. 3b). The differences between models were consistent. The major control was differences in \( f_{eff} \) values.

Differences in total net-radiation were largely determined by those in absorbed solar radiation (Figs. 3c and 3a). The differences explained above between the Park & Tuller model and the other models were shown in the averaged values by time in Fig. 3d.

4. CONCLUSION

Radiation data collected from six directions were used to compare the radiation components of 5 existing human thermal exchange models (COMFA, MENEX, PET, OUT_SET* and Burt models) for outdoor areas and one experimental model (6 directional method from VDI 3787 (1998)).

The major differences in human net-radiation between models were from the absorbed solar radiation component. Moreover, the \( f_p \) values were a major contributor to the absorbed solar radiation differences. Direct beam solar radiation incident on a human body has a major effect on the human total net radiation, but the effect
in urban outdoor areas can be limited because of the shadows created by urban morphology. Diffuse and reflected solar radiation controlled by $f_{att}$ can be a key variable in dense urban outdoor areas. The $f_{att}$ differences were constant for all times and locations yielding relatively consistent differences between models in the various components of human-environment radiation exchange. The differences of $f_{p}$ and $f_{att}$ make a significant contribution to the human radiation exchange.

Therefore, proper $f_{p}$ and $f_{att}$ values should be used to make an accurate estimation of absorbed solar and net longwave radiation. The Park & Tuller model’s body area factors ($f_{p}$ and $f_{att}$) are close to those of a number of recent studies and seem to hold promise for improving radiation analysis in human thermal exchange models.

References