Predict the quality of outdoor thermal environment with equivalent transformation of thermal boundary condition models

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ABSTRACT
As a worldwide used commercial CFD software, FLUENT, with later version combined with solar model, has comparably robust computational core for airflow and solar radiation. However, for complex heat exchange between airflow and urban underlying surface, FLUENT with built-in boundary condition models has obvious deficiency in the discription of heat balance of urban underlying. Based on the form of mixed boundary condition model included in FLUENT, this paper proposes equivalent absorptivity coefficient to describe the absorption of solar beam radiation with the consideration of vegetation shadow and evaporation cooling effect. This paper also presents equivalent form for convective heat transfer between surface and free stream flow, combined with heat flux into building interior zone and underground soil. For long wave radiant heat transfer from surface to sky and ground, this paper puts forward equivalent form suitable for FLUENT radiation boundary condition model. Compared with experimental data of underlying surface temperature in a residential district, equivalent transformation of thermal boundary condition model is validated.

KEYWORDS
Computational fluid dynamics simulation, Quality of outdoor thermal environment, Equivalent transformation of thermal boundary condition models

1. INTRODUCTION
Considering climate change and rapid trend towards urbanization, research work of urban microclimate is gaining importance. The Urban Heat Island (UHI) effect can significantly affect urban microclimate with negative consequences for human mortality, morbidity and building energy demand. Although there are several subtopics which can be a part of urban microclimate research (e.g. wind flow, water balance, energy exchange), the urban temperature field and the UHI effect constitute some of the most common subjects covered (Arnfield 2003). According to the review paper by Mirzaei and Haghighat (2010), techniques to study the UHI effect can be divided into two groups. One is termed “observational approaches” which can be field measurements, thermal remote sensing or small-scale modeling (models built for wind-tunnel tests or for measurements in the outdoor environment). The other group is called “simulation approaches” which can be either energy balance models or numerical studies using Computational Fluid Dynamics (CFD). The main advantage of simulation studies compared to observational studies is

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the possibility to perform comparative analyses based on different scenarios. Moreover, as opposed to observational studies, simulations can provide results for any relevant variable in the whole computational domain. On the other hand, the main drawback of simulation approaches is the necessity to apply several simplifications, as the mechanism of airflow and heat exchange over underlying surface is very complex. Therefore, effective validation of the simulations is very important. Generally speaking, there are two types of simulation approaches according to the simulation tools used. One approach is the simulation performed with self-programmed software package, like Simulation Platform for Outdoor Thermal Environment (SPOTE) developed by Lin (2008) and coupled simulation tools proposed by Ooka (Chen and Ooka 2004). Consisting of airflow model, energy model, radiation model, vegetation model and underlying surface model, self-programmed simulation tools can perform complex numerical simulation with more reliability. Powerful as computational cores are, self-programmed software packages have apparent shortcomings in grid mesh for objects with complex geometry, which seriously confines the application in comparably simple project. The other approach is the simulation carried out with commercial CFD software, like ANSYS FLUENT. Although commercial CFD software has flexible mesh methods to adapt objects with complex shape, general while fixed forms of thermal boundary condition model are unsuitable to describe heat balance on underlying surface. However, it is cheap and reachable for the simulation performed with commercial CFD software (Toparla 2014). Therefore, to improve the reliability of commercial CFD software in urban microclimate analysis, equivalent transformation of built-in thermal boundary condition model is desperately needed. This paper proposes equivalent transformation of thermal boundary condition model built in FLUENT to describe heat balance of underlying surface.

2. METHODOLOGY

The mixed thermal boundary condition model built in FLUENT can be written as follows (Fluent Inc. 2005):

\[ q = \alpha_f (T_w - T_f) + \varepsilon_{ext} \sigma (T_{\infty}^4 - T_w^4) \]  

(1)

where \( \alpha_f \) is convective heat transfer coefficient, \( \varepsilon_{ext} \) is surface emissivity, \( T_w \) is wall temperature, \( T_f \) is fluid temperature, \( T_{\infty} \) is environment radiant temperature.

Formula (1) only describes convective and radiative component. In order to simulate urban microclimate accurately, several physical phenomena should be considered, which can be expressed as UHI causes. Oke (1982) identified the following possible UHI causes: 1. Amplified short-wave radiation gain; 2. Amplified long-wave radiation gain from the sky; 3. Decreased long-wave radiation loss; 4. Anthropogenic heat sources inside urban areas; 5. Increased heat storage; 6. Less evapotranspiration; 7. Decreased turbulent heat transport. To involved those complex UHI causes, heat balance of underlying surface can be written as follows (Chen and Ooka 2004):

\[ S_i + R_i + H_i + C_i + L \cdot E_i = 0 \]  

(2)

where \( S_i \) is solar beam radiant heat gains, \( R_i \) is long wave radiant heat gains, both
from sky and ground, $H_i$ is convective heat gains from fluid, $C_i$ is conductive heat loss to building interior zone and ground soil, $L \cdot E_i$ is latent heat loss due to evapotranspiration or evaporation, $L$ is latent heat, and $E$ is evaporation rate.

To observe the form of mixed thermal boundary condition model built in FLUENT, equivalent transformation is needed to make each item in formula (2) to be included in boundary condition model. For solar beam heat gains, solar calculator built in FLUENT considers a beam using the position of the sun at any time during a year and applies radiative heat flux on all of the wall type boundaries. However, FLUENT takes no consideration of vegetation evapotranspiration, leading to amplified short-wave radiation gain. In FLUENT, vegetation shadow effect and evapotranspiration can be included by equivalent transformation of absorptivity coefficient, which can be defined as follows:

$$\rho_{s,e} = \frac{\rho_s I_s - L \cdot E - \rho_s (1 - \tau_s) \xi I_s}{I_s}$$  \hspace{1cm} (3)

where $\rho_s$ is surface absorptivity coefficient, $\tau_s$ is transparency coefficient of plant crown, $\xi$ is shadow area ratio of plant crown on the ground, $I_s$ is total solar beam radiant heat on the underlying surface.

For radiant heat gains, components of radiant heat transfer from surface to sky and that from surface to ground are both considered as follows:

$$R = C_b \varepsilon_{0,0} \varphi_{0,0} \left[ \left( \frac{T_e}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] + C_b \varepsilon_{0,g} \varphi_{0,g} \left[ \left( \frac{T_w}{100} \right)^4 - \left( \frac{T_g}{100} \right)^4 \right]$$  \hspace{1cm} (4)

The equivalent item of radiant component can be described as following form:

$$C_b \varepsilon_{e,0} \left[ \left( \frac{T_w}{100} \right)^4 - \left( \frac{T_{s,e}}{100} \right)^4 \right]$$  \hspace{1cm} (5)

Where $T_{s,e}$ is equivalent temperature of sky, which can be calculated as follows:

$$T_{s,e} = T_s \left( \frac{\varepsilon_{e,2}}{\varepsilon_{e,1}} \right)^{1/4}, \text{ in which } T_s = \frac{4}{0.51 + 0.208 \sqrt{a} \cdot T_a}$$  \hspace{1cm} (6)

Where $a$ is the pressure of vapour in atmosphere, $T_a$ is atmosphere temperature. $\varepsilon_{e,1}$, $\varepsilon_{e,2}$ are equivalent coefficients of surface emissivity, calculated by following formula.

$$\varepsilon_{e,1} = \varepsilon_{0,0} \varphi_{0,0} + \varepsilon_{0,g} \varphi_{0,g} \varepsilon_{e,2} = \varepsilon_{0,0} \varphi_{0,0} + \varepsilon_{0,g} \varphi_{0,g} \left( \frac{T_g}{T_s} \right)^4$$  \hspace{1cm} (7)
Where $T_g$ is ground temperature, $\phi_{0r}$, $\phi_{0g}$ are angle factors of surface to sky and ground.

For underlying surface, convective and conductive heat loss can described as follows:

$$H + C = \alpha_f (t_w - t_f) + K(t_w - t_n)$$  \hspace{1cm} (8)

The formula can be written as equivalent form as follows:

$$\alpha_f (t_w - t_{f,e})$$  \hspace{1cm} (9)

where $\alpha_f$ is equivalent coefficient of convective heat transfer, $\alpha_f = \alpha_f + K$, $K$ is conductive heat transfer coefficient of building envelope or underground soil, $T_n$ is indoor air temperature or soil temperature, $t_{f,e}$ is equivalent temperature of free stream, $t_{f,e} = \frac{\alpha_f t_f + K t_n}{\alpha_f + K}$.

3. CALCULATION OF EQUIVALENT SOLAR ABSORPTIVITY COEFFICIENT

For all equivalent item in boundary conditions model, equivalent absorptivity coefficient of solar absorption needs detailed analysis. Based on equivalent formula of coefficient, underlying surface of permeable pavement and green belt with plant crown are selected for calculation and analysis. The variation curve of absorptivity coefficient for each case is shown as Figure 1 and Figure 2. From the analysis of coefficient, following main points can be summarized:

(1) Equivalent solar absorptivity coefficient for permeable pavement varies with its initial humitiy and evaporation period. Low initial humidity and long evapration period lead to high coefficient because of languishing cooling effect of evaporation.

(2) Equivalent solar absorptivity coefficient for green belt with plant crown varies with LAD and shadow area on ground. High LAD and high shadow area percentage on ground lead to low coefficient because of shading effect of crown.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Curve of equivalent solar absorptivity coefficient for permeable pavement}
\end{figure}
For FLUENT, the parameter of absorptivity in radiation boundary conditions setting panel can be substituted by equivalent absorptivity coefficient, which has taken vegetation shadow and evapotranspiration in consideration.

4. CASE STUDY AND SIMULATION VALIDATION

To validate the reliability of equivalent transformation proposed, the case study of a residential district, located in Foshan, South China, is carried out. In Case study, both the simulation analysis and field measurement are performed for comparison. In simulation approach, 3D unsteady Reynolds Averaged Navier-Stokes (URANS) equations are solved with the realizable k-ε turbulence model for closure. For the radiation transfer throughout atmosphere, the P-1 radiation model is used (Fluent Inc. 2005) and the Boussinesq approximation is used for buoyancy. At domain inlet, an exponential wind speed profile is used, which can written as follows:

\[
v = v_0 \left[ \frac{h}{h_0} \right]^n
\]

(10)

where \(v_0\) is the velocity in the height of 10m, \(h_0\) is the height of 10m, \(n\) is exponential index related to terrain conditions. In the case, \(n = 0.16\). Turbulent kinetic energy (k) (m²/s²) and turbulence dissipation rate (ε) (m²/s³) are given by Richards (1993). For free stream stream temperature, Meteorological data are chosen as listed in following table.

<table>
<thead>
<tr>
<th>Table 1. hourly temperature of free stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours</td>
</tr>
<tr>
<td>Free stream temperature/°C</td>
</tr>
</tbody>
</table>

Simulation results of underlying surface temperature are shown from Figure 3 to Figure 6. In each figure, the surface with a sunny exposure and that within sunny shadow are shown for comparison.

![Figure 2. Curve of equivalent solar absorptivity coefficient for green belt](image)
In the study, experimental and calculated data are compared to verify the approach of
simulation and effectiveness of coefficient, as shown in Table 2 to Table 4. Temperature data of field measurement of different underlying surface are shown in Figure 7. Contrast results show well agreement between experimental and calculated data with acceptable deviation in engineering application.

**Figure 7.** Hourly temperature of underlying surfaces

**Table 2.** Comparison of experimental and calculated results for permeable pavement

<table>
<thead>
<tr>
<th>Results</th>
<th>Maximum temperature/°C</th>
<th>Minimum temperature/°C</th>
<th>Average temperature/°C</th>
<th>Max deviation/°C</th>
<th>Occurred hour</th>
<th>Max relative deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>47.5</td>
<td>28.2</td>
<td>35.2</td>
<td>2.2</td>
<td>8:00</td>
<td>6.8%</td>
</tr>
<tr>
<td>Calculated</td>
<td>47.0</td>
<td>27.1</td>
<td>35.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.** Comparison of experimental and calculated results for grassland

<table>
<thead>
<tr>
<th>Results</th>
<th>Maximum temperature/°C</th>
<th>Minimum temperature/°C</th>
<th>Average temperature/°C</th>
<th>Max deviation/°C</th>
<th>Occurred hour</th>
<th>Max relative deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>40.8</td>
<td>27.3</td>
<td>32.3</td>
<td>2.1</td>
<td>15:00</td>
<td>5.4%</td>
</tr>
<tr>
<td>Calculated</td>
<td>40.7</td>
<td>26.9</td>
<td>32.4</td>
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</tbody>
</table>

**Table 4.** Comparison of experimental and calculated results for green belt with plant crown

<table>
<thead>
<tr>
<th>Results</th>
<th>Maximum temperature/°C</th>
<th>Minimum temperature/°C</th>
<th>Average temperature/°C</th>
<th>Max deviation/°C</th>
<th>Occurred hour</th>
<th>Max relative deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>34.0</td>
<td>28.2</td>
<td>30.6</td>
<td>1.5</td>
<td>13:00</td>
<td>4.3%</td>
</tr>
<tr>
<td>Calculated</td>
<td>34.8</td>
<td>27.2</td>
<td>30.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. DISCUSSION
In above analysis of equivalent solar absorptivity coefficient, only sunny day is taken into consideration. However, the equivalent coefficient varies with the change of weather...
conditions. Further study will extend efforts to the variation of equivalent solar absorptivity coefficient in typical weather conditions.

6. CONCLUSION
For the simulation of urban microclimate, commercial CFD software takes advantage over self-programmed software package not only in flexible mesh method and powerful computational core, but also in cheap and reachable calculation. With equivalent transformation of built-in boundary conditions model, FLUENT can describes coupled solar radiation absorption, convection and conduction heat transfer, radiation heat transfer between surface and environment, and vegetation shadow and evapotranspiration as well. For validation of equivalent approaches, comparison results show well agreement between experimental and calculated data with acceptable deviation in engineering application, which opens a way for simple and fast simulation of outdoor thermal environment with acceptable results in engineering application.

7. ACKNOWLEDGEMENTS
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8. REFERENCES