CityFFD/CityBEM – Modeling Urban Microclimate, Thermal, and Energy Performances

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Abstract

Urban microclimate and building energy models have been developed to address the increasing concerns over thermal and wind comfort and building energy consumption due to climate change. Modeling urban scale problems is computationally extensive. In this study, we developed an integrated simulation model by combining CityFFD (City Fast Fluid Dynamics), an urban-scale computational fluid dynamics model for microclimate modeling, and CityBEM (City Building Energy Model), an urban building energy model with a library of 1700 building archetypes for facilitating urban model creation. Local aerodynamics and heat transfer information are exchanged between both models at each time step. Graphics processing unit computing is also applied for CFD simulation speedup. The simulation of a real urban area is validated to demonstrate its performance.

Keywords: CityFFD, CityBEM, Urban microclimate, Building energy performance, Integration.

Key Innovations

CityFFD/CityBEM is an in-house model for simulating urban microclimate and building energy consumption based on CUDA-C++ and novel CFD schemes to improve the simulation's accuracy and speed, including the 4th-order scheme for modeling urban problems on personal computers.

Practical Implications

CityFFD/CityBEM can be used on personal computers with graphic cards. This platform can model large urban scale problems by a two-way interaction between outdoor and indoor environments.

Introduction

In the past decades, population growth, rapid urbanization, and climate change have created an increasing concern over thermal and wind comfort and building energy consumption in cities. Rapid urbanization and global climate change have an adverse impact on pollution, pedestrian comfort, energy consumption, and greenhouse gas (GHG) emission (Li et al., 2017). Global climate change causes increased earth surface temperature, drought, declining water supplies, etc., which are directly impact indoor/outdoor environment, human health, and building energy performance.

On the other hand, urbanization has also significant impact on human life in the cities. Urban morphology and building configurations, which are important urban features, can directly impact urban microclimate (Tong et al., 2017; Mortezaeezadeh et al., 2021). For example, Tong et al. (2017) showed that the radiation heat flux from buildings and roads into the outdoor environment is the main contributor to nighttime UHI (Urban Heat Island). Mortezaeezadeh et al. (2021) showed that building configurations could directly impact local thermal and wind distribution in an urban area. On the other hand, the outdoor environment can also impact the indoor environment and building energy performance (Katal et al., 2019). Katal et al. (2019) demonstrated the significant impact of local microclimate during an extreme event on building resiliency.

Understanding the urban microclimate phenomena, such as UHI and extreme events, and their impact on the local environment and building energy performance may be achieved by simulation techniques, such as computational fluid dynamics (CFD) simulations (Mortezaeezadeh et al., 2021; Toparlar et al., 2015) and UBEM tools (Urban Building Energy Models) for building energy performance (Reinhart and Davila, 2016). Integration of these two models is necessary to model the neighborhood's impact and generate comprehensive and high accurate data in an urban environment (Hong et al., 2020). Hong et al. (2020) mentioned that coupling UBEM with urban microclimate tools to capture the two-way interaction between buildings and the urban atmosphere is a remaining challenge because of complexity and computation cost.

In this study, a new and in-house urban microclimate model, CityFFD (City Fast Fluid Dynamics) (Mortezaeezadeh, 2019; Mortezaeezadeh et al., 2021), is coupled with a new UBEM tool, CityBEM (Katal et al., 2019). CityFFD is based on the semi-Lagrangian and fractional step methods with a group of novel numerical schemes to improve the model's accuracy and reduce its computational cost (Mortezaeezadeh and Wang, 2017; Mortezaeezadeh and Wang, 2019; Mortezaeezadeh and Wang, 2020). CityFFD has been equipped with a 4th-order numerical interpolation scheme that reduces numerical dissipation and dispersion errors even on the coarse grids (Mortezaeezadeh and Wang, 2017). This model has been written based on CUDA-C++ and OpenMP to access computer resources' maximum power (Mortezaeezadeh and Wang, 2020). We recently showed that CityFFD could model large scale problems quickly on personal computers (Mortezaeezadeh and Wang, 2020, Mortezaeezadeh et al., 2021). On the other hand, CityBEM is an in-house building energy model with a library of
1700 building archetypes for facilitating the urban model creation of a group of buildings.

The methodology, including CityFFD, CityBEM, and integration procedure, is presented in the following section. In the next section, the first accuracy of CityFFD will be discussed by modelling a generic urban area. The performance of CityFFD/CityBEM is investigated by considering an urban area in Montreal, Canada. The results are validated by the measurement data of weather stations. The last section summarizes the study with conclusions and proposed future work.

**Methodology**

In this section, CityFFD and CityBEM are introduced. Then, the integration process and exchanging data between these two models are presented.

**CityFFD (City Fast Fluid Dynamics)**

CityFFD is based on the semi-Lagrangian approach and fractional stepping method running on the graphics processing unit (GPU) to simulate urban microclimate features for modeling large-scale urban problems. CityFFD solves the following conservation equations:

\[
\nabla \cdot \vec{U} = 0
\]

\[
\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla) \vec{U} = -\nabla p + \left(\frac{1}{Re} + \nu_t\right) \nabla^2 \vec{U} - \frac{6\nu}{Re^2} \theta
\]

\[
\frac{\partial \theta}{\partial t} + (\vec{U} \cdot \nabla) \theta = \frac{1}{Re Pr} + \alpha_t \nabla^2 \theta
\]

where \(\vec{U}\), \(\theta\), and \(p\) are the velocity, temperature, and pressure in the fluid equations. \(Re\), \(Pr\), \(\nu\), and \(\alpha\) are the Reynolds number, Prandtl number, turbulent viscosity, and turbulent thermal diffusivity. The advection terms of Eqs. (1) and (2) are solved by using the Lagrangian approach:

\[
\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla) \vec{U} = \frac{d\vec{U}}{dt}
\]

\[
\frac{\partial \theta}{\partial t} + (\vec{U} \cdot \nabla) \theta = \frac{d\theta}{dt}
\]

where \(S_c\) is the characteristic curve and shows the fluid particles' path. The fluid-particle positions, \(S_max\) at the time \(n\) and \(S_{max} + 1\) at the time \(n + 1\) can be related by the following equation:

\[
dS_c = \vec{U}dt \rightarrow S_{n+1} = S_{n} + \vec{U}dt
\]

To calculate the values for the unknown variables (e.g., velocity and temperature, \(\vec{U}\) and \(\theta\)) at the position \(S_{max} + 1\), we need to compute the values of \(\vec{U}\) and \(\theta\) at the position \(S_{max}\) in Eq. 6. Thus, an interpolation scheme is needed. CityFFD is equipped with a 4th-order interpolation scheme to model airflow on the coarse grids and overcome the high dissipation errors. Details of the proposed method have been comprehensively investigated in our previous work (Mortezazadeh and Wang, 2017). To capture the flow's turbulence behavior, the LES-SGS turbulence model is applied (Mortezazadeh and Wang, 2020). Based on this model, turbulent viscosity is calculated by:

\[
\nu_t = (c_s \Delta)^2 |\vec{S}|
\]

where \(c_s\), \(\Delta\), and \(\vec{S}\) are the Smagorinsky constant, the filter width, and the large scale strain rate, respectively. Smagorinsky constant is mostly in the range of \(0.1 < c_s < 0.24\) (Klaus and Hoffman, 2000).

CityFFD has been well validated by several CFD benchmarks and represented acceptable accuracy for modeling an urban microclimate (Mortezazadeh and Wang, 2020).

**CityBEM (City Building Energy Model)**

CityBEM is a building energy model for urban thermal loads and energy prediction. The model's inputs include building information, such as geometry, construction materials, lighting, and building uses and operations, such as occupancy schedules. The schematic of the model is shown in Figure 1.

![Figure 1: Schematic of the CityBEM model.](https://doi.org/10.26868/25222708.2021.30495)

CityBEM considers the building as a single zone with the well-mixed assumption. The total thermal load of each building \(\left(\dot{Q}_t\right)\) is a combination of convective heat transfer from indoor surfaces, fenestration radiation heat, infiltration heat transfer, and internal heat gains.

\[
\dot{Q}_t = \dot{Q}_{wall} + \dot{Q}_{es} + \dot{Q}_{inf} + \dot{Q}_{int}
\]

Details of each component in Eq. 8 can be found in our previous work (Katal et al., 2019).

Building information, such as building thermal properties, occupancy schedules for internal load calculations, and Window-Wall-Ratio (WWR) for solar heat gains, is provided based on an archetype library. This library was developed and implemented into CityBEM based on the building year of construction and usage (Katal et al., 2019). Then, the required parameters are assigned to each group of buildings. 19 reference building types, including single-family houses, Multi-Unit Residential Buildings (MURB), and 17 commercial buildings, are used to estimate WWR. Building envelope properties were estimated based on the classification of buildings' years of construction. To estimate the internal load, the building stock was divided into 10 building types. The operation hours, average loads by occupants, appliances, lighting, and the average usage rate are the parameters defined for each group and used to estimate the transient internal load of buildings. Comprehensive information about the proposed archetype library can be found from Katal et al. (2019).

**CityFFD/CityBEM integration**

Proposed urban microclimate and building energy models are automatically integrated using the Ping-Pong coupling
strategy (Hensen, 1995). Based on this model, CityFFD and CityBEM run in sequence (i.e., one data exchange at each time step). The integration method is shown in Figure 2. The typical timestep of integrated simulation is 1 hour, which is suitable for microclimate simulation. The typical internal timestep of CityFFD and CityBEM is 1 to 10 seconds and 5 minutes, respectively. At each time step, CityFFD simulates the urban microclimate and obtains an average air temperature and wind speed for each façade or specified sections of a building facade. CityBEM uses these data to calculate the thermal load, indoor air temperature, and building surface temperature. The simulated surface temperature of each building facade is transferred to CityFFD as a surface temperature boundary condition for the next timestep simulation.

![Figure 2: Dynamic urban building and microclimate simulation (CityFFD/CityBEM) workflow](image)

### Generic urban microclimate simulation

In this section, the airflow in a generic urban area is simulated. In this case, based on the previous wind tunnel and numerical studies conducted by Yoshie et al. (2005), a high-rise building is surrounded by a group of low-rise buildings (Figure 3).

![Figure 3: Building configuration (Generic urban area)](image)

The dimension of the high-rise building is $62.5 \times 62.5 \times 250 \text{m}^3$ and the low-rise buildings are with $100 \times 100 \times 25 \text{mm}^3$. Street's width is 25 m, and the wind speed at the inlet is equal to 6.61 m/s. The total grid number is about 17 million with a computational time of around 1.5 hours on one PC with a GPU NVIDIA Titan V card. Figs. 3 and 4 illustrate the wind tunnel setup and the measuring point locations, respectively. Figure 4 shows the measuring points around the high-rise building.

Figure 5 compares the velocity calculated by CityFFD at different measuring point locations around the high-rise building between the present work and the wind tunnel and three different numerical simulations using the standard $k-\varepsilon$, RNG, and LK from the previous work (Yoshie et al. 2005). The results show a good agreement with the measurement data in the wind tunnel. The proposed method can provide accurate results with the RMSE of about 0.09, which is in the same range as the reference (Yoshie et al. 2005): RMSE = 0.08.

![Figure 5: Comparison of dimensionless velocities at different measuring point locations](image)

### Urban microclimate simulation

In this section, CityFFD/CityBEM is applied to investigate the accuracy of urban microclimate estimation during a day in a heatwave event by comparing with measurement data. The onsite measurement data were documented by Environment and Climate Change Canada during a temporarily field campaign during the summer of 2013. Figure 6 shows the aerial image of the case study (downtown of Montreal, Canada), and the highlighted point shows the weather station location. The arrow shows the dominant wind direction in the domain.
The building cluster with the size of 1.5 km ×1.5 km is located in downtown Montreal. The overall domain size is 4 km × 4 km. The distance to the domain boundary is chosen as ten times of maximum building height (Tominaga et al., 2008). Vertical surfaces of the domain are inlet or outlet, depending on the wind direction. The floor boundary condition was considered as a wall, and the top boundary condition was symmetry. Buildings’ surfaces' temperatures are calculated by CityBEM and used as a boundary condition in CityFFD. The total mesh number is 54 million, and the minimum mesh size near the building is 1 m. Twenty-four simulations were conducted with the timestep of one hour.

The CFD inlet boundary conditions were provided by the weather station located at the airport, about 13 km away from the downtown of Montreal (Figure 8).

Based on the literature, because of urban morphology, building configuration, and terrain impacts, the microclimate properties recorded at the airport are different from the local microclimate near the downtown (Wieringa, 1992). We can estimate the variation of wind speed at Montreal’s downtown empirically by using the airport weather station data. However, it cannot accurately estimate the airflow at the street canyon. Using CityFFD/CityBEM, we could accurately estimate the wind conditions and air temperature in the urban area by using the weather station data about 13 km away from the case study region. The 2013 summertime overheating period is selected in this study: from 0:00 to 23:00 July 15, 2013 (Figure 9). Here we can see that temperature differences recorded at the Montreal Downtown and the airport can reach up to 8 degrees. Most temperature differences are observed during the nighttime, possibly due to the UHI effects. Buildings act as solar storage and release the heat into the urban microclimate during the nighttime (Sobstyl, 2018). Figure 9 shows that the proposed integration model could significantly improve the urban temperature accuracy: the RMSE of the temperature prediction is 0.6 °C.
the wind magnitude in the urban area. The RMSE for wind velocity is 0.265 m/s. As mentioned before, CityFFD is equipped with the 4th-order interpolation scheme to reduce numerical dissipation errors and capture wind patterns near the buildings.

Figure 10: Daily velocity variation at the centre of the case study (15 July 2013)

Figure 11 represents the velocity and temperature contours at the pedestrian level height (2 m) at 12:00 pm, 15 July 2013. It can be seen that airflow in the urban region is decelerated. The reduced wind could increase the thermal diffusion and consequently the air temperature near the buildings. Due to solar heat gain, the buildings’ surface temperature becomes higher than the outdoor air temperature. Then, the airflow is heated by the buildings’ surface, and the air temperature inside the street canyon rises. The high air temperature appears in the region close to the building surface up to 31.4 °C.

(b) Temperature distribution

Figure 11: Velocity and temperature distribution at the pedestrian level height (2m), 12:00 pm

The validation results have been shown that the CityFFD/CityBEM is capable of predicting accurate results from the large-scale simulation with high resolution at a low computational cost. It can be beneficial to other urban microclimate investigations like building energy consumption, urban wind energy prediction, outdoor thermal comfort estimations.

Conclusion

An integrated urban model (CityFFD/CityBEM) has been proposed to model indoor and outdoor environments in urban areas in the present work. The main focus was the validation of predicted urban microclimate data by weather station measurements. CityFFD is a fast and accurate urban microclimate model for large urban-scale simulations on personal computers. CityBEM can model buildings’ indoor environment and generate high-accurate buildings’ surface temperature used as a boundary condition in CityFFD. In future work, both models will continue to be developed for more advanced urban simulations, including vegetations, green building envelops, rain and solar radiation modeling with more application for urban microclimate and building thermal and energy analysis.

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References


