A Case Study on Urban Ventilation Assessment with Local Climate Zone (LCZ) Parameters

Yunwei Zhang1,*, Xiaoqian Zhang1, Wen Xu1 and Binbin Jiao1
1School of Human Settlement and Civil Engineering, Xi’an Jiaotong University, Xi’an, China

*Corresponding author email: zhangyunwei@mail.xjtu.edu.cn

Abstract. The local climate zone (LCZ) partitions are widely used in urban climate investigations. Parameters characterizing LCZ types could be used in investigations about urban heat island (UHI) intensity and air ventilation modelling and assessment. In the current work, modelling methods of UHI intensity and wind environment are investigated based on the LCZ parameters. A drag source term with a porous media model of the urban canopy layer was proposed to simulate the urban scale wind environment with the CFD method. Vertical and horizontal airflow in the urban canopy layer was analysed. The upward and downward wind was found in the urban canopy model influenced by the variations of building height and density. On the other hand, the heat balance models could also be conducted on LCZ. Results showed the potential capabilities in urban wind assessment. A summary of models and the requirement on LCZ parameters were proposed.

Keywords: Local climate zone; UHI; Urban climate map; Wind assessment; Parameters.

1. Introduction
With the rapid urbanization, more and more people migrate to towns, which induced the expanding of urban area and the transforming of underlying surface structure. The urbanization ratio in China has increased from 17.92% in 1978 to 58.52% in 2017 [1]. In the urban areas, vegetation decreases and impervious surface increases dramatically. Most land surface is now covered by artificial materials such as asphalt, cement and metal, which interferes with the transmission of heat and pollutants in urban areas [2]. Meanwhile, residential activities accelerated the metabolism of cities, which result in the emitting of a large amount of waste heat and pollutants to the surrounding environment [3]. These changes on surface structure and emission intensity lead to the accumulation of pollutants and heat within the urban canopy layer, and cause the urban micro climate in urban areas, such as higher pollutant concentration and air temperature than that in suburbs [4, 5].

Aimed to improve the urban micro climate conditions through reasonable urban planning, investigations on the urban climate, local climate zone (LCZ), wind corridor and the air ventilation assessments in urban areas are frequently carried out in recent years [6,7].

In general, in a certain region that covered with uniform surface structure and material, which is usually in scale of hundreds of metres, there would be of similar local climate characteristics. Thus, the urban areas could be classified into a number of LCZ types [7,8]. Stewart and Oke proposed the method of LCZ by distinguishing the structure of urban canopy layer, so as to investigate the air temperature conditions in urban areas [7]. It has been proved that the LCZ method is effective in investigations of the urban heat island (UHI) characteristics, as comparing the temperature differences among LCZ categories makes it more realistic than the traditional method that comparing the
temperature differences between “urban” and “rural” [9,10]. The LCZ method has been considered to be an international standard method describing the effects of land cover properties on urban heat island. In fact, parameters characterizing the LCZ types could be also used in describing the porous media model of the urban canopy layer, according to the geometric and the surface cover properties of the LCZ types. On the other hand, air temperatures in each LCZ type could be estimated with the energy balance model in the idealized LCZ samples. In the current work, methods of studying on urban microclimate based on LCZ parameters will be introduced, following a case study on the wind condition in Luoyang City will be proposed.

2. Models and Parameterization

Methods of numerical simulation on urban wind environment with porous media model and assessment of air temperature with energy balance model have been proposed in literatures [11-14].

2.1. Mathematic Model on Simulation with the Porous Media Urban Canopy Model

In recent years, several urban canopy models for wind environment simulation have been proposed. In the urban canopy models, physical effects of the canopy layer on airflow and energy balance are parameterized, for example, the resistance of buildings on wind is parameterized as a drag force term in the control equations, which could be calculated with parameters of building height and building density; while the anthropogenic heat could be parameterized as a heat source term. Other effects such as convective heat fluxes and radiation could be calculated based on the parameters of LCZ types as well [11]. The spatial structures of the urban canopy layer is significantly similar to the porous media. Hence some researchers regarded the urban canopy as the porous media in simulating on the urban wind and/or heat environment, which is composed of solid buildings, tree plantings and street canyons [11, 12].

In the porous media model of urban canopy layer, the significant dynamic and/or thermodynamic effects of solid buildings and tree plantings are represent based on the locally geometric and thermal parameters of the urban canopy layer. In the porous media model, solid buildings are regarded as void, and there is no need to track the outlines of buildings; while the resistance of buildings on wind is estimated with the drag force. The drag force resulted from the resistance of solid buildings could be represented by three terms in the control equations, which are the Darcy term, the Forchheimer term and the Brinkman term, respectively [12]. Moreover, the additional source term in the energy equation could be calculated based on the energy balance model as well [12].

The flow regimes within a porous media could be classified into four types according to the pore Reynolds numbers. If the pore Reynolds number is lower than 1, the flow within the porous media is defined as the Darcy flow; while the pore Reynolds number is between 1 and 150, the flow within the porous media is defined as the Forchheimer flow; while the pore Reynolds number is between 150 and 300, the flow within the porous media is defined as the post-Forchheimer flow or unsteady laminar flow; and when the pore Reynolds number is larger than 300, it is defined as the fully developed turbulent flow [15]. When concerning the flow within the urban canopy layer, the pore Reynolds number (setting the characteristic length with the building height) is as large as $10^5$. Thus, the airflow within the urban canopy layer is fully developed turbulent flow.

In the current work, control equations for incompressible flow is used, with the continuity equation is shown in equation (1).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

For the momentum equation, the Brinkman–Forchheimer extended Darcy model, which is widely applied in many industry and/or engineering cases [12], is adopted, as shown in equation (2).

$$\frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\mu} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial u_i}{\partial x_j} \right] + S \quad (2)$$

Where $S$ is the additional source term, including the drug force of the porous media model ($F_D$) and the buoyancy term ($F_B$), which could be calculated by equations (3) and (4), respectively.
\[ F_D = -\frac{\mu}{K} u_i - \frac{\rho C_F \omega^2}{\sqrt{K}} u_i (u_j u_j)^{1/2} \]  \hspace{1cm} (3)

\[ F_B = \delta_{13} \frac{\rho}{\varphi} g [\beta (T - T_B) - 1] \]  \hspace{1cm} (4)

In these equations, \( \mu \) and \( \mu_t \) are the dynamic viscosity and the turbulent viscosity, respectively, while \( \varphi \) is the porosity and \( C_f \) is the Forchheimer inertia coefficient. \( K \) and \( C_f \) can be calculated by the following equations,

\[ K = \frac{h^2 \varphi^2}{150(1 - \varphi)^2} \]  \hspace{1cm} (5)

\[ C_f = \frac{1.75}{\sqrt{150 \varphi}} \]  \hspace{1cm} (6)

In the current work, the porosity of each LCZ type could be estimated by typical samples [7, 16].

2.2. Energy Balance Model
The variation of air temperatures (\( \Delta T \)) near the ground could be calculated by equation (7).

\[ \Delta Q_s + \Delta Q_L + Q_{hi} + Q_{LE} = \rho c_p \Delta T \]  \hspace{1cm} (7)

where \( \Delta Q_s \) and \( \Delta Q_L \) are short- and long-wave radiations, \( Q_{hi} \) is the convective heat flux, and \( Q_{LE} \) is the latent heat flux.

3. A Case Study on Wind Environment in Luoyang City
The above methods were used to simulate the canopy layer wind environment in the urban canopy layer of Luoyang City.

3.1. LCZ Classification and the Parameters
Each LCZ category could be illustrated by one (or more) distinguished surface property. In most cases, the average height of buildings and/or roughness objects, and the surface cover fraction of buildings are usually used to illustrate the surface property [7]. The physical properties of some LCZ types that used in the current work are listed in Table 1. Values of the key parameter, \( \varphi \), could be estimated from typical training samples used in LCZ classification, or estimated by idealized building array models, as shown in Figure 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** A sketch of an idealized building array layout model.

The characteristic length in the porous media model, \( h \), could be calculated by the “Height of roughness elements” in Table 1. In the current work, a case study on the wind environment simulation in Luoyang City was carried out. The main simulation domain and the LCZ classification results are shown in Figure 2. The simulation domain is 20km×20km horizontally and 300m vertically. The horizontal resolution is 120m×120m. A large eddy simulation method is used for the turbulent flow. The prevailing wind is northeast. The reference wind speed at 10 metres height is 5m/s.
Table 1. Values of geometric/surface cover and thermal properties for LCZs (after [7, 16]).

| LCZ type      | Training sample | Aspect ratio | Building surface fraction | Height of roughness elements | Surface albedo | Anthropogenic heat output |
|---------------|-----------------|--------------|---------------------------|-----------------------------|----------------|---------------------------|
| LCZ 1 Compact high-rise | >2              | 0.4-0.6      | <25m                      | 0.10-0.20                   |                | 50-300                    |
| LCZ 3 Compact low-rise    | 0.75-1.5        | 0.4-0.7      | 3-10                      | 0.10-0.20                   |                | <75                       |
| LCZ 4 Open high-rise      | 0.75-1.25       | 0.2-0.4      | >25                       | 0.12-0.25                   |                | <50                       |
| LCZ 8 Large low-rise      | 0.1-0.3         | 0.3-0.5      | 3-10                      | 0.15-0.25                   |                | <50                       |
| LCZ B                 | 0.25-0.75       | <0.1         | 3-15                      | 0.15-0.25                   |                | 0                         |

3.2. Results and Discussions

Figure 3 shows the calculated values of $\phi$, it clearly shows the river runs through the city and forms a band of low-density zone. Generally, in the center of the city, buildings are tall with high surface cover fraction. In the horizontal plan at 3m height, wind speeds are generally lower than 2m/s, which indicate weak wind conditions within the urban canopy layer of Luoyang City. The simulated wind field reveals an evident wind corridor formed along the river, as shown in Figure 4. In most of other investigations, wind corridor were suggested according to the topographic and land-use characteristics [17]. The current work revealed the wind conditions along a potential wind corridor.
Figure 3. Isosurface on the porosity of urban canopy porous media model with $\phi = 0.6$.

The prevailing wind is northeast. As showed by the streamlines in Figure 5, the variation of building height and surface cover fraction has obviously influence on the wind field, especially the vertical airflow. In front of tall-compact built areas, upward wind developed, while in open areas wind blows down. However, the expected horizontal bypass flow around compact areas was not found in the current simulations. It should be point out that, the vertical airflow variations haven’t been reported in literatures yet.

The current simulations were carried out with a horizontal resolution of 120m×120m. With the current resolution, main designed wind corridors could be distinguished. In classify the LCZ map, the initial data have a resolution of 30m. The current method could be used in wind corridor analysis.

4. Conclusions

In the current work, vertical and horizontal airflow in the urban canopy layer model of Luoyang City was analysed. The simulated results revealed the effects of building height and surface cover fraction on the wind field within the urban canopy layer, including the upward and downward wind within the canopy layer model. On the other hand, the heat balance models could also be conducted on LCZ. Results showed the potential capabilities and advantages of LCZ and porous media method in urban wind assessment. The current work would be useful in urban environment planning and management, so as to support the sustainable development of the city.
Acknowledgements

The current work was supported by the National Natural Science Foundation of China (Grant No. 41977182), the National Science and Technology Foundation Project (Grant No. 2013FY112500), and the Basic Research Plan of Natural Science of Shaanxi Province (Grant No. 2019JM-387).

References

[1] National Bureau of Statistics of People’s Republic of China. (2018) Statistical Bulletin of the People’s Republic of China on National Economic and Social Development in 2017.

[2] Kesikoglu M.H., Atasever U.H., Ozkan C., Besdok E. (2016) The usage of rusboost boosting method for classification of impervious surfaces. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B7, pp. 981-985

[3] Zhang Y. and Gu Z. (2013) Air quality by urban design. Nature Geoscience, Vol. 6, pp. 506

[4] Chan C.K. and Yao X. (2008) Air pollution in mega cities in China. Atmospherionpheric Environment Vol. 42, pp. 1-42

[5] Zhang Y., He S., Gu Z., et la. (2019) Measurement, normalization and mapping of urban-scale wind environment in Xi’an, China. Indoor and Built Environment Vol. 28, pp. 1171-1180

[6] Ren C., Ng E., Katzsehner L. (2011) Urban climatic map studies: a review International Journal of Climatology Vol. 31, pp. 2213-2233

[7] Stewart I.D. and Oke T.R. (2012) Local climate zones for urban temperature studies. Bulletin of American Meteorological Society Vol. 93, pp. 1879-1900

[8] Bechtel B., Alexander P.J., Bohner J., et al. (2015) Mapping local climate zones for a worldwide data base of the form and function of cities. ISPRS International Journal of Geo-Information Vol. 4, pp. 199-219

[9] Yang J., Jin S., Xiao X., et al. (2019) Local climate zone ventilation and urban land surface temperatures: towards a performance based and wind sensitive planning proposal in megacities. Sustainable Cities Society Vol. 47, pp. 101-1487

[10] Zhang Y., Zhang J., Zhang X., et al. (2021) Analyzing the Characteristics of UHI in Summer Daytime Based on Observations on 50 Sites in 11 LCZ Types in Xi’an, China. Sustainability Vol. 13, pp. 83

[11] Hu Z., Yu B., Chen Z., et al. (2012) Numerical investigation on the urban heat island in an entire city with an urban porous media model. Atmospheric Environment Vol. 47, pp. 509-518

[12] Wang X., Li Y., Hang J. (2017) A combined fully-resolved and porous approach for building cluster wind flow. Building Simulation Vol. 10, pp. 97-109

[13] Grimmond C.S.B., Jarvi J., Lindberg F., et al. (2015) Urban energy budget models (Chapter 9), in Chrysoulakis N., Castro E., Moors E. ed. Understanding urban metabolism, pp. 91-105

[14] Liu D., Grimmond C.S.B, Ta J. et al. (2018) A new model to downscale urban and rural surface and air temperature evaluated in Shanghai, China. Jounal of Applied Meterorology and Climatology Vol. 57, pp. 2267-2283

[15] Pedras M.H.J. and de Lemos M.J.S. (2001) Macroscopic turbulence modeling for incompressible flow through undeformable porous media. International Journal of Heat and Mass Transfer Vol. 44, pp. 1081-1093

[16] He S., Zhang Y., Zhang J. (2018) Urban local climate zone mapping and apply in urban environment study. IOP Conference Series: Earth and Environment Science Vol. 113, pp. 012055

[17] Dang B., Fang X., Lu H., et al. (2017) Preliminary study on building urban ventilation corridors based on meteorological research: taking Nanjing jiangbei new region as the example. Meteorological Monthly, Vol. 43(9), pp. 1130-1137.