The Influence of Solar-Induced Thermal Effect on Outdoor Ventilation within Generic Urban Neighbourhood

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Abstract

As the ever-fasting urbanization, it is important to understand urban flow for the health of urban dweller. The previous studies on urban flow are conducted under the isothermal condition, and seldom pay attention to the solar-induced thermal effect. In this paper, one-way coupling CitySim-CFD is conducted to evaluate influence of solar-induced heating on urban flow within generic urban neighbourhood based on the climate characteristic and building codes of China. The results show that the differences in urban flow between isothermal condition and solar-induced heating condition become significant as the increase of Richardson number. The solar-induced heating have strong influence on outdoor wind environment, while the impact on outdoor ventilation is not significant. Meanwhile, the hourly distributions of Richardson number in each investigated city are presented in this paper, which can be a guideline for whether the results from isothermal cases are feasible. More investigations should be conducted to characterize the effect of solar-induced heating on urban ventilation parametrically.

Introduction

With the rapid urbanization, the portion of the population living in urban areas has continuously increased. In 2018, 55% of the world's population was lived in urban area, while it is estimated to reach 68% by 2050 (The Population Division, 2018). As the building density becomes higher, the air quality has been deteriorating within the urban canopy layer, also the urban heat island effect (UHI). Good outdoor ventilation is one of the possible solution to help diluting pollutant and heat.

Current studies of flow in urban mainly conducted with generic building configurations and real complex building configurations in the spatial scale of regional (< 200 km), city (<20 km), neighbourhood (<2 km) and street (<0.2 km) (Britter and Hanna, 2003). Most of the studies on pedestrian comfort were conducted at the scale from street to neighbourhood with field measurement, wind-tunnel experiment and computational fluid dynamics (CFD) simulation (Blocken, Janssen and van Hooff, 2012; Shahrestani et al., 2015; Antoniou et al., 2017). As the flow patterns are determined by the building configurations, studies with real building configurations are performed as case study of local wind environment (Panagiotou et al., 2013; Toparlak et al., 2015), or

investigate the possibilities and limitations of CFD for real urban areas (Antoniou et al., 2017). Studies with generic buildings configuration not only provide wind-tunnel experimental data for CFD validation (Brown et al., 2000; Uehara et al., 2000; Allegrini, Dorer and Carmeliet, 2013), but also provide the basic insights of the relationship between urban morphology and urban ventilation (Abd Razak et al., 2013; Ignatius, Wong and Jusuf, 2015; Ramponi et al., 2015; Taleghani et al., 2015).

Large parts of urban flow have investigated the influence of urban length, building height variations, building layouts, wind directions etc. (Hang et al., 2010, 2015; Yuan and Ng, 2012; Buccolieri et al., 2015) the under neutral atmospheric condition. Thermal effect is another key issue determining urban microclimate. Field measurement in Nantes (Louka et al., 2002) during summer time shown that the maximum building walls' temperature in the afternoon exceed 50 °C, which cause strong buoyancy effect on the flow around the buildings. Wind-tunnel experiment with uniform wall heating (Allegrini, Dorer and Carmeliet, 2014) indicates that the air change rate (*ACH*) inside the street canyon increases strongly with increasing walls' temperature. As building walls are heated up by solar radiation which depends on solar position and site location, the building walls' temperature are not uniform in real scenario. The orientation of thermal stratification will affect the flow structure (Jae-Jin and Jong-Jin, 1999).

One of the most employed simulation tool is ENVI-met, which is simplified 3D model designed to simulate the interaction between surfaces, plants and air in an urban environment (Bruse and Fleer, 1998). While its resolution is rather too low (minimum 0.5 m), and has shortcoming in capturing the long-wave and short-wave radiations (O'Malley et al., 2015). Coupling CFD and solar radiation model can capture the solar radiation and obtain higher spatial resolution of local wind-thermal environment. Saneinejad, etc., (2014) conducted CFD simulation with radiation and porous media model to study the local UHI within a two-dimension street canyon. Santiago, etc., (2014) coupled CFD simulation with TUF3D model to investigate the influence of solar radiation within a three-dimension street canyon. The results show that the flow regime is completely changed with respect to neutral case. Nazarian and Kleissl (2016) simulated the urban environment with solar-induce surface heating by using ANSYS Solar Load Model, it shows that the *ACH* inside the street canyon is a function of horizontal temperature

gradient. The urban energy model, CitySim, has detailed radiation models for solar radiation and radiation exchange between neighbouring buildings, the ground and environment with scale ranging from a small neighbourhood to an entire city. It is capable of computing the hourly irradiation on building surfaces and the corresponding surfaces' temperature. Researchers have coupled CitySim and CFD to reveal the influence of neighbourhood morphologies, building height topology and surface albedo on local heat island (Allegrini, Dorer and Carmeliet, 2015; Allegrini and Carmeliet, 2017, 2018).

As the ever-fasting urbanization of China, the building density will be higher on the foreseeing days, it is important to improve urban ventilation for the health of people and energy saving. Meanwhile China covers a wide temperature gradient decreasing from south to north and a large precipitation gradient decreasing from southeast to northwest (WU, 2005), it can be an ideal place to study the wind-thermal environment within urban neighbourhood. In this paper, One-way coupling CitySim-CFD is applied to investigate the influence of solar-induced heating on the outdoor ventilation within typical generic urban neighbourhoods.

Methods and materials

λ_f (frontal area ratio, ratio of building frontal area to ground surface area) and λ_p (plan area ratio, ratio of building roof to ground surface area) are the typical parameters to describe the urban morphology (Grimmond and Oke, 1999). For typical urban morphology, $\lambda_f = \lambda_p = 0.25$ (medium size). The typical urban neighbourhood-scale models in the field of urban ventilation are square layout and staggered layout.

In this paper, we take the medium size square layout as the investigated target. The building width (B), building height (H) and distance between buildings (W) are the same ($B=H=W=30$ m), as Figure 1 shows.

Figure 1: The studied neighbourhood-scale model.

With the fixed array's parameters, CitySim and CFD are coupled to study the outdoor ventilation within the generic neighbourhood-scale building array under the five different climate zones of China. The numerical simulation methodology is that the CitySim generates the solar-induced temperatures of building walls and ground surfaces as thermal boundary conditions for CFD simulation.

CitySim setup

The climate data (typical year) and horizon characteristics of the investigated locations for CitySim simulation are derived from Meteonorm.

The key building thermal parameters and glazing ratio of each investigated city are summarized in Table 1, which are complied with Chinese Design Standards for energy efficiency of public buildings and the standards of each investigated city (MOHURD, 2016; Tong et al., 2016). The infiltration is set as 1 h^{-1} , with space heating and cooling to maintain the indoor air temperature between 18 and 26 °C. The openable fraction of windows is 50% with the shading device of 50%, and the solar reflectance of all surfaces is 0.5. The ground surfaces inside the building array is set as asphalt with a reflectance of 0.5.

Table 1: Building thermal parameters and glazing ratio of investigated cities.

		Guangzhou	Kunming	Shanghai	Beijing	Harbin
Surfaces' U-value [$W/(m^2 \cdot K)$]	Wall	0.72	0.72	0.54	0.46	0.35
	Roof	0.44	0.44	0.39	0.39	0.25
	Floor	1.32	1.32	0.46	0.46	0.25
Windows' U-value [$W/(m^2 \cdot K)$]	U-value	2.40	2.40	2.30	1.77	1.76
	G-value	0.20	0.20	0.32	0.37	0.68
Glazing ratio	North	0.45	0.40	0.35	0.30	0.25
	East	0.30	0.35	0.25	0.35	0.30
	South	0.50	0.45	0.50	0.50	0.45
	West	0.30	0.35	0.25	0.35	0.30
	Roof	0.04	0.04	0.04	0.04	0.04

CFD setup

All simulation cases are conducted as steady state with standard $k-\epsilon$ model that solves turbulence equations and the energy conservation equation with temperature as the solved variable. In addition, buoyancy terms are accounted for with Boussinesq's approximation. The simulation cases are solved by the commercial code

STARCCM+. The computational domain extends $6.7H$ upstream and $50H$ downstream of the building array, height of the domain is $5H$.

The inlet vertical profile of stream-wise velocity $U(z)$, the turbulent kinetic energy $k(z)$ and the turbulence dissipation $\epsilon(z)$ was described by equation (1) to (3). This neutral atmospheric boundary layers (Richards and

Hoxey, 1993) are commonly used in CFD simulations of urban flow.

$$U(z) = \frac{u_{ABL}^*}{k} \ln\left(\frac{z+z_0}{z_0}\right) \quad (1)$$

$$k(z) = \frac{u_{ABL}^*}{\sqrt{C_\mu}} \quad (2)$$

$$\varepsilon(z) = \frac{u_{ABL}^*}{k_v(z+z_0)} \quad (3)$$

$$k_s = 9.793 z_0 / C_s \quad (4)$$

Where, u_{ABL}^* is the atmospheric boundary layer friction velocity, m/s. k is von Karman constant (0.42). $C_\mu=0.09$ denotes the model constant. Roughness $z_0=0.1$ m and roughness constant $C_s=4$, then the roughness height of the ground, $k_s=0.245$ m. The distance between the centre point P of the ground adjacent cell and the ground surface (z_p) should be larger than k_s , $z_p=0.25$ m is adopted. The reference velocities (U_{ref}) at the reference height 10 m are based on the investigated cities' weather data.

At the lateral sides and roof of the computational domain, the symmetry boundary condition is applied. The building walls are simulated as smooth, and the floors are simulated as rough with the roughness height of $z_p=0.25$ m.

The thermal boundary conditions of building walls and ground surfaces within the building array are set as the

temperatures simulated by CitySim. The ground surfaces within the building array are divided into patches of 10 m x 10 m. While the thermal boundary condition of the ground outside the array is set as ambient temperature in order to avoid heating up of the air in the approach flow (Allegrini and Carmeliet, 2017). Even though the two-way coupling, where the walls' temperatures would also change as the local wind velocities, would gain more precise results of wind-thermal environment. While the aim of this study is to investigate the influence of solar-induced thermal effect, the lower precise results obtained by one-way coupling can be accepted.

In mesh generation, polyhedral mesh and prism layer mesh are employed, the first prism layer is set as 0.5 m. The cells number of each the case is around 7 million, and the wall y^+ ranges from 70 to 3000 of the wall surfaces within the building array. The isothermal case is validated with wind tunnel experimental data (Brown et al., 2000), grid sensitivity study is also conducted.

The hottest hours are chosen as the investigated summer scenarios. In addition, the winter scenarios are set at 17:00 PM at 15th January when the ambient air temperatures are closer to the coldest temperatures. The weather data of the investigated scenarios are summarized in Table 2 and Table 3. The wind speed is measured at height of 10 m. For wind direction, 360° represent the north.

Table 2: Weather data of the summer scenarios in the investigated cities.

City	Month	Day of the month	Hour	Ambient air temperature (°C)	Wind speed (m/s)	Wind direction (°)	Richardson number
Guangzhou	7	31	16:00	38.1	7.4	291	0.09
Kunming	7	9	16:00	29.8	5.7	294	0.26
Shanghai	7	21	16:00	38.0	1.8	82	3.35
Beijing	7	9	14:00	37.8	5.1	283	0.35
Harbin	6	19	16:00	34.3	3.4	296	0.61

Table 3: Weather data of the winter scenarios in the investigated cities.

City	Month	Day of the month	Hour	Ambient air temperature (°C)	Wind speed (m/s)	Wind direction (°)	Richardson number
Guangzhou	1	15	17:00	8.9	3.7	357	0.17
Kunming	1	15	17:00	7.4	4.1	357	0.20
Shanghai	1	15	17:00	-0.8	3.8	42	0.00
Beijing	1	15	17:00	-5.0	4.3	42	0.12
Harbin	1	15	17:00	-21.9	3.9	357	0.05

Evaluation indices

Velocity ratio (V_r) is a simple index to indicate the wind environment at pedestrian level of the investigated site, is calculated as:

$$V_r = U_p / U_{ref} \quad (5)$$

Where U_p is the wind velocity at pedestrian level (1.75 m above the ground), U_{ref} is the wind velocity at the top of the wind boundary layer not affected by investigated site feature (ground roughness and buildings). In this study, the U_{ref} is the same as inlet boundary, at the reference height 10 m.

Air change rate (ACH), air exchange per hour for a control volume, is widely used in urban ventilation to represent the overall ventilation efficiency.

$$ACH = 3600 * Q_T / vol \quad (6)$$

Where Q_T is the total flow rate entering the control volume; vol is control volume, the entire neighbourhood model; 3600 represent 1 hour is 3600 seconds.

Normalized velocity ratio (V_r^*), the difference between heating condition and isothermal condition, indicates the change of wind environment caused by buoyancy effect:

$$V_r^* = V_{r, heating} / V_{r, isothermal} \quad (7)$$

Normalized air change rate (ACH^*), the difference between heating condition and isothermal condition, indicates the change of outdoor ventilation efficiency caused by buoyancy effect:

$$ACH^* = ACH_{heating} / ACH_{isothermal} \quad (8)$$

Richardson number (Ri), the ratio of buoyancy to inertia forces, is non-dimensional number reflect the importance of buoyancy.

$$Ri = g\beta H(T_0 - T_{ref}) / U_{ref}^2 \quad (9)$$

Where T_{ref} is the reference temperature, U_{ref} is the reference velocity, here we take ambient air temperature and reference velocity at the inlet as reference temperature and velocity. T_0 is temperature of walls, here we take it as the average temperature of all building walls and ground surfaces inside the neighbourhood model. $g=9.81 \text{ m}\cdot\text{s}^{-2}$ is the gravity acceleration. H is the building height. β is the thermal expansion rate of air, here is 0.0033 K^{-1} .

Figure 2: Temperatures of buildings' walls in the hottest hours (A: Guangzhou, B: Kunming, C: Shanghai, D: Beijing, E: Harbin; Red line: ambient air temperature, Blue line: south wall, Green line: north wall, Purple line: east wall, Yellow line: west wall).

Pedestrian wind-thermal environment

Figure 3 to Figure 7 present the V_r and Δt at pedestrian level in the five investigated cities under isothermal condition and solar-induced heating condition. Generally, for the case in Guangzhou ($Ri=0.09$), Kunming ($Ri=0.26$) and Beijing ($Ri=0.35$) the airflow patterns are similar under isothermal condition and solar-induced heating condition. But still exist small differences in the downstream. When the Richardson number is getting larger, in the case Harbin ($Ri=0.61$), the local differences in flow pattern become obvious.

Results

Solar-induced thermal condition

The temperatures of building walls within the layout are proximately the same in each orientation. Figure 2 shows the average wall temperature of each studied city in the hottest day respectively. The walls' temperature are resulted from solar radiation and buildings' thermal characteristic (especially the albedo), it will be the same under the same building distance in specified time. In the hottest hour of each investigated city, west orientation walls have the highest temperature. The highest wall temperature happens in Shanghai, exceed 60°C . The temperatures of walls and ground surfaces in the investigated hours are set as thermal boundary conditions in CFD to simulate the outdoor wind-thermal environment.

For the case in Shanghai ($Ri=3.35$), the flow pattern is totally different with respect to isothermal case. The V_r within the canyon is larger than 1, which means the buoyancy force is dominating the airflow and increases wind velocity. Consequently, more heat is diluted from the canyon.

The Richardson numbers of the winter scenarios selected here are quite low (see Table 3), the general airflow pattern between the isothermal condition and solar-induced heating are similar.

Figure 3: V_r and Δt in the hottest hour of Guangzhou ($Ri=0.09$).

Figure 4: V_r and Δt in the hottest hour of Kunming ($Ri=0.26$).

Figure 5: V_r and Δt in the hottest hour of Beijing ($Ri=0.35$).

Figure 6: V_r and Δt in the hottest hour of Harbin ($Ri=0.61$).

Figure 7: V_r and Δt in the hottest hour of Shanghai ($Ri=3.35$).

Analysis of solar-induced thermal effect

The Ri of each case are calculated to quantify the solar-induced thermal effect. The variation of V_r^* and ACH^* with Ri are presented in Figure 8. In this paper, Ri ranges from 0 to 3.35. When Ri closes to 0, the difference of velocity ratio between isothermal and heating condition is quite small, even can be ignored. As the Ri becomes larger, the buoyancy effect becomes obvious and even dominates the airflow. The influence of solar-induced

thermal effect on the air change rate are not significant. The maximum normalized air change rate is 1.14 with $Ri=3.35$. For $Ri<0.5$, the normalized air change rate is almost 1, the solar-induced heating does not affect the ventilation efficiency of the neighbourhood canopy. Previous research indicates that the street canyon flow is buoyancy dominated for $Ri>0.5-1.0$ (Fernando et al., 2010), which is also coincided with this study of neighbourhood canopy flow.

Figure 8: Variation of V_r^* and ACH^* with Richardson number.

While the investigated Richardson numbers are the extreme hottest and coldest hours in the five cities. Figure 9 shows the distribution of hourly Ri in each investigated city. The hourly Ri is divided into $Ri<0$, $0\leq Ri<0.5$ and $Ri>0.5$. The solar-induced thermal stratification of each city are not the same as their own climate conditions and building thermal characteristics. For the five cities, the Richardson number is smaller than 0 for more than half the times. When $Ri<0$, the walls' temperature are lower

than the ambient temperature, which likely occur in the cold hours or night-time. Further investigations should be conducted to demonstrate the solar-induced thermal effect under $Ri<0$. For the five cities, the influence of solar-induced heating is small or can be ignored in less than 20% of the time. The hours of $Ri>0.5$ increases in the northern cities of China, where have lower ambient temperature than the southern cities.

Figure 9: Distribution of hourly Richardson number in each investigated city.

Discussion

In order to obtain the corresponding Ri , the inlet boundary conditions (ambient air temperature, reference wind velocity and wind angle) of each case are consistent with the boundary conditions of CitySim. The initial conditions of each case are not the same, later investigation should consider the influence of wind speed and direction. Meanwhile the setting of albedo is neutral (0.5), but it did reflect the complicated thermal stratification within the urban neighbourhood canopy. As Richardson number is depend on the climate characteristic and building configurations (building layout, canopy length, building height and surface albedo), further investigation should be done with wider range of Ri (especially $Ri < 0$) for more general conclusions. Meanwhile, this paper just investigated one urban morphology ($\lambda_f = \lambda_p = 0.25$), the influences of urban morphology and building thermal characteristics on Ri are another topic under consideration.

Conclusion

In this paper, one-way coupling CitySim-CFD is employed to investigate influence of solar-induced heating on outdoor ventilation within generic urban neighbourhood. Results show that the solar-induced thermal effect will affect the pedestrian level wind environment significantly, while it is not significant in analysis of urban ventilation. Unlike the previous studies under isothermal condition or uniform-heating condition, the solar-induced heating will cause non-uniform thermal stratification within the urban neighbourhood canopy, which alters the airflow pattern consequently. Whether the conclusions from isothermal cases are feasible should base on the investigated scenarios of location and time. More investigations should be conducted to characterize the effect of solar-induced heating under different urban morphologies parametrically.

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