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An integrated simulation method for building energy performance assessment in urban environments

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A B S T R A C T

The microclimate around a building, establishing through the interaction with other buildings or the natural environment, is a significant factor in the building energy consumption. This paper presents a method for the quantitative analysis of building energy performance under any given urban contexts by linking the microclimate model ENVI-met to the building energy simulation (BES) program EnergyPlus. The full microclimatic factors such as solar radiation, long wave radiation, air temperature, air humidity, and wind speed have been considered in the proposed scheme. A case study has been conducted to analyze the effects of different microclimatic factors on the energy balance of an individual building. The method outlined in this paper could be useful for urban planning and building design.

1. Introduction

Building thermal performance and its energy consumption are affected by the energy exchange processes taking place between the outer skin of the building and the surrounding environments. A number of building energy simulation (BES) programs are capable of modelling building systems in detail (such as building geometry, construction, indoor environment, infiltration, ventilation, and HVAC system) and analyzing building energy performance in a dynamic model. Nonetheless, the outdoor meteorological boundary conditions adopted in such tools are usually derived from the long-term observations of the local weather station. These data series are usually smoothed and averaged or even entirely based on statistics, which ignore the modifying effect of the surroundings. On the other hand, microclimate simulation tools offer the possibility for small-scale climate predictions with respect to different urban configurations. However, the features and the thermal processes of buildings are either simplified or totally neglected in these models. Therefore, the integration of the two kinds of programs could be a possible solution to achieve the quantitative evaluation of the microclimate effects on building thermal behaviour and energy use.

Some previous studies have attempted to integrate different numerical tools to assess the effect of local climate on building energy performance. He et al. [1] developed a 3D-CAD integrated system to simulate the interaction between indoor and outdoor thermal environment. It was based on the assumption of homogenous distribution of ambient air temperature and wind velocity. Flor et al. [2] reported an estimation method to evaluate building energy requirements for a given urban context by using the outputs of an urban canyon model as the inputs of a building thermal simulation program. Bouyer et al. [3] established a coupling simulation platform for building energy evaluation in an urban context by integrating a home developed thermoradiative code into the commercial computational fluid dynamics (CFD) software Fluent. However, there was no investigation to integrate the existing urban microclimate models with the sophisticated building energy simulation tools.

In this study, we established an integrated simulation system for building energy assessment in urban environments based on three programs: the urban microclimate model ENVI-met [4], the building energy software EnergyPlus [5] and the coupling platform Building Controls Virtual Test Bed (BCTVB) [6]. All the three programs are freeware and available online. The ENVI-met model is used for the outdoor thermal environment prediction with respect to various urban configurations. The software BCTVB is used for developing a coupling module to transfer the simulation results of ENVI-met into the EnergyPlus model. The hourly 3D distributions of the microclimate such as air temperature, air humidity, wind field, and ambient surface temperature are extracted from the ENVI-met simulation results and then taken as the outside boundary conditions of the EnergyPlus model. Through this method, the microclimate effects on building energy performance can be incorporated into the EnergyPlus simulation. A case study has been

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carried out to analyze the effects of different microclimatic phenomena on building performance using the proposed method.

2. Methodology

2.1. Introduction of simulation tools

ENVI-met 4.0, EnergyPlus 6.0 and BCVTB 1.0 were used in this work. EnergyPlus, developed by U.S. Department of Energy, has been widely applied in building energy simulation field. Besides the general functions of BES programs, EnergyPlus also provides an external interface to link with other programs. In addition, a series of controller's so-called "actuator" had been built in EnergyPlus, which allow users to override the original values of different variables at each model time step. In this study, these functions were used to import the microclimate data into the EnergyPlus model.

ENVI-met is a 3D prognostic microclimate model based on computational fluid dynamics and thermodynamics, with a typical resolution of 0.5–5 m in space and 1–10 s in time. The model is capable of simulating:

- flow around and between buildings;
- exchange processes of heat and vapor at urban surfaces;
- turbulence;
- exchanges of energy and mass between vegetation and its surroundings;
- particle dispersion and simple chemical reactions.

The main input parameters of an ENVI-met simulation include weather conditions, initial soil wetness and temperature profiles, structures and physical properties of urban surfaces, and plants. It should be mentioned here that the new version of ENVI-met (V 4.0) provides a new function called "full forcing" which allow users to specify various meteorological conditions for their simulations by forcing the model with a predefined weather profile. The customizable climatic variables include direct/diffuse solar radiation, long wave radiation, and 1D vertical profile of atmospheric parameters (air temperature, air velocity, and air humidity) from 0 to 2500 m above ground. This function offers the possibility of using the observed weather information or the data from existing weather files such as EnergyPlus Weather File (EPW) as the meteorological boundary conditions of ENVI-met simulations. ENVI-met 4.0 can also make a rough estimation for the energy performance of a building. However, such estimation would be suitable for the conceptual design of buildings as its main analyzing domain is focused on outdoor. The full equation system and further details about this model are given in [4,7,8]. ENVI-met has been applied for urban microclimate studies in different climate regions (e.g. [9–11]), and verified with field experimental data by some researchers [8,12–15].

The BCVTB is a software environment that aims to couple different simulation programs for co-simulation, and to couple simulation programs with actual hardware. In this paper, a coupling module named "E-E module" has been developed in BCTVB to extract the required data from the ENVI-met simulation results, and then to couple these data with the EnergyPlus model.

2.2. Coupling method

2.2.1. Correspondence of the building surfaces between ENVI-met and EnergyPlus

In EnergyPlus, the components of a building envelop are treated as single entities while the structured meshes are used for ENVI-met. To pass the microclimate data of the ENVI-met model into the EnergyPlus model, we need to establish the correspondence of the building surfaces between the two programs. For this purpose, a building envelop is divided into a number of linking units, and each linking unit can be represented in both ENVI-met model and EnergyPlus model. The linking units of a given building are defined as follows: for exterior walls, each facade of each floor is defined as a linking unit; for roof, each plane is treated as a linking unit. A four-story building was artificially constructed here to illustrate this scheme (see Fig. 1). The ground floor is divided into 4 linking units (a, b, c, and d), and the same principle is used for other floors. The double-pitched roof is treated as two linking units. In the ENVI-met model, the gird cells in front of the building facades are assigned to the respective linking units belonged. Firstly, the microclimate data of the grid cells within a linking unit are averaged, and then the average value is passed to the corresponding surfaces of the EnergyPlus model. For those cross-floor grid cells, as shown in the right side of Fig. 1, the variable values are split into two portions proportionally and then added to the adjacent units respectively. Note that the same outside boundary condition is allocated to all the building components that belong to a same linking unit in the EnergyPlus model. For instance, the opaque wall, window and door in the ground floor have a same outside boundary condition, as shown in the right side of Fig. 1. Through this approach, the microclimate information of the air layer around the building can be passed to the corresponding EnergyPlus model. As seen in Fig. 1, there are some inconsistencies between the ENVI-met model and the EnergyPlus model for the sloped roofs and the facades. These building components that are not parallel or perpendicular to the model axes have been processed to be serrated shapes in the ENVI-met model. Such space inconsistencies can be diminished by improving the resolution of the ENVI-met model. However, enhancing model resolution means that the computing cost will increase remarkably.

2.2.2. Microclimate factors

The energy balance equation for a zone (room) air in EnergyPlus is

$$Q_{\text{loads}} = Q_{\text{int}} + Q_{\text{conv,int}} + Q_{\text{inf}} + \Delta E_{\text{air}} \tag{1}$$

where Q_{loads} is the building heating/cooling loads, Q_{int} is the internal heat gains from lights, people and equipments, $Q_{\text{conv, int}}$ is the convective heat transfer between zone interior surfaces and zone air, Q_{inf} is the heat transfer due to infiltration with outdoor air, and ΔE_{air} is the change of energy stored in the zone air. The energy balance equation for building exterior surfaces can be written as

$$q_{\text{tsol}} + q_{\text{asol}} + q_{\text{lw}} + q_{\text{conv}} - q_{\text{cond}} = 0 \tag{2}$$

where q_{tsol} is the transmitted solar radiation, q_{asol} is the absorbed solar radiation, q_{lw} is the net long wave radiation flux, q_{conv} is the convective heat flux exchanged with outside air, and q_{cond} is the conduction heat flux into the wall. From Eqs. (1) and (2), it can be concluded that building surrounding environments influence energy performance through the following ways: (1) the amount of solar radiations reaching building surfaces, which are likely to be affected by the adjacent obstructions such as neighbor buildings, trees, and hills; (2) the convective heat flux at the exterior surface, which is determined by the convective heat transfer coefficient (CHTC) and the difference of the surface temperature and the air temperature near the surface; (3) the intensity of incoming long wave radiation; and (4) the heat and moisture transfer with outside air by infiltration. The following parts demonstrate how to incorporate these microclimatic factors into an EnergyPlus simulation.

2.2.2.1. Solar radiation flux. For shadowing calculation, the "ray-tracing" method is adopted by both EnergyPlus and ENVI-met. However, there are still considerable differences between them due to the disparities of the physical models and the numerical schemes. Four main distinctions of the solar radiation models exist between

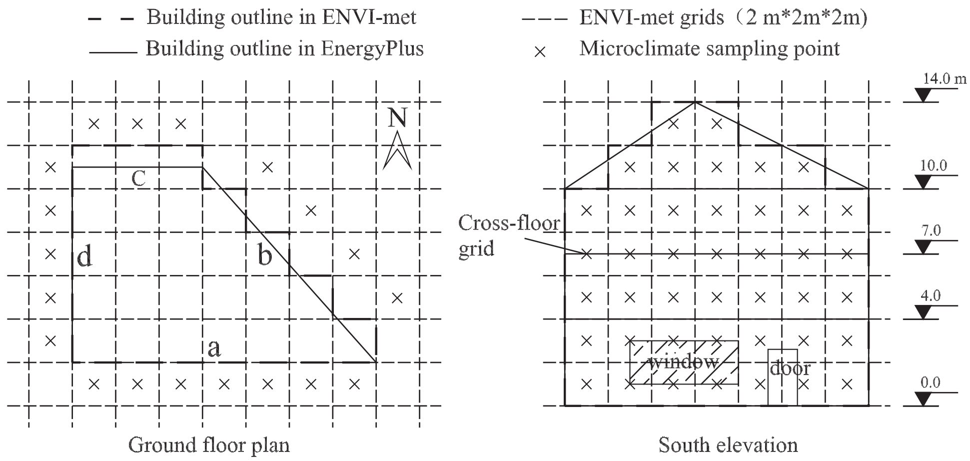

Fig. 1. Sketch of the linking unit between ENVI-met and EnergyPlus models.

ENVI-met and EnergyPlus. The first one comes from the numerical schemes: in ENVI-met, only one state, sunlit or shaded, can be presented in a grid cell at each model time step, while EnergyPlus calculates the incoming solar radiation based on the sunlit area of the surface. The second one is related to the diffuse solar radiation models: an isotropic distribution model is used in ENVI-met, while an anisotropic distribution model is adopted in EnergyPlus. The third one is from the calculation of solar reflection: ENVI-met assumes that only diffuse reflection occurs, while EnergyPlus calculates all three patterns of reflection (beam to beam, beam to diffuse, and diffuse to diffuse). Moreover, in ENVI-met, the albedos of various artificial ground surfaces can be defined by users, and the albedo values of natural soil are determined by the model itself based on the solar incident angle and the water content of the top soil layer. However, a homogenous ground surface with a given albedo is assumed in EnergyPlus. The last one comes from the shadowing effect evaluation of plants: ENVI-met considers vegetation as a turbid medium and calculates the transmittance of vegetation as a function of the optical path of solar beam through leaves and the leaf area index, while EnergyPlus treats trees as obstructions like other shadowing elements such as neighbor buildings, with a constant or scheduled transmittance.

From the point of view of building energy simulation, EnergyPlus provides a realistic description for the calculations of shadowing, diffuse solar radiation and solar reflection, but simplifies the parameters like ground reflectance and tree transmittance. Therefore, we employ the following methods to predict the actual solar radiation flux at building surfaces: (1) the incident solar radiation on building facades and the shadowing effects of adjacent obstructions are calculated by EnergyPlus itself by constructing the surrounding obstructions of the building into the EnergyPlus model and (2) the average ground reflectance and tree transmittance determined by ENVI-met are used for the EnergyPlus simulation.

2.2.2.2. Convection heat flux. Equation for the convective heat flux of building exterior surfaces is

$$q_{\text{conv}} = h_c(T_a - T_s) \tag{3}$$

where h_c is the convective heat transfer coefficient, T_a is the ambient air temperature, and T_s is the surface temperature. The positive value is defined as heat flux to the surface. CHTC is generally determined by empirical correlations. There are many correlations existing and significant differences can be found between them [16]. Several correlations for CHTC are available in EnergyPlus, but all of them are correlated with the wind speeds from the local weather station. While introducing the flow field around the building predicted by ENVI-met (basing on CFD) into the EnergyPlus simulation, these correlations are no longer applicable. We chose the linear law from the standard ISO 6946 [17], which is suitable for the wind speed range of 1–10 m/s:

$$h_c = 4 + 4v \tag{4}$$

where v is the wind speed in front of the building surface. In this study, the average wind speed of each linking unit was used to calculate the actual CHTC values. As for the condition of zero wind speed in the EnergyPlus weather file, the CHTC was determined using the natural convection correlations from Walton [18], called "TARP" model in EnergyPlus. The algorithm correlates the CHTC to the surface orientation and the temperature difference between the surface and outside air. The actuator "Exterior Surface Convection Heat Transfer Coefficient" of EnergyPlus is adopted to override the original CHTC values inside EnergyPlus. Convection heat flux is also affected by the air temperature near the surface which should be replaced with the actual air temperature predicted by ENVI-met. Since the actuator for controlling the surface outside air temperature is not available in the current version of EnergyPlus (only if modify EnergyPlus source code), a workaround is implemented by modifying the CHTC as

$$h'_c = h_c \frac{(T_a^{\text{met}} - T_s^{e+})}{(T_a^{e+} - T_s^{e+})} \tag{5}$$

where h'_c is the new CHTC, h_c is the original CHTC, T_a^{met} is the air temperature from ENVI-met, T_a^{e+} and T_s^{e+} are the original air temperature and surface temperature inside EnergyPlus. By combining Eqs. (5) and (3), the difference of outside air temperature between the EnergyPlus and ENVI-met models can be accounted for.

2.2.2.3. Long-wave radiation flux. EnergyPlus calculates the long wave radiative heat flux at the building exterior surface based on several assumptions (see Ref. [19]). One of the assumptions is that the surface temperatures of ground and obstructions are the same as the outdoor air temperature. This assumption is useful when there is a lack of information for the local thermal radiative environment. In reality, the intensity of thermal radiative flux should be different for different urban contexts, such as a park versus a central business district. As a microclimate model, ENVI-met provides a more realistic description for outdoor thermal radiation by computing the surface temperatures of various urban elements based on their own energy balance processes. Therefore, we replace the origin ground/obstruction surface temperature (equals to the outdoor air temperature) inside EnergyPlus with the mean surface temperature of all surfaces (ground, buildings and

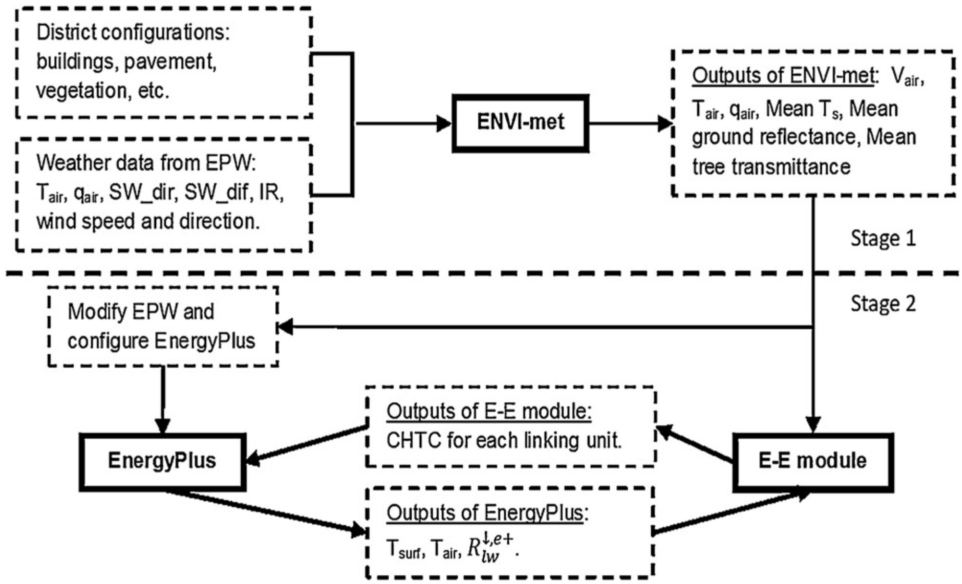

Fig. 2. Sketch of coupling ENVI-met with EnergyPlus.

vegetation) within the ENVI-met model space. Then the difference of the absorbed long wave radiation at the building exterior surface is

$$\Delta q_{\mathrm{lw}}^{\mathrm{abs}} = \varepsilon\sigma f_{\mathrm{gnd}}(T_{\mathrm{gnd,met}}^4 - T_{\mathrm{air}}^4) \quad (6)$$

where ε is the long wave emittance of the surface, σ is Stefan-Boltzmann constant, f_{gnd} is the view factor of the building surface to ground and obstructions, $T_{\mathrm{gnd,\,met}}$ is the mean surface temperature of all surfaces within the ENVI-met model area, T_{air} is the outdoor air temperature. Also, since there is no actuator to override the thermal radiative heat flux in the current version of EnergyPlus, we combine the actual long wave radiative flux at building external surfaces into the component of convection heat transfer using the same procedure as considering the actual outside air temperature. The new CHTC incorporated with the actual absorbed long wave radiation can be written as

$$h''_c = h'_c + \frac{\Delta q_{\mathrm{lw}}^{\mathrm{abs}}}{(T_a^{e+} - T_s^{e+})} \quad (7)$$

where h'_c is the CHTC determined by Eq. (5). After the above two steps modification, the final form of the convection heat flux at building exterior surfaces becomes

$$q'_{\mathrm{conv}} = h''_c(T_a^{e+} - T_s^{e+}) = \left\{ h_c\frac{(T_a^{\mathrm{met}} - T_s^{e+})}{(T_a^{e+} - T_s^{e+})} + \frac{\Delta q_{\mathrm{lw}}^{\mathrm{abs}}}{(T_a^{e+} - T_s^{e+})} \right\} \times (T_a^{e+} - T_s^{e+}) \quad (8)$$

By this way, the influences of the actual convective and thermal radiative heat fluxes on the surface energy balance can be taken into account. However, it should be pointed out that the above workarounds might produce negative CHTC values, which will lead to numerical instability for EnergyPlus iteration. This problem can be eliminated when the new actuator for controlling the outside air temperatures of building facades is to be added in the future version of EnergyPlus. In this paper, an additional constraint is employed to avoid the potential numerical problem: if $h''_c < 0$, set $h''_c = 0$ for approximation.

2.2.2.4. Heat and moisture transfer by infiltration. The heat and moisture transfer between indoor and outdoor by infiltration plays a role in building energy consumption. In this coupling scheme, the air temperature and specific humidity along the whole building facades simulated by ENVI-met are averaged, firstly. The average air temperature is taken as the reference outdoor air temperature at the height of the building centroid above the ground, which is then converted to the air temperature at the height of the local meteorological station using the same model inside EnergyPlus [20]. The average specific humidity from ENVI-met is converted to dew point temperature and relative humidity using the auxiliary program "Weather Converter" of EnergyPlus. Then we replace the original air temperature, dew point temperature and relative humidity of the EnergyPlus Weather File with the new data derived from the ENVI-met simulation results. Through this way, the infiltration impact of local air can be taken into account.

2.2.3. Procedures of linking ENVI-met to EnergyPlus

Fig. 2 outlines the procedures of using ENVI-met simulation results as the boundary conditions of EnergyPlus computation, which include two stages. The first stage is to complete the ENVI-met simulation, and the second stage is to perform the EnergyPlus simulation coupling with the ENVI-met simulation results. Note that this is a one-way coupling simulation and no data feedback to the ENVI-met model. The specific processes are described below.

First, the district configurations such as buildings, pavements and greeneries are modeled in ENVI-met. The desired forcing weather information for the simulating days is derived from the EPW file. The forcing climatic variables include dry bulb temperature, specific humidity (converted from dry bulb temperature, relative humidity and barometric pressure), direct/diffuse solar radiation, infrared radiation, wind speed, and wind direction. To avoid the potential numerical problem, we replace the zero wind speed in EPW with a low wind speed of 0.3 m/s with a constant direction of 0°. The "receptor" function of ENVI-met is used to record the hourly microclimate data along the building facades. During the stage of coupling simulation, the hourly climate data are interpolated to match the time step of the EnergyPlus model. The original EPW is modified using the method mentioned in Section 2.2.2. The ground reflectance and tree transmittance in the EnergyPlus model are derived from the ENVI-met simulation data. At the first time step, EnergyPlus sends the initial values of the required variables such as surface temperatures and air temperatures to the E-E module. Using the received data and the microclimatic information from the ENVI-met simulation results, the E-E module

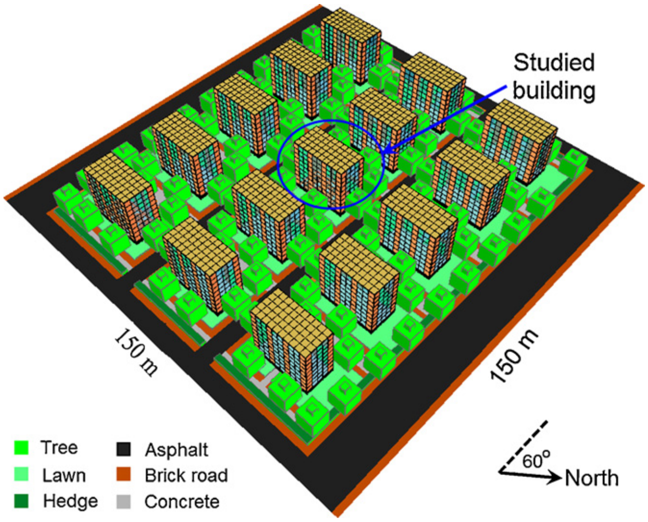

Fig. 3. ENVI-met model.

calculates the actual convective heat transfer coefficient for each linking unit of the building, and then sends them back to EnergyPlus to override the original CHTC for the next time step calculation. The same procedure is repeated for the iterations of the subsequent time steps until the end of the EnergyPlus simulation.

3. Case study

3.1. Description of the simulation cases

We conducted a case study to demonstrate the benefit of the proposed coupling simulation. A 150 m × 150 m district with a row layout of buildings was modeled in ENVI-met, as shown in Fig. 3. The building in the centre of the district was selected as the target building for energy analysis. Fig. 4 shows the EnergyPlus model of the studied building and its neighbor shielding obstructions (trees are simplified as triangles). In order to analyze the microclimate effects under different weather conditions, we defined two running conditions for the building system: cooling condition for three typical summer days (10–12 August) and heating condition for three typical winter days (4–6 January). The cooling condition is assumed that the district is located in Guangzhou (23.13°N, 113.23°E), China, which endures a humid sub-tropical climate. The heating condition is assumed that the district is located in Frankfurt am Main (50.05°N, 8.6°E), Germany, which has a temperate marine climate. In addition, we also defined four simulation cases with different configurations to observe the effects of various microclimatic factors on building loads. Table 1 presents the descriptions of the simulation cases. Cases 1 and 2, calculated by EnergyPlus only, are used to analyze the shadowing effect of the adjacent buildings and trees. Case 3 represents the actual local urban context. In Case 4, all the vegetation is removed and the nature soil surface is replaced with brick pavement. The four simulation cases were performed for both the cooling and heating conditions.

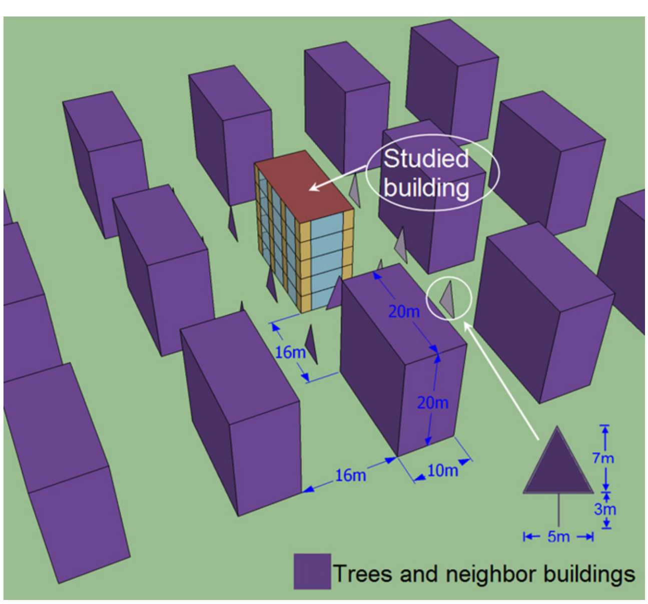

Fig. 4. EnergyPlus model.

Table 1
Description of the simulation cases.

Case no.	Computational features
Case 1	EnergyPlus only (isolated building)
Case 2	EnergyPlus only (with obstructions)
Case 3	Coupling (with greenery)
Case 4	Coupling (without greenery)

The settings of EnergyPlus simulations and ENVI-met simulations are presented in Tables 2 and 3. The changes of leaf area density (LAD) of deciduous tree and grass between winter and summer have been considered. The main climatic features of the selected summer days are hot (average 29.7 °C), humid (average relative humidity of 77%) and low wind speed (average 0.93 m/s). While low solar radiation (maximum global horizontal solar radiation of 140 W/m^2) and high wind speed (average 5.01 m/s) are presented during the selected winter days.

3.2. Results

3.2.1. Comparisons of outdoor meteorological conditions

Fig. 5 shows the average air temperature around the studied building (T_{air}) and the average ambient surface temperature (T_{surf})

Table 2
Settings of EnergyPlus simulations.

Air conditioned area	1000 m^2 (5 storeys, floor height: 4 m)
U-values (W/m^2 K)	Wall: 1.969, roof: 0.844 (albedo of wall and roof: 0.3), window: 2.967 (SHGC[a] = 0.712)
Window-wall ratio	60% for each facade
The name of weather files	
Cooling	CHN_Guangdong.Guangzhou.592870_CTYW
Heating	DEU_Frankfurt.am.Main.106370_IWEC
Simulation period	
Cooling	Workdays: August 10 – Thursday, August 11 – Friday Weekend: August 12 – Saturday
Heating	Workdays: January 4 – Thursday, January 5 – Friday Weekend: January 6 – Saturday
Temperature setpoint	
Cooling	26 °C from 08:00 to 18:00 on workdays Free running for all other time
Heating	18 °C from 08:00 to 18:00 on workdays 15 °C for all other time
Infiltration rate	
Cooling	1 air change per hour
Heating	0.5 air change per hour
Internal load	0 (no internal heat gains)
HVAC system	"Ideal load air system"
Ground reflectance and temperature	Without greenery: 0.18, all other case: 0.2 summer: 25 °C, winter: 18 °C
Transmittance of Tree	0.32 in summer, 0.74 in winter (from ENVI-met)

[a] Solar heat gain coefficient.

Table 3
Settings of ENVI-met simulations.

Domain	150 m × 150 m × 50 m
Meshes and size	75 × 75 × 25 (dx = dy = 2 m; dz = 2 m)
Environment	With/without greenery
Simulation period	August 10–12 (Guangzhou), January 4–6 (Frankfurt)
Weather data	From the corresponding EnergyPlus weather files
Plants	
Summer	Tree: high 10 m, crown width 5 m, clear 3 m, LAD = 2
	Hedge: high 1 m, LAD = 2
	Grass: high 0.4 m, LAD = 0.3
Winter	Tree: high 10 m, crown width 5 m, clear 3 m, LAD = 0.5
	Hedge: high 1 m, LAD = 2
	Grass: high 0.4 m, LAD = 0.1
Ground	Asphalt concrete: thickness 8 cm, albedo 0.2
	Gravel concrete: thickness 20 cm, albedo 0.23
	Brick pavement: thickness 6 cm, albedo 0.15

in Case 3 (with greenery) and Case 4 (without greenery) for the summer days in Guangzhou. It was observed that the site-specific air temperatures in Cases 3 and 4 were significantly higher than the meteorological air temperature during the daytime, especially around noon. Compared to the original weather data, the average air temperature increases during the time period of 08:00–18:00 for the three days in Cases 3 and 4 were 0.9 and 1.2 °C, respectively. The maximum increases in air temperature for Cases 3 and 4 occurred at 12:00 on August 10, reaching up to 2.6 and 2.8 °C, respectively. The air temperature of Case 3 was lower than that of Case 4 for most of the time, indicating that the vegetation can cool the air by evapotranspiration and shading. For the thermoradiative environment, it was found that the ambient surface temperatures in Cases 3 and 4 were higher than their ambient air temperatures over the whole studied period, especially during the daytime. This means that the EnergyPlus model underestimates the incoming long-wave radiation fluxes at the building envelop in this study, because in EnergyPlus the ambient surface temperature is assumed to be the same as the outdoor air temperature. The ambient surface temperature of Case 3 was lower than that of Case 4 throughout the three days, indicating that the ambient surface temperature was also lowered by the vegetation.

Fig. 6 shows the average specific humidities around the studied building in Cases 3 and 4 for the summer days in Guangzhou. Significant increase in humidity for Case 3 was observed compared to the original meteorological data, especially during the daytime. This is due to the fact that the processes of evaporation or evapotranspiration from vegetation and soil surface are enhanced by

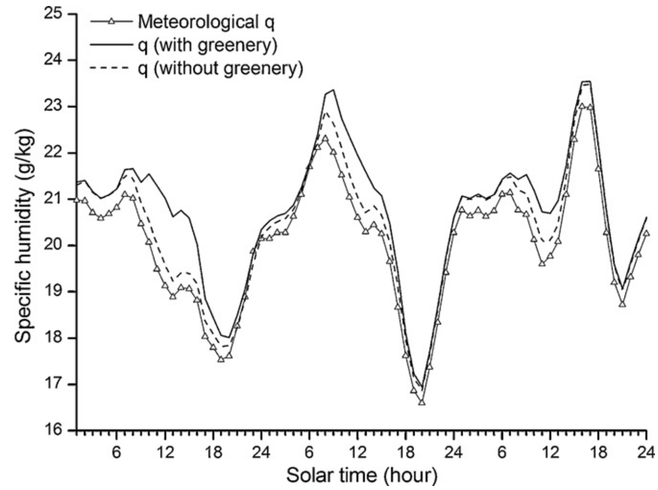

Fig. 6. Comparison of the average specific humidity around the studied building between Case 3 (with greenery) and Case 4 (without greenery) for the summer days (August 10–12) in Guangzhou.

solar radiation. The specific humidity of Case 4 was lower than that of Case 3 throughout the period due to the absence of vegetation. Compared to the original meteorological data, the average humidity increases during the time period of 08:00–18:00 for the three days in Cases 3 and 4 were 5.1% and 2.1%, respectively. The comparison between Cases 3 and 4 clearly shows that the vegetation can lower the temperature of the air and increase the humidity of the air during hot summer, which is consistent the measurement results [21].

Fig. 7 shows the average air temperature around the studied building and the average ambient surface temperature in Cases 3 and 4 for the winter days in Frankfurt. There were no obvious air temperature rises in Cases 3 and 4 compared to the meteorological air temperature due to the weather condition of low solar radiation and high wind speed (see Section 3.1). Since the shading and evaporative cooling effect of the vegetation is hugely reduced in winter, there was no significant air temperature difference between Cases 3 and 4. Compared to the original weather data, the average air temperature increases during the winter days in Cases 3 and 4 were only 0.17 and 0.18 °C, respectively. The ambient surface temperatures in Cases 3 and 4 were slightly higher than their ambient air

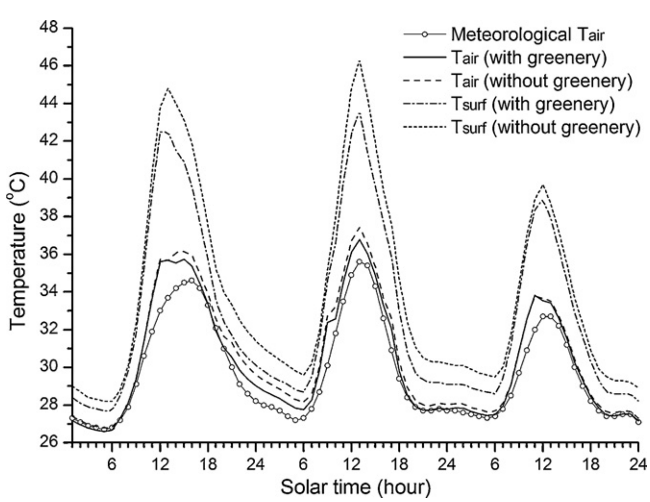

Fig. 5. Comparison of the average air temperature around the studied building and the average ambient surface temperature between Case 3 (with greenery) and Case 4 (without greenery) for the summer days (August 10–12) in Guangzhou.

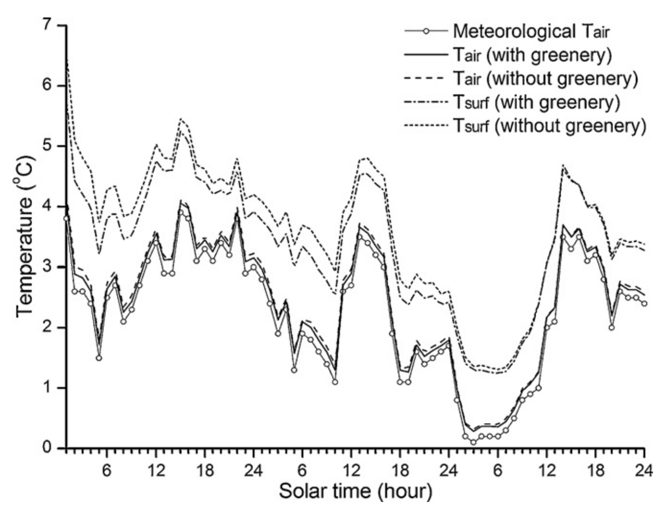

Fig. 7. Comparison of the average air temperature around the studied building and the average ambient surface temperature between Case 3 (with greenery) and Case 4 (without greenery) for the winter days (January 4–6) in Frankfurt.

Table 4
Average surface wind speed $\bar{v}$ and average exterior surface convection coefficient $\bar{h}_c$ of the building for the simulation period for each case.

	Guangzhou		Frankfurt	
	$\bar{v}$ (m/s)	$\bar{h}_c$ (W/m^2 K)	$\bar{v}$ (m/s)	$\bar{h}_c$ (W/m^2 K)
Case 1 (only EnergyPlus)	–	2.7	–	8.6
Case 2 (only EnergyPlus)		2.6		8.6
Case 3 (with ENVI-met)	0.41	4.3	2.34	13.4
Case 4 (with ENVI-met)	0.40	4.3	2.51	14.0

temperatures over the whole period. The humidity data are not presented since it has little effect on heating load.

Table 4 presents the average surface wind speed and the average exterior surface convection coefficient (before modifying by the actual long wave radiation fluxes and air temperature) for the whole simulation period for each case. For the non-coupling cases (1 and 2), we chose the built-in "DOE-2" algorithm of EnergyPlus for the CHTC calculation. It was found that, for both the summer and winter days, the average CHTC values determined according to the flow field around the building from ENVI-met were greater than the CHTC values determined by EnergyPlus alone. The CHTC values of the winter cases were much greater than those of the summer cases as the wind speed during the winter days in Frankfurt was much higher than that during the summer days in Guangzhou.

3.2.2. Building thermal behaviour and energy performance

Fig. 8 shows the hourly sensible and latent cooling loads during the air-conditioned time period (08:00–18:00) for each case. It was observed that the sensible cooling load of Case 1 (isolated building) was much higher than the other cases (overshadowed by surrounding obstructions). That means the sensible cooling load is strongly influenced by the local solar radiation environment. The sensible cooling load increased significantly after considering the impact of the local microclimate for Cases 3 and 4 compared to Case 2. The main reason for this is the district "heat island" phenomenon, as shown in Fig. 5. Another observation is that the latent cooling load of Case 3 was significantly higher than the other cases due to the humidification effect of vegetation. The simulation results from Bouyer et al. [3] also showed that the moisture production by urban vegetation caused the building latent cooling load to rise. Therefore, air humidity should be a non-negligible microclimatic component for building cooling load for the cities located in the hot-humid climate region like Guangzhou.

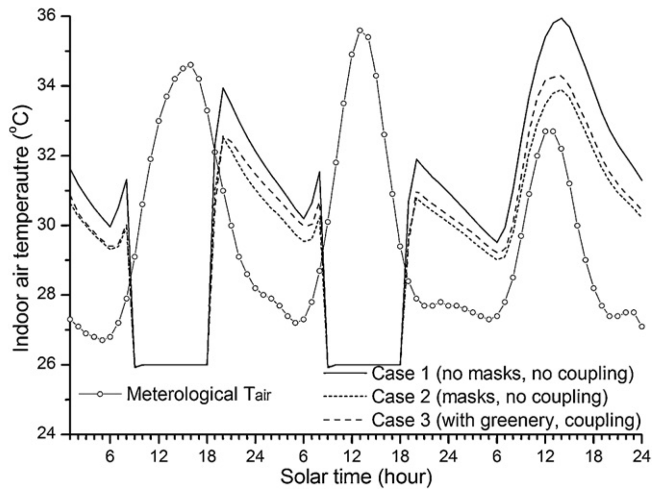

Fig. 9. Mean indoor air temperature for Cases 1–3 in Guangzhou.

The local microclimate also influences the indoor environment. Fig. 9 shows the mean indoor air temperature in Cases 1–3. During the weekdays, the indoor air temperatures rose rapidly after turning off the cooling system at 18:00. As there was still sunshine for about half an hour after 18:00, the indoor temperature of Case 1 with isolated building was significantly higher than the other two screened cases, and this trend will continue until the cooling system running again. On the free-running Saturday, the meteorological air temperature was lower than the previous two days. However, significant indoor temperature differences at noon were observed: 2.1 °C between Cases 1 and 2, and 0.8 °C between Cases 3 and 2.

Fig. 10 shows the hourly heating load for the winter cases. It was found that during the weekdays the heating demand of Case 1 (isolated building) was less than the other cases during the daytime with a setpoint of 18 °C, but was more than the other cases during the nighttime with a setpoint of 15 °C. A possible explanation for this would be that, in an open environment, there was more solar heat gain during the daytime but more heat loss by long wave radiation during the nighttime compared to an urban context. However, the heating demand of Case 1 was generally less than the other cases during the weekend day (January 6). The diffrences in heating demand among Cases 2–4 were small, and there were no clear relationships among them.

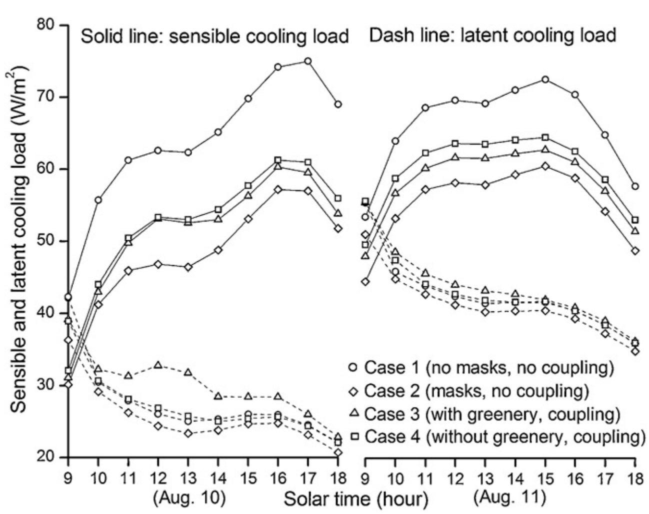

Fig. 8. Hourly sensible and latent cooling loads for Cases 1–4 in Guangzhou.

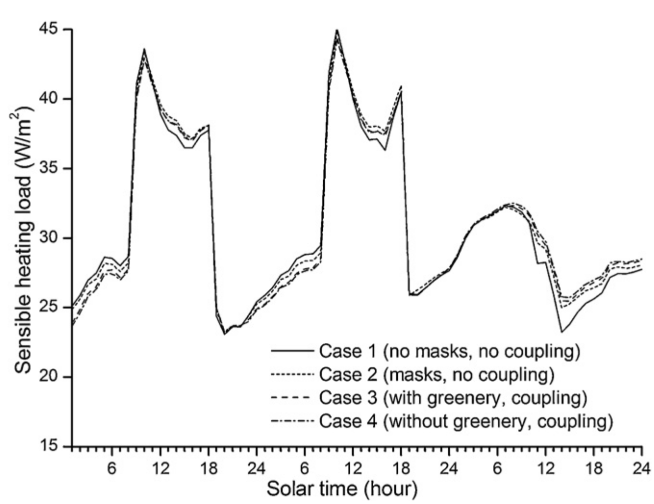

Fig. 10. Hourly heating load for Cases 1–4 in Frankfurt.

Table 5
Evaluation of the effect of different microclimatic factors on cooling energy consumption.

Influencing factors	Selected case	Compared to	ΔQ_{load} (kW h)	Reduction (−) or increase (+)
Solar heat fluxes	Case 2	Case 1	1555 − 1916 = −361	−18.8%
Greenery	Case 4	Case 3	1712 − 1714 = −2($\Delta Q_{sensible}$ = 35, ΔQ_{latent} = −37)	−0.1%
Convective heat fluxes	Case 3[a]	Case 2	1543 − 1555 = −13	−0.8%
IR radiative exchange	Case 3[b]	Case 2	1573 − 1555 = 18	+1.1%
Infiltration	Case 3[c]	Case 2	1702 − 1555 = 147 ($\Delta Q_{sensible}$ = 64, ΔQ_{latent} = 83)	+9.4%
Convection + IR + infiltration	Case 3	Case 2	1714 − 1555 = 159	+10.2%
Whole local environment	Case 3	Case 1	1714 − 1916 = −202	−10.6%

[a] Only convection coupling.
[b] Only infrared radiation (IR) coupling.
[c] Only infiltration coupling.

3.2.3. *Impacts of different microclimatic factors*

In order to understand the effects of different microclimatic factors on building energy performance, we carried out a series of comparisons. Table 5 compares the variations of cooling loads from considering a single microclimatic factor to including the full microclimate. A significant cooling load reduction of 18.8% was found while the solar shading effect by the surrounding obstructions was considered. Another notable observation is that the total cooling load decreased slightly (0.1%) after removing the vegetation from the district. The reason is that compared to Case 3, the reduction of latent cooling load (37 kW h) due to the decrease of air humidity in Case 4 exceeds the increase of sensible cooling load (35 kW h) due to the relatively higher air temperature in Case 4. That implies that the humidification effect of vegetation could be a negative factor for building cooling load under hot and humid climatic conditions. The cooling load decreased by 0.8% after introducing the relatively greater CHTC values from ENVI-met because more solar heat absorbed by the building envelop was brought back to the outdoor air through convection. A considerable increase of 1.1% on the cooling load was observed after taking into account the actual thermoradiative environment. A remarkable increase of 9.4% on the cooling load was observed after considering the impact of infiltration of the local hotter and more humid atmosphere, and about 56% of the cooling load increase was the increase of latent cooling load. That implies that the site-specific atmospheric conditions, both temperature and moisture, could have significant impacts on building cooling load by way of infiltration. The total cooling load increased by 10.2% after considering the comprehensive effect of the three factors above. The total cooling load reduces by 10.6% after taking into account the full microclimatic environments including solar radiation, long wave radiation, air temperature, air humidity and building surface wind speed.

Table 6 compares the heating load variations in the same way as the cooling cases. There was no obvious increase in heating load (only 0.8%) after considering the shadowing effect of the neighbor buildings and trees because of the low solar radiation intensity during the winter days. The change of heating load after removing all vegetation was negligible due to the inactive evaporation from vegetation and the deciduous nature of trees in winter. The heating load increased by 1.8% after introducing the relatively greater CHTC values from ENVI-met as the heat loss through the building envelop increased. The heating load decreased by 2.3% after considering the actual thermoradiative balance. The heating load decreased by 1.4% after considering the air infiltration effect since the local outdoor air temperature was higher than the meteorological air temperature. The total heating load decreased by 0.5% after considering the comprehensive effect of the three factors above. The total heating load increased by 0.3% after taking into account the full microclimatic environments.

4. Discussion

Some preliminary conclusions can be drawn from the above results. First, building cooling load is strongly affected by the amount of solar radiation reaching the building surface. Though the results of the winter cases show only a tiny heating energy increase related to overshadowing, we should note that it is not a common situation for building heating load because of the rather low solar radiation during the winter days. Many other studies have shown that the reduction of solar radiation due to overshadowing can dramatically affect heating energy consumption [e.g. 3, 22]. Second, the wind-induced convection heat transfer at building exterior surfaces can be an important factor on both cooling and heating loads, depending on a number of factors such as the thermal insulation of building envelop, the air temperature difference between indoor and outdoor, and the ratio of window to wall. Third, thermoradiative environment seems to be an important factor for both cooling and heating loads. Finally, the heat or/and moisture transfers between indoor and outdoor via air infiltration could have significant impacts on building cooling and heating loads. In addition, the humidification effect of vegetation should be taken into account for the hot humid climate.

Some advantages have been shown by linking the microclimate model ENVI-met to the BES program EnergyPlus. First, we can benefit from the “full forcing” function of ENVI-met 4.0 by using dynamic weather data as the meteorological background of microclimate simulations. That could provide a more realistic description for urban microclimate. Moreover, the weight of each microclimatic

Table 6
Evaluation of the effect of different microclimatic factors on heating energy consumption.

Influencing factors	Selected case	Compared to	ΔQ_{load} (kW h)	Reduction (−) or increase (+)
Solar heat fluxes	Case 2	Case 1	2229 − 2211 = 18	+0.8%
Greenery	Case 4	Case 3	2219 − 2218 = 1	+0.0%
Convective heat fluxes	Case 3[a]	Case 2	2270 − 2229 = 41	+1.8%
IR radiative exchange	Case 3[b]	Case 2	2177 − 2229 = −52	−2.3%
Infiltration	Case 3[c]	Case 2	2197 − 2229 = −32	−1.4%
Convection + IR + infiltration	Case 3	Case 2	2218 − 2229 = −11	−0.5%
Whole local environment	Case 3	Case 1	2218 − 2211 = 7	+0.3%

[a] Only convection coupling.
[b] Only infrared radiation (IR) coupling.
[c] Only infiltration coupling.

factor can be evaluated under any given urban contexts. In addition, as indicated by Djunaedy [23], we can benefit from the continuous development of both ENVI-met and EnergyPlus programs by employing this external coupling strategy.

However, we should point out that there are some disadvantages in this coupling scheme. The first one is the computation cost of ENVI-met. For the model time of three days, the computing times for Cases 3 and 4 are around 168 h (PC). Hence, it is necessary to choose an appropriate model resolution according to the research objectives or the design stages. The second one is the disparities of the numerical schemes and the physical models between ENVI-met and EnergyPlus. For instance, it is difficult for ENVI-met to describe a building with many sloped or cambered surfaces. Moreover, there are also some uncertainties produced by the current "indirect" approach for the coupling of the actual long wave radiation and air temperature.

5. Conclusion

This paper outlines a quantitative evaluation method for the microclimate effects on building energy performance by linking the microclimate model ENVI-met to the building energy simulation program EnergyPlus. A coupling module has been developed in the software platform Building Controls Virtual Test Bed (BCVTB) to use the outputs of ENVI-met as the outdoor boundary conditions of EnergyPlus. A case study has been conducted to show the basic features of the proposed method. Some advantages and disadvantages of this method are also summarized. Simulation results show that the proposed method is capable of quantifying the effects of various microclimatic factors on building energy performance under any given urban contexts. The method could be useful for urban planning and building design.

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