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Numerical Evaluation of the Local Weather Data Impacts on Cooling Energy Use of Buildings in an Urban Area

Jiying Liu[a,b,c,]*, Mohammad Heidarinejad[d], Min Guo[a], Jelena Srebric[d,]†

[a]*Key Laboratory of Renewable Energy Utilization Technologies in Buildings of the National Education Ministry, Jinan 250101, China*
[b]*Shandong Provincial Key Laboratory of Renewable Energy Utilization Technologies in Buildings, Jinan 250101, China*
[c]*School of Thermal Energy Engineering, Shandong Jianzhu University, Jinan 250101, China*
[d]*Department of Mechanical Engineering, University of Maryland, College Park 20742, USA*

Abstract

Accurate weather data plays an important role in the evaluation of building energy consumption in urban areas. The local air temperature and local wind speed can vary significantly due to the influence of microclimate conditions, while those parameters have a significant effect on energy demand especially in the summer. This study provides a new coupled numerical approach that building energy simulation (BES), using the airport weather data, transfers building surface temperature data to computational fluid dynamics (CFD) as the boundary conditions. In addition, the outdoor thermal environment is simulated using the CFD method and local weather data is calibrated and transferred to BES as the real-time meteorological data. A daily coupled simulation is performed for a building located in a specified urban density accounting for actual wind speed and direction. The comparison shows that the difference for daily building energy consumption is up to 2.5% using the airport weather data and local weather data. Therefore, accurate estimation of local weather data is necessary when on-site measured data is not available.

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Keywords: Urban microclimate; Building Energy Simulation (BES); Computational Fluid Dynamics (CFD); Coupled CFD and BES

* Corresponding author. Tel.: +86-531-86361236.
E-mail address: j.y.liu@hotmail.com
* Corresponding author. Tel.: +1-301-405-7276.
E-mail address: jsrebric@umd.com

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Nomenclature

H_b	offset equal to zero for the troposphere
H_z	geopotential altitude
ΔH	difference between the ground level and the height of z
L	air temperature gradient, equal to -0.0065K/m
T_b	air temperature at the base of the layer, i.e., ground level
T_z	air temperature at altitude z
$T_{z,met}$	air temperature at 1.5m above the ground measure at the meteorological station height
Z_{met}	height of standard meteorological wind speed measurement
α	wind speed profile exponent at the site,
δ	wind speed profile boundary layer thickness at the site
δ_{met}	boundary layer thickness at the height of meteorological station

1. Introduction

Accurate weather data plays an important role in the evaluation of building energy consumption in urban areas. Weather stations usually record weather parameters in a specified location such as the airport weather station that is usually far from the building location. The corresponding local air temperature and local wind speed can vary significantly due to the influence of microclimate conditions, while those parameters have a significant effect on energy demand especially in summer. Literature review[1, 2] shows that it is crucial to account for the influence of thermos-fluid properties of air, surfaces, and sky in the local built environment on the building energy consumption. For example, due to the sheltering effect considering the urban terrain types, the heat energy consumption can decrease up to 3.5% while the cooling energy consumption can increase up to 6.7% [3]. In addition, due to the local thermal environment effect, the simulated building energy consumption can vary by ±5% [4] and ±7% [5] using local site data and meteorological station data. One study pointed out that accounting for the effect of the exhaust of air conditioning waste heat in summer, the performance of the cooling systems in urban environments can have the reduction of 17% [6]. Therefore, accurate estimation of energy consumption in the urban area, accounting for the impact of surrounding buildings on the local thermal/wind environment, is extremely important.

Large amounts of studies [7-11] have considered different aspects of local thermal environment on the buildings energy consumption in urban areas; however, the majority of the researches conducted the steady/stable prediction. In other words, the local weather data representing the local thermal environment was not updated in real-time. The surrounding buildings in the urban area tend to influence the local meteorological data that is measured as close as possible to the actual site, affected by the incoming/shielding solar radiation. Therefore, it is necessary to provide the thermal environment properties by conducting sufficient numerical simulations when the meteorological station is too far and local whether data is not available. Therefore, this study lays out a framework to conduct coupled building energy simulation (BES) and outdoor airflow simulations using weather data. BES use uses weather data far from the meteorological station and transfers building surface temperature data to computational fluid dynamics (CFD) as the boundary conditions. In addition, the outdoor thermal environment is simulated using the CFD method and local weather data is calibrated and transferred to BES as the real-time meteorological data. A daily coupled simulation is performed for a building located in a specified urban density accounting for actual wind speed and direction.

2. Methods

2.1. Introduction of local parameters setup in BES program

The EnergyPlus [12] program is used to evaluate the building energy consumption in urban areas, where the local outdoor air temperature and local air velocity are calculated via the Equation (1) ~ (3). The local outdoor air temperature calculation is expressed as follows:

$$T_z = T_b + L \cdot \Delta H = T_b + L(H_z - H_b) \tag{1}$$

where, T_z is Air temperature at altitude z, T_b is the air temperature at the base of the layer, i.e., ground level, L is the air temperature gradient, equal to -0.0065K/m, ΔH is the difference between the ground level and the height of z, H_b is the offset equal to zero for the troposphere and H_z is the geopotential altitude. To solve the air temperature at the ground level, T_b can be calculated via the following equation:

$$T_b = T_{z,met} - L\left(\frac{6356000 z_{met}}{6356000 + z_{met}} - H_b\right) \approx T_{z,met} + 0.0065(1.5 - H_b) \tag{2}$$

where, Z_{met} is the height of standard meteorological wind speed measurement, $T_{z,met}$ is air temperature at 1.5m above the ground measure at the meteorological station height. Note that T_b is approximately equal to $T_{z,met}$ for low-rise building (<30m) and its difference in latitude is not considered here. To calculate the local wind speed, the equation is utilized as follows:

$$U_{loc} = U_{met}\left(\frac{\delta_{met}}{z_{met}}\right)^{\alpha_{met}}\left(\frac{z}{\delta}\right)^{\alpha} \tag{3}$$

where, the exponent α is the wind speed profile exponent at the site, the exponent δ is the wind speed profile boundary layer thickness at the site. δ_{met} is boundary layer thickness at the height of meteorological station. Fig. 1 shows the temperature distribution at different site locations. The results show that the temperature differences using these interior empirical expressions can only reach ±1.0°C; therefore, its influence is not significantly obvious. In addition, these equations are designed to calculate the local parameters in urban thermal environments specifically accounting for the temperature difference in latitude and velocity difference between urban terrains. However, in this way, the building neighborhood's impact on building energy and airflow are neglected. Finally, this study only chooses the flat and open country exponent (α) and corresponding thickness (δ) to most probability reduce the impact of urban terrain between target building location and meteorological station site.

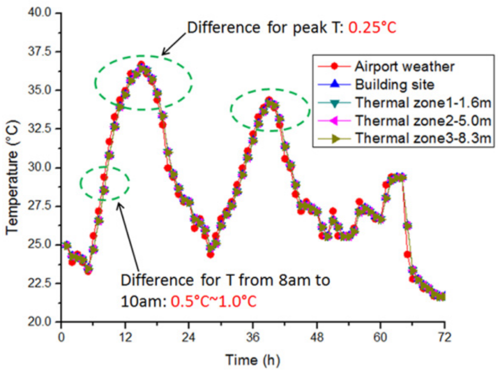

Fig.1. Temperature distribution at different site locations.

2.2. Coupled simulation strategy

This study employed the on directional coupling strategy, in which for one time-step one 'script' file is first employed using the FORTRAN program to post-process and exchange the simulation data between PHOENICS [13] and EnergyPlus, and the 'q1' file is also simultaneously generated in the same format as the PHOENCIS program.

Moreover, the 'EPW' file is updated with a variety of velocity and temperature data transferred from PHOENICS simulation results, correspondingly, specified building surface temperature from EnergyPlus is outputted to the 'q1' file in PHOENICS. Fig. 2 shows the simplified coupling strategy between CFD and BES program. Fig. 3 shows the detailed coupling strategies between the CFD and BES programs for modeling the effect of the local microclimate environment on energy consumption in a neighborhood. In Fig. 3, the surface temperature from EnergyPlus is transferred to PHOENICS, while the local parameters such as local air temperature and air velocity from PHOENICS are transferred to EnergyPlus, more accurately the EPW weather file.

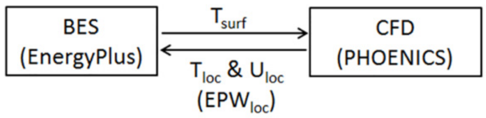

Fig.2. The simplified coupling strategy between CFD and BES program.

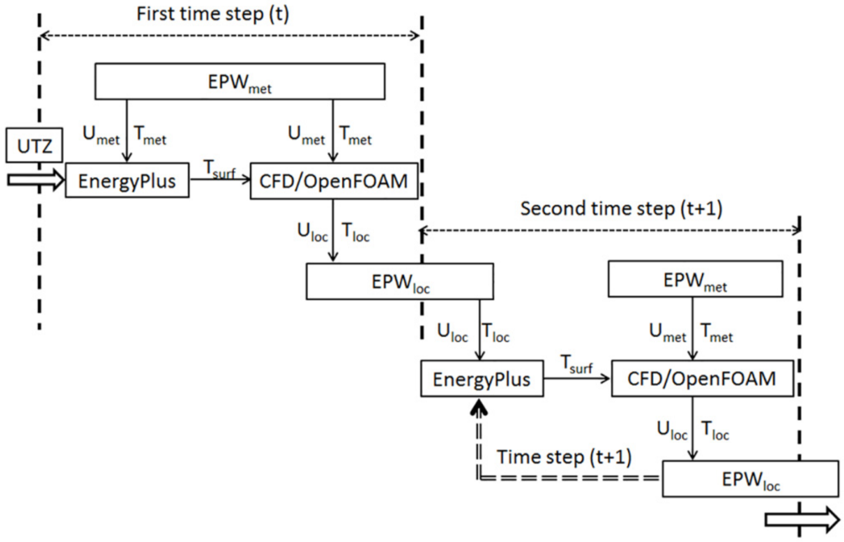

Fig.3. The detailed coupling strategies between CFD and BES

2.3. Simulation setup in CFD and BES

In this paper, the coupling BES and CFD is developed as one platform for modelling the effect of the local microclimate environment on energy consumption in neighborhoods. To test the performance of this platform, one case study is performed using the BESTEST Case 600, which is a three story cubic building ($10 \times 10 \times 10m^3$) with a single thermal zone per floor, no interior partitions, and $15m^2$ of windows on the south exposure. Detailed simulation setup in the EnergyPlus can be found in the reference [14]. Fig. 4 shows the simulated model in EnergyPlus and PHOENICS, in which the window-to-wall ratio is considered to represent the southern wall temperature different from other wall surfaces. Note that the surface color only indicates that each floor has the specified surface temperature transferred from EnergyPlus at one time-step. For the local parameters that are required for EnergyPlus, simulated point distribution is presented according to the reference that studied the measured point in the wind tunnel experiment, as shown in Fig. 5. Fig. 6 illustrates the simulation setup for weather data in PHOENICS. The Philadelphia weather data is used in this study. In PHOENICS, the weather data file is imported at every time-step, and the relevant temperature, velocity magnitude and direction are updated, correspondingly. In addition, the sun setup is also used to keep the variation of direct solar radiation.

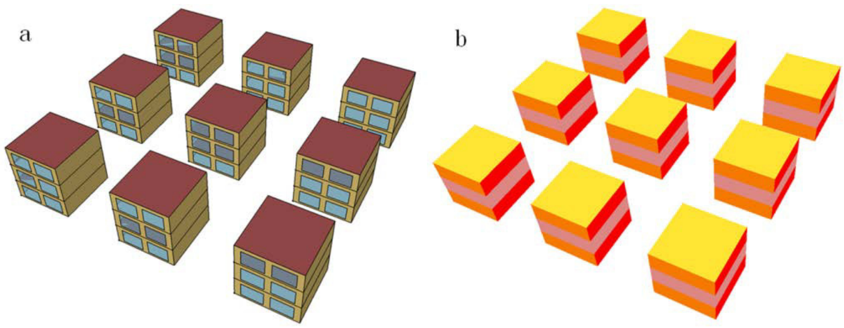

Fig.4. (a) the simulated model in EnergyPlus; (b) the simulated case in PHOENICS

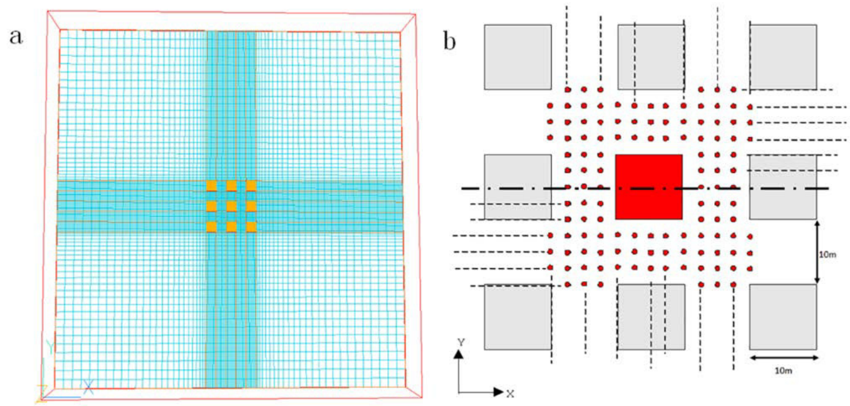

Fig.5. (a) grid distribution in the simulation case; (b) simulated points distribution in the horizontal plane.

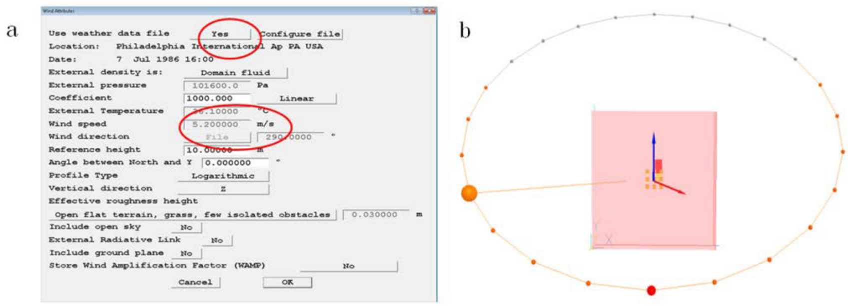

Fig.6. (a) weather data setup in PHOENICS; (b) sun setup description.

3. Results

3.1. The effect of air temperature variation on energy consumption

To demonstrate the effect of local air temperature on the building energy consumption, this study first runs simulation for an isolated building with the variation of air temperature. Fig. 7 shows the cooling energy use in an isolated building due to the increase of temperature in the weather data file. The results show that from 11am to 4pm, with the increase of air temperature by 1% (0.35 to 0.37°C), 5% (1.7 to 1.8°C) and 10% (3.4 to 3.7°C), the increase of energy consumption can be up to 1.9%, 9.6% and 19.9%, respectively. Therefore, accounting for the impact of local thermal environment on energy consumption is important.

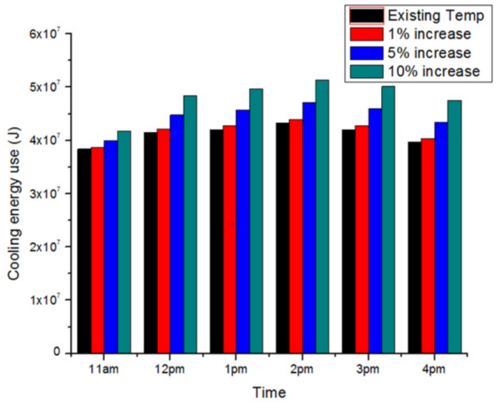

Fig.7. cooling energy use variation with the increase of temperature in the weather data file

3.2. The neighborhood effect on energy consumption

The main goal of this study is to evaluate the impact of local weather data on the cooling energy use of buildings in an urban area, with the use of a coupled numerical approach combined CFD and BES. Fig. 8 shows the temperature and velocity magnitude variation on June 22 outputted during the simulation process. The results indicate that an increase of up to 2.4% was observed for local air temperature, while a decrease of up to 22.1% was examined for the local air velocity. Through accounting for the above changes, the coupled simulation was performed which took roughly 10 hours. The deviation (%) (equals to $(E_{Simulated}-E_{Weaherdata})/E_{Weatherdata})$ is used to analyze the impacts.

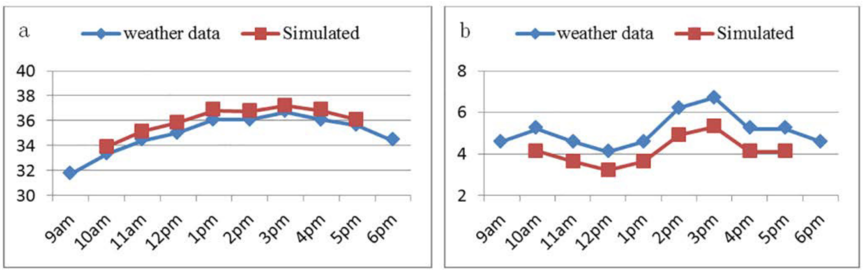

Fig. 8. (a) temperature (℃) variation; (b) velocity magnitude (m/s) variation in one day.

Fig. 9 shows the cooling energy use using the weather data and simulated local weather data. A deviation of up to 2.5% was observed using the airport weather data and local weather data. Although the deviation is not too large, as expected, the numerical approach was demonstrated with the limited case studies being only one density of the building environment. In addition, this study indicated that local air velocity does not play an important role in the energy consumption because the infiltration rate has a negative effect on the energy consumption with the decrease of local air velocity. Therefore, there is a need to consider more simulations to qualify the impact of infiltration rate on the energy consumption by utilizing this coupled simulation platform.

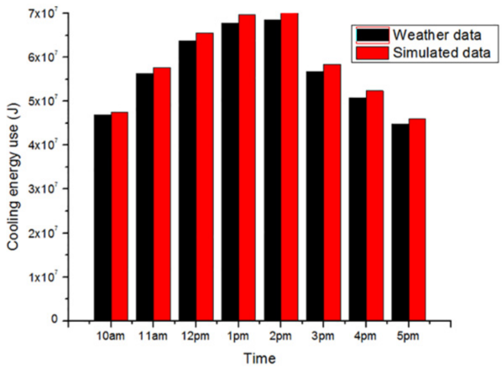

Fig.9. the comparison of cooling energy use using the weather data and simulated local weather data.

4. Discussion

This study demonstrated the practicability using coupled CFD and BES programs to evaluate the effect of local weather data on the cooling energy use of buildings in an urban area. The daily coupled simulation results only show the average discrepancy up to 2.5% using the airport weather data and simulated data. This is mainly due to the smaller building area located in a relatively small urban density, and the unobvious terrain difference between the local area and airport station. Future studies will focus on the denser urban areas and high-rise buildings, as well as the field measurement in a real neighborhood accounting for the ground coverage such as the grass and concrete to validate the accuracy for this coupled simulation platform.

5. Conclusions

This study provides a new coupled numerical approach that BES and CFD co-transfer local parameters including local air temperature and local air velocity outputted from CFD to BES, and BES transfers building surface temperature outputted from EnergyPlus to CFD simulations. The local weather data is calibrated and transferred as the real-time meteorological data. This study also demonstrates the effect of local air temperature on the building energy consumption using a target of one isolated building; the discrepancy can be doubly increased with the variation of air temperature. Finally, coupled simulation is performed for one day for a building located in a specified urban density accounting for actual wind speed and wind direction. The comparison shows that the difference for daily building energy consumption is up to 2.5% using the airport weather data and local weather data. Therefore, accurate estimation of local weather data is necessary when on-site measured data is not available.

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