Building and Environment 131 (2018) 32–43

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal buoyancy driven canyon airflows inside the compact urban blocks saturated with very weak synoptic wind: Plume merging mechanism

Shuo-Jun Mei[a,b,c], Jiang-Tao Hu[a,b,c], Di Liu[d], Fu-Yun Zhao[a,b,c,*], Yuguo Li[e], Han-Qing Wang[f]

[a] Key Laboratory of Hydraulic Machinery Transients (Wuhan University), Ministry of Education, Wuhan, Hubei Province, China
[b] Hubei Key Laboratory of Waterjet Theory and New Technology (Wuhan University), Wuhan, Hubei Province, China
[c] School of Power and Mechanical Engineering, Wuhan University, Wuhan, Hubei Province, China
[d] College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, Shandong Province, China
[e] Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China
[f] School of Civil Engineering, University of South China, Hengyang, Hunan Province, China

A R T I C L E I N F O

Keywords:
Buoyancy-driven ventilation
Thermal plumes merging
Urban heat island
Urban city size
Urban street canyon

A B S T R A C T

During the sunny days with very weak wind, thermal buoyancy forces will play a crucial role in the airflow and urban thermal environment. The merging effect of urban building plumes is particularly investigated by the use of unsteady Reynolds-averaged Navier Stokes (URANS) methodology. After testing against benchmark theoretical results, the SST k-ω model showing better performance in capturing the near wall processes and it was adopted to simulate the urban turbulent flows. The airflow patterns and temperature fields are analyzed for seven urban sizes ranging from 3 to 10 rows of buildings and six aspect ratios ranging from 0.5 to 3.0. The merging of thermal plumes induces a horizontal convergence flow, resulting in stagnant region at the urban center. A typical urban heat island temperature distribution with a peak value at the urban center is then found. Additionally, with the increase of urban size, the averaged velocity with the canyon decreases and averaged temperature increases. The average velocity within the street canyon decreases monotonously and the vortices number increases with the aspect ratio (building height H to the street width W). The average temperature also increases with aspect ratio, except when the aspect ratio increases from 2.0 to 2.5, where the flow structure within the street canyon changes from a three vortices structure into a four vortices structure. This research could provide a new idea about how urban heat island is formed and the relation between its intensity with urban size and geometry.

1. Introduction

Earth has become an urban planet. More than half of the world's people now live in cities, and the proportion is still growing. By 2050, nearly two out of three of us will live in cities [15]. The newly built city is characterized by superstructures and high-rise buildings. The construction of the high-rise buildings and the increase in building density will block the prevailing wind [9]. Additionally, low heat capacity materials such as concrete and asphalt are widely used in modern cities, resulting in very high temperature at the building exterior surfaces. The pedestrian thermal comfort is deteriorated and energy consumption increases in urban area [38]. The microclimate in urban areas differs significantly from the climate in rural areas. There is a clear need for basic scientific understanding on airflow and heat transfer processes in urban area for improving outdoor thermal comfort and lowering energy consumption particularly resulting from heating, ventilation and air conditioning units.

1.1. Urban morphology and ventilation

The conventional concept of urban ventilation is thought as the process of wind flow through the city and brings pollutants out of the city [7]. The ventilation capability of the urban canopy layer is directly related to the building geometries and planning layouts. A large number of studies investigated the relations between outdoor ventilation and urban morphology, including the canyon aspect ratio [26], building packaging density [8], building height variations [20], building arrangements [21], etc. The interaction of prevailing wind with buildings creates complicated flow structures, which exerts a strong control on the urban air flows and airborne pollutant dispersion processes. Ref. [5] identified that small turbulent fluctuation results in large deviation around the buildings when dividing streamlines were

* Corresponding author. Correspodning author. School of Power and Mechanical Engineering, Wuhan University, Dong-Hu Southern Road, 430072, Wuhan, Hubei Province, China.
E-mail addresses: liudi66@163.com (D. Liu), fyzhao@whu.edu.cn (F.-Y. Zhao).

https://doi.org/10.1016/j.buildenv.2017.12.035
Received 24 September 2017; Received in revised form 28 December 2017; Accepted 30 December 2017
Available online 06 January 2018

formed by wind flow impinging on buildings. Apart from the pollutant dispersion, the urban morphology also remarkably affects the energy consumption. Ref. [1] found that the convective heat transfer also depends on building geometry and strength of buoyancy. Their later research [2] suggested that the wind-driven ventilation is an efficient way of removing heat from urban areas. The computational results of [30] demonstrated that the convective heat transfer coefficients on the external surfaces of a building are crucial parameters for buildings thermal performance and associated building energy consumption, which could be altered by about 15% by the building packaging density.

1.2. Effects of buoyancy force on airflow in urban canyons

In addition to the effects of urban morphology and boundary layer wind, airflow and heat transfer inside the urban canyons are also significantly influenced by the buoyancy-driven flow induced by temperature differences between urban surfaces and prevailing wind. Air temperature distribution could be altered by the heated exterior surface, as this temperature variation induces significant upward or downward thermal convection flows [10]. Ref. [43] discussed the effects of solar heating conditions on the pollutant spread within the street canyons. Their numerical results indicated that non-neutral conditions could alter the pollutant dispersion and ventilation performance of street canyons through thermal buoyancy forces. Ref. [3] concluded that the vortex rotation could be accelerated when the leeward wall was heated, whereas it could be suppressed when the windward wall was heated. Ref. [45] found a second-order polynomial functional relationship between total air exchange rate and Gr/Re^2 (Gr is Grashof number and Re is Reynolds number) in the combined wind-buoyancy canyon flow. A similar relationship was also found by Ref. [34] in a neighbourhood scale. Further investigations suggested that the ground heating could significantly enhance the mean flow, turbulence fluctuation, and pollutant flux inside the street canyons [12].

1.3. Merging processes of building thermal plumes

Most of those former investigations indicated that the urban pollutants are well ventilated and exhausted under strong synoptic wind condition. However, heavy pollution most likely happens in windless or weak wind scenarios. Until now, urban ventilation under low synoptic wind is a little-understood subject. Ref. [4] suggested that buoyancy exerts a dominant influence on urban air flow when approaching wind speed is less than 2.5 m/s, which occurs about 18% of the whole calendar year and frequently inside the low latitudes cities. Ref. [46] found that the building surface flow due to buoyancy force is important in removing ambient airborne pollutants in the high-rise dense city Hong Kong at no-wind conditions. The vertical velocity of this kind of flow was found about 1.0–2.0 m/s along a 60 m height building walls [17]. The flow will become more complex when buildings are grouped together. The building plumes can interact with each other due to shear layers between plumes. An early investigation on the interaction of two equal turbulent plumes resulting from heat source was conducted by Ref. [6]. They found that the flow arising from the interaction of the turbulent plumes behaves like a single plume downstream far above the sources. Similar experiments concerning the interaction between laminar thermal plumes were conducted by Ref. [36]. The water flume experiments conducted by Ref. [33] considered many impact factors, including separation distances, exit velocity ratios and configurations. They summarized that the analysis of the near-field behaviour of merging plumes requires insight into several physical mechanisms: momentum shielding, buoyancy enhancement, vorticity interactions and reduced entrainment. Numerical results from Ref. [22] showed that the upward motion could be divided into three patterns depending on the pitch of two heated sections. The first pattern is the unification of two thermal plumes like one for short pitch. The second one is the separate upward motion after the unification. The third one is the independent motion for long pitch. The interaction between square fire arrays consisting of multiple equidistant fires was investigated by Ref. [32]. They found when the fires are close to each other within certain ranges, the effect of heat feedback enhancement is more significant than the air entrainment restriction, inducing more intense burning compared with one single fire with the same fuel area. With increasing fire spacing, the heat feedback decays rapidly than the improvement of air entrainment. For the specific issue of building plume merging was recently experimentally investigated by Ref. [47] using 2-D particle image velocimetry (PIV) measurements. Their results showed that multiple building plumes from the building cluster interact with each other, gradually forming neighbourhood scale merging flows.

Despite the increasing literature on the urban ventilation, it is clear that important gap remains in our basic understanding. In particular, the effect of building plumes merging on the air exchange processes within and above the urban canopy layer is a little-understood subject. For the urban planning applications, there is a need for systematic researches concerning the ventilation and thermal comfort in the thermal buoyancy dominated urban air environment. The present investigation will numerically investigate the air flow and pollutant dispersion within the urban area, where synoptic wind flow is intentionally avoided. Section 2 displays urban street canyon models regarding of different building geometries and building types, together with appropriate mathematical modelling and boundary conditions. In section 3, the reliability of the turbulence model and the independency of computational domain and meshes are first evaluated. Following that, the resulting temperature distributions and plume airflow patterns for different situations are analyzed in details. Finally, conclusions will be drawn in Section 4.

2. Methodology

Urban airflow and heat transfer could be generally investigated by three methodologies, numerical, experimental and analytical ones. In the present work, Computational Fluid Dynamics (CFD) simulations will be carried out to disclose the mechanism of urban heat and air transports.

2.1. Numerical modelling approach

Thermal buoyancy-driven turbulent flow is characterized by unsteadiness, energy non-equilibrium, counter-gradient diffusion and lack of universal scaling, which is associated with distinctive large coherent structure. Kumar and Dewan suggested that these large coherent structures were difficult to be captured by Reynolds-averaged Navier Stokes (RANS) models; however, they could be captured well by the unsteady Reynolds-Averaged Navier Stokes (URANS) formulations [28].

Regarding of URANS, time-averaged Navier-Stokes equations are used to model turbulent flows. All scales of turbulent motions are modelled by the RANS approach and then the mean flows will be presented. The governing equations for the conservations of mass, momentum, and scalar transport are respectively written in the following tensor notations,

$$\frac{\partial \overline{\rho}\,\overline{u}_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial(\overline{\rho}\,\overline{u}_i\overline{u}_j)}{\partial x_j} = -\left(\frac{\partial \overline{p}}{\partial x_i}\right) + \frac{\partial}{\partial x_j}(\overline{\tau_{ij}} - \overline{\rho}\,\overline{u_i' u_j'}) + \overline{\rho}\beta(T - T_0)g_i, \tag{2}$$

$$\frac{\partial(\rho\overline{h})}{\partial t} + \frac{\partial(\overline{\rho}\,\overline{u}_j\overline{h})}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\,\overline{u_j' h'} - \frac{\mu}{\mathrm{Pr}}\frac{\partial \overline{h}}{\partial x_j}\right) = 0, \tag{3}$$

where, $\overline{u}$, $\overline{\rho}$, $\overline{h}$, and $\overline{p}$ represent the resolved-scale velocity, density,