VENTILATION POTENTIAL BY THERMAL BUOYANCY IN AN URBAN CITY: NUMERICAL SIMULATION AND FIELD EXPERIMENT STUDY

Lina Yang*, Yuguo Li
Department of Mechanical Engineering, The University of Hong Kong, HKSAR, China

Abstract

The thermal buoyancy induced air flow may become important under the calm conditions. A 3D RNG *k*-*ε* turbulent model was used for the numerical simulation of a simple city model. The results show that the ventilation effectiveness is highly depends on the thermal buoyancy intensity, urban planning and geometry, and the atmospheric conditions. In addition, the field measurement using the infrared thermography was also conducted to obtain the diurnal thermal variation of the urban objects and analyze the thermal induced flow. Both studies provide a good understanding of urban ventilation by thermal buoyancy and useful information for urban planning.

Key words: City ventilation, Thermal buoyancy, CFD simulation, Infrared thermography

1. INTRODUCTION

Located along the southern coast of China, Hong Kong has a rugged terrain with the hills rising steeply from the sea. Many complex thermally-induced flows, such as natural convection flows on the vertical wall and mountain slope flows, land-sea breezes, mountain-valley winds, and UHI circulations, occur over the complex terrain in Hong Kong (Tong et al., 2005). Particularly in Hong Kong Island, most commercial/residential buildings have been built on the rugged terrain at different levels. The vertical natural convection wall flows and mountain slope flows become more important in such a high-rise city under windless days. The interaction between these thermally-induced flows may lead to certain complexity of the Hong Kong urban boundary layer structure, which has a direct relationship with the transport and diffusion of urban heat and pollutants. Questions remain as to how to quantitatively estimate the ventilation by thermal buoyancy and assess the ventilation effect. There is a lack of systematic research concerning the urban surface temperatures and ventilation effect of buoyancy-induced flows in a high-rise city such as Hong Kong. Hence, we carried out this study on the city ventilation of Hong Kong by thermal buoyancy, attempting to advance the understanding of how the thermally-induced air flows are induced in the urban city as well as assess the ventilation effect. The results may be useful to establish an optimum ventilation strategy for urban areas.

2. METHODOLOGIES

2.1. Numerical model

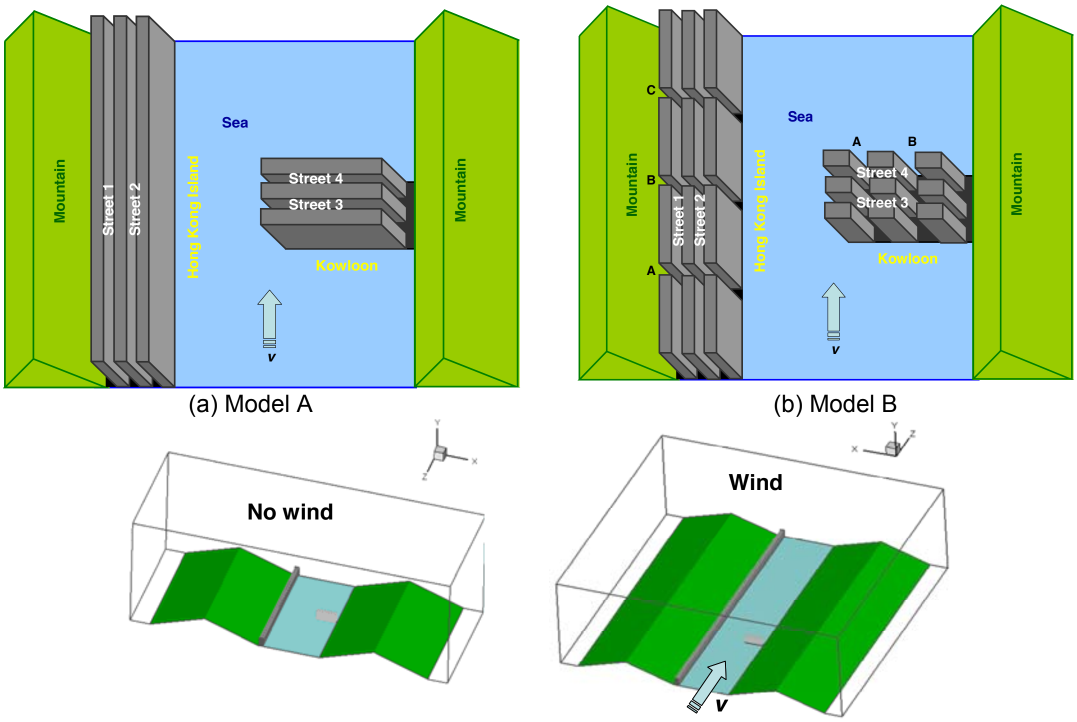
Hong Kong has very complex terrain with the hills and mountains rising steep from sea. Most of the territory's urban development exists on Kowloon peninsula and along the northern edge of Hong Kong Island. Between them, there is a Victoria harbor. For simplicity, two simple scaled Hong Kong city models with complex terrain are considered here (see Figure 1). The same buildings/streets structures are considered in the Hong Kong Island and Kowloon in the present study. Compared Model A, Model B is much more complicated with the increased secondary streets. We intend to know the urban ventilation by thermal buoyancy and study how to ventilate the urban area effectively based on the reduced scaled model with the geometrical scale of 1/100. The need for a small-scale model is due to the resolution requirements in modeling of the surface convection flows (slope flows and the wall flows) (less than 1 mm) and the relatively large computational domain (8 km). The 3D RNG k- ε model (Yakhot and Orszag, 1986) was adopted here.

The Reynolds number Re and Grashof number Gr was based on the identical building height, *H*, the buoyancy velocity $u_b = (g\beta\Delta TH)^{1/2}$ (no wind case) or velocity u_H (wind speed at the height of building for wind case), and temperature $\Delta T = T_b - T_a$ (temperature difference between the building and air). In the no wind case, the total computational domain is 30m×80.32m×30m. The total computational domain is 76m×80.32m×30m and the length of the streets and buildings for Hong Kong Island is 76m in wind case. In the wind cases, the upstream length in front of the buildings of Kowloon is about 5*H* and the downstream length is about 10*H* in the z direction. Only east wind is considered here. In both cases, while the minimum mesh size near the wall and ground is 0.0008m.

The pressure outlet/inlet boundary is used at the lateral domain sides and top for no wind case. In wind case, the velocity inlet boundary is used at the inlet with a power law relationship in the neutral atmosphere by $u(y) = u_H(y/H)^{0.143}$. Outflow boundary is defined at the outlet of domain. The symmetry boundary (zero flux of all quantities) is used at the top surface and two surfaces at two domain sides. All the grounds and building walls were specified as no-slip condition. Enhanced wall treatment in FLUENT, which combines a two-layer model with an enhanced

*Corresponding Author: Department of Mechanical Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

wall function, is employed as the wall model. According to the field measurements and annual mean temperature data from Hong Kong Observatory, the constant temperature is given for the mountain (T_m = 15°C), sea harbour (T_s = 22°C) and atmospheric air (T_a = 20°C). In addition, different building/street temperatures T_b (25°C, 30 °C and 40°C) and wind speeds at the height of building u_H (0.5m/s, 0.91m/s and 1.5m/s) are considered for both no wind and wind case. The numerical simulation process is performed using Fluent 6.3.26. Using Standard scheme for pressure interpolation, the second-order upwind scheme for the momentum equations and equations of turbulent kinetic energy, dissipation rate and energy, The SIMPLE algorithm is used for the coupling between velocity and pressure.



(a) Model A (b) Model B

(c) Computational domain

Figure 1. Illustrations of simple small-scale Hong Kong city models and computational domain

2.2. Field measurements

The urban area selected for the study is the Central district, located in the center of Hong Kong Island. The site of the camera is on the Peak (400m above the sea level). Two series of measurements were carried out for comparison and analysis in a warm season and a cold season respectively. The thermal behaviors of different urban surfaces were compared. The ventilation rates due to both vertical wall flows and mountain slope flows were estimated. The details have been described by Yang and Li (2009).

3. RESULTS AND DISCUSSIONS

3.1. Numerical simulations

An important concept about urban ventilation was introduced by Skote and Sandberg (2005): The air flow has a choice on the windward side of the urban canopy: flowing over the roof; flowing around the urban canopy; flowing into the street. And the amount of air flowing into the street is very important for the dilution ability in street cavity. When there is wind, the air flow may depend on the wind force, city geometry and arrangement. When there is no wind, the thermal buoyancy is the main force to drive the air into the street canyon from the lateral openings and out through the street roof. The flow rate can be an important index for the ventilation effectiveness. The net volume flow rate for a plane is defined as:

$$q = \int_A (ui + vj + wk)\vec{n}dA \tag{1}$$

where u, v, w is velocity in x, y, z direction, $\vec{n}$ is the normal direction of a plane.
The flow rate at roof level by turbulence can be also important for the ventilation efficiency:

$$q_{turb+} = q_{turb-} = \int_A \frac{1}{2}\sigma_w dA \tag{2}$$

*Corresponding Author: Department of Mechanical Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

where the fluctuation velocity $\sigma_\omega=(2k_r/3)^{1/2}$, k_r is the turbulence kinetic energy at roof level.
For each street, the flow rate can be normalized by the characteristic flow rate ($Q = q/q_0$). For the no wind case, the characteristic flow rate is defined as $q_0 = u_b \times A_{roof}$, where A_{roof} is the area of each street roof, i.e. 30m(L)×0.2m(W) for the street in HK island and 5m(L)×0.2m(W) for the building in Kowloon for Model A; while for model B, A_{roof} is the total area of streets roof, i.e. 12.36 m^2 for Hong Kong Island and 2.24 m^2 for Kowloon. For the wind case, the characteristic flow rate is $q_0 = u_H \times A_{s\_in}$, where A_{s_in} is the cross section area of each street, i.e. 0.2m(W)×2.5m(H)for model A and 1m^2 (two street openings) for Model B. The results of Model A and the calculated normalized flow rates for both models don't shown here due to the space limit.

3.1.1. No wind case

Given different buildings/street surface temperatures, the ventilation by the thermal buoyancy can be studied (i.e. Gr = 1.15×10^{10}, 2.29×10^{10}, 4.58×10^{10}). Figure 3 shows the temperature iso-surfaces, temperature contour and streamlines along the street centreline for Model B. The simulation results of Model B are very similar as that of Model I for the no wind case. As shown in Figure 3, the larger the thermal buoyancy intensity, the more the fresh air can be driven into the street cavity and the stronger the turbulence fluctuation occurs at roof level. The normalized flow rate through each street opening is kept almost constant. For the streets S3 and S4, the air flow through right-side openings (mountain side) is relatively larger than left-side openings (sea side). Different thermal conditions and terrains at the both sides of the street cause the non-symmetrical flow. The same total normalized flow rate can be found for streets with increasing thermal buoyancy for both models. The flow rate is a function of thermal buoyancy u_b, which determines the relative strength of the thermal buoyancy force of the buildings/streets. But the increased secondary street openings in Model B can bring more mountain wind and sea breeze into the street canyon for pollution dispersion and heat removal.

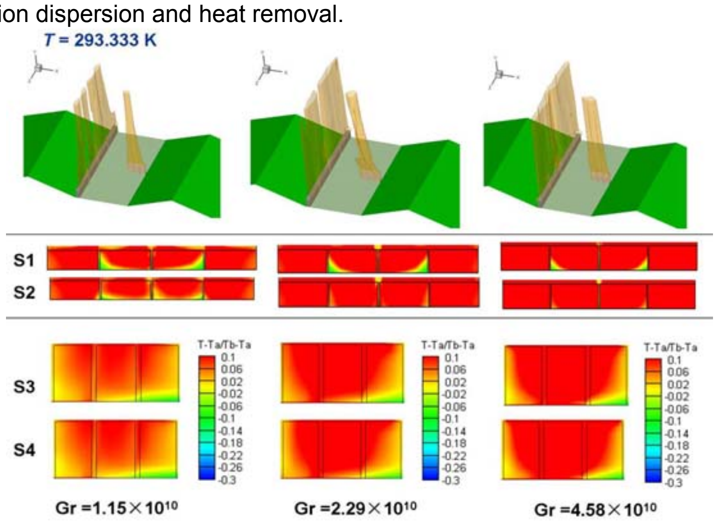


Figure 3. The temperature iso-surfaces and temperature contour along the street centreline for the no wind case (the contour legend is the same for all the streets S1-S4)

3.1.2. Wind case

By giving different wind speed (i.e. u_H = 0.5m/s, 0.91m/s and 1.5m/s), different strength of the wind to the thermal buoyancy can be considered (i.e. Gr/Re^2 = 0.37, 1.01, 3.34). A larger value of Gr/Re^2 means the effect of the thermal buoyancy is relatively higher compared to the wind effect. The temperature iso-surfaces and temperature contour along the street centreline for Model B are summarized in Figure 4. As shown in Figure 4, with the increasing Gr/Re^2, the thermal buoyancy becomes dominated and the rising thermal plume increases correspondingly. The temperature distributions in the streets S1-S4 are different with the increasing Gr/Re^2. When the wind is relatively larger, the wind can block the downslope flow (mountain wind) and sea breeze entering into the streets from the mountain side. When the wind reduces and the thermal buoyancy becomes dominated, more cold air from mountain and sea side can flow into the streets and drive the heat away. Therefore, the temperature near the openings of mountain side and sea side for the streets S1-S2 decreases with the increasing Gr/Re^2. But the relatively lower wind is insufficient to drive the heat out through the long streets. Hence a large amount of heat is accumulated at the end of the long streets S1 and S2 when the wind reduces. Similarly, for the streets S3-S4, more cold air from mountain side and sea side is introduced into the streets S3-S4 and decrease the temperature in the street canyon.

*Corresponding Author: Department of Mechanical Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

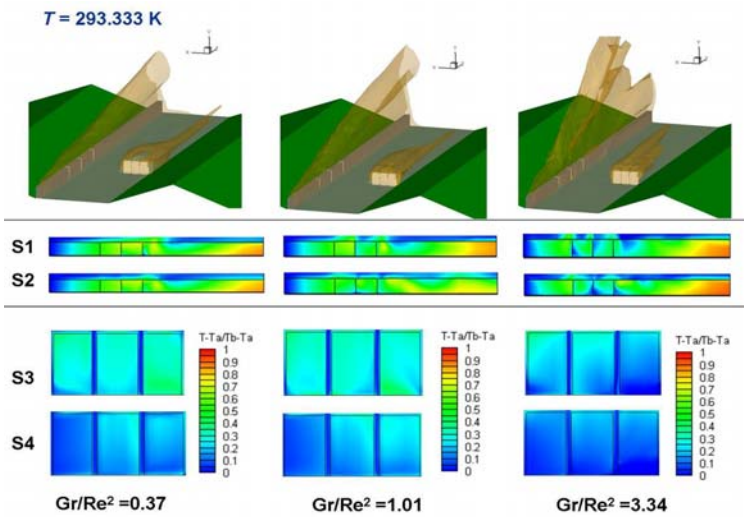


Figure 4. The temperature iso-surfaces and temperature contour along the street centreline for the easterly wind case (the contour legend is the same for all the streets S1-S4)

In Model A, almost identical total normalized flow rate can be found for the streets S1-S2; while the total normalized flow rate for Model B increases with the increasing Gr/Re2 with more secondary street openings. The wind dominated flow block the airflow through the side openings can be the reason.

3.2. Results of field measurements

The thermal data acquired by infrared camera show the diurnal thermal behavior of urban surfaces in Hong Kong. The mean temperature profile of all urban objects (mountain and buildings) are obtained and analyzed. Generally, the maximum urban surface temperature was measured in the late noon hours (14:00-15:00h) and the minimal temperature was observed before sunrise (5:00h). The solar radiation and the albedo of the various urban elements are important factors affecting the surface temperatures. The maximum temperature differences between the four selected exterior walls can be up to 16.7^{o}C in the early afternoon hours. By using the integral method, the city ventilation potential for the thermally-induced wall/slope flows was estimated through the temperature differences between the urban surface and surrounding air. The building wall flow by thermal buoyancy was found to be more significant than the slope flow along the mountain due to larger building exterior surface areas and temperature differences with surrounding air (about 2-4 times) (Yang and Li, 2009).

4. CONCLUSIONS

Both the preliminary simulation results and the field measurements can provide an overall estimation of city ventilation by thermal buoyancy. Such ventilation potential estimation can help us to gain an understanding of the ventilation rates in a dense high-rise city by thermal buoyancy, and as well as to identify the optimum city ventilation strategy.

5. ACKNOWLEDGEMENT

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*Corresponding Author: Department of Mechanical Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong SAR, China