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Diurnal variation of natural convective wall flows and the resulting air change rate in a homogeneous urban canopy layer

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ABSTRACT

The natural convective wall flows along an exterior wall of a 16-story high-rise building were measured in Guangzhou city, China. The Rayleigh number reached as high as 10^{14}. The correlation between the vertical velocity along the wall and the temperature difference between the wall surface and ambient air was analyzed. The diurnal variation of the mean vertical velocity calculated according to a two-layer structure theory agreed well with the measured values. In this theory, the boundary layer along a high wall is characterized as a two-layer structure: the inner viscous layer is dominated by viscous force and buoyancy force/shear stress and has laminar flow, while the outer turbulent layer is dominated by buoyancy force, inertia and Reynolds stress. The velocity profile of the vertical component normal to the wall across the outer turbulent layer can be represented by a Gaussian profile. The air change rate due to natural convection for a homogeneous urban area, presenting a diurnal variation, was also estimated. As the mean building height h increases, the mean air change rate due to natural convection along the building walls increases slightly in the form of $h^{1/30}$. The marginal benefit to the air change rate caused by natural convection decreases as the building height increases.

1. Introduction

The ventilation of a city is important for removing anthropogenic heat, moisture and airborne pollutants. Urban ventilation is determined by the amount of exterior air entering into an urban area. The absence of background wind can be considered the worst ventilation condition in a city. Yang and Li [24] suggest that the ventilation of an urban canopy may be estimated from the basic theory of natural convection as a first-order estimate. The wall flows due to natural convection are important for the study of urban ventilation; see Barlow et al. [2], Yang and Li [24], Rotach et al. [19] and Hang et al. [11]. By analogy with the slope flow, i.e., the natural convection along a slope, Fan et al. [6] refer to the natural convection flow along vertical building walls as wall flow. According to the basic theory of natural convection, the higher the building, the greater the velocity in the natural convection boundary layer. This suggests that a higher building will lead to stronger natural convection flows along the building height. Would a higher building always produce a greater natural convection flow rate? If yes, what does the increase curve look like? Note that the temperature of the same building wall may not be uniform, particularly for a high-rise building in an urban boundary layer, which affects the natural convection. To answer these questions, we first consider a simplified case in which the building wall temperature is uniform.

Characterizing natural convection along a building wall is a challenging problem. The laminar flow adjacent to a heated plate has been solved by Ostrach [17]. Eckert and Jackson [5] solved the turbulent flow by assuming a power law velocity profile. When the Rayleigh number is sufficiently small (10^9–10^{11}), the temperature profile calculated by a power law closely matches experimental results, although the velocity profile of the measured results deviates from the theory, as described by Mehrabian [15]. The Rayleigh number is defined as Eq. (1):

$$\mathrm{Ra}_x = \frac{g\beta\Delta T x^3}{\nu\kappa} \quad (1)$$

where x is the length scale in the vertical direction, g is acceleration due to gravity, β is the thermal expansion rate, ΔT is the difference between the fluid temperature and ambient temperature, ν is kinematic viscosity and κ is thermal diffusivity. Cheesewright [3], Tsuji and Nagano [20] and Tsuji and Nagano [21] carried out extensive experimental studies to characterize the turbulent flow adjacent to a heated vertical plate at Ra numbers from 10^9 to 10^{11}. All of these studies focused on low-Ra situations, i.e., small-scale convec-

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tion, due to the limitation of the experimental conditions to small characteristic length scales (e.g., 2–3 m in height).

Do the existing measurements and theories hold true for the natural convection along a vertical plate on very large scales (20–400 m)? The natural convection flows on such scales in an urban canopy layer with high-rise buildings have not been fully studied. George and Capp [9] first proposed that the boundary layer adjacent to a vertical wall could be modeled by a two-layer structure. Hölling and Herwig [13] performed an asymptotic analysis of natural convection flows and obtained wall functions based on empirical constants. Wells and Worster [23] solved the boundary equations by coupling the inner viscous layer and the outer turbulent layer, assuming that the outer layer was dominated by plume equations when this layer developed into turbulent flow. The results were expected to be valid for Ra numbers as large as 10^{20}. Fan et al. [6] carried out a field study of natural convection flows along a high-rise building wall, and found that the theory of Wells and Worster [23] gave accurate results.

In this paper, the ventilation flow rate due to wall flows will be studied as a function of the building height using the theory of Wells and Worster [23], by performing further measurements of the natural convection of a high-rise building following Fan et al. [6].

2. Methodologies

2.1. Field measurement

A detailed description of the experimental location, the instrumentation used and the condition of the test building can be found in Fan et al. [6]. A schematic of the experimental principle and the coordinate system along the tested building is shown in Fig. 1. A detailed view of the installation of 14 3D ultrasonic anemometers (Gill Instruments, Hampshire, UK) is shown in Fig. 2, in which the instruments are labeled as A1–A14 (A5 and A10 run at 50 Hz and the others run at 20 Hz). The local background weather conditions were monitored using two weather stations (PortLog-Weather station, RainWise Inc., Trenton, Maine), marked in Fig. 2, which were installed on the roofs of two buildings. The background weather conditions in Guangzhou city were obtained from the Guangzhou Weather Bureau, based on measurements from over 200 stations.

2.2. Vertical velocity along the wall

Based on the results in Fan et al. [6], the flow during the experimental period was assumed to be in the buoyancy instability region (Region II, for details see Refs. [23,6]. The asymptotic solutions are given as Eqs. (2)–(4):

$$R = \frac{3}{4}E_2 x' \tag{2}$$

$$U_w = \left[\frac{4\beta_1}{5E_2\left(1+\beta_1\right)\left(\mathrm{Pr}\mathrm{Ra}_{\delta c}\right)^{1/3}}\right]^{1/3}\left(g'\kappa\right)^{1/9}\left(g'x'\right)^{1/3} \tag{3}$$

$$\theta_0 = \left(T_0 - T_\infty\right)/\left(T_w - T_\infty\right) = \frac{5}{3\mathrm{Pr}}\left[\frac{4\beta_1\mathrm{Pr}}{5E_2\left(1+\beta_1\right)\left(\mathrm{Pr}\mathrm{Ra}_{\delta c}\right)^{1/3}}\right]^{2/3}\left[\frac{\nu}{\left(g'\kappa\right)^{1/3}x'}\right]^{1/3} \tag{4}$$

where $x' = x - 700\nu/(g'\kappa)^{1/3}$ is the distance from the leading edge after the virtual origin correction, R is the width of the outer turbulent layer, U_w is the mean velocity across the boundary layer at a certain height, θ_0 is the mean non-dimensional temperature outside the building, $E_2 = 0.135$ and $\beta_1 = 0.34$ are constants related to the entrainment, Pr = 0.72 is the Prandtl number of the air, $\mathrm{Ra}_{\delta c} = 11$ is the critical Rayleigh number based on the width of the inner viscous layer, $g' = g\beta\Delta T$ is the reduced gravity, g is acceleration due to gravity, β is the thermal expansion rate, T_0, T_∞ and T_w are the mean temperature in the outer turbulent layer, the ambient air temperature and the wall surface temperature, respectively, $\Delta T = T_w - T_\infty$ is the temperature difference between the wall and ambient air, κ is thermal diffusivity and ν is kinematic viscosity.

Fig. 1. Photo of the tested building and schematic of the experimental principle. x, y and z are the coordinates along the vertical wall, perpendicular to the wall and parallel to the wall, respectively. u, v and w are the velocity components in the x, y and z directions, respectively. The tested wall shown in the figure faces south.

To non-dimensionalize the vertical velocity and simplify the formula, the vertical velocity scale $U_h = \left(g\beta\Delta T\right)^{4/9} x^{1/3}\kappa^{1/9}$ is defined. After the experimental data are non-dimensionalized, the function acting on non-dimensional parameters can be expressed in the form of Eq. (5):

$$\hat{u}\left(\hat{y}\right) = \hat{f}\left(\hat{y}\right) \tag{5}$$

where $\hat{u} = u/U_h$ is the non-dimensional vertical velocity along the wall, $\hat{y} = \left(y/x\right)\mathrm{Gr}_x^{0.1}$ is the non-dimensional coordinate normal to the wall, u is the vertical velocity along the wall, x is the vertical coordinate along the wall, y is the coordinate normal to the wall and $\mathrm{Gr}_x = g\beta\Delta T x^3/\nu^2$ is the Grashof number.

Fan et al. [6] verified that the boundary layer adjacent to a vertical wall can be divided into an inner viscous layer and an outer turbulent layer, and the outer turbulent layer is governed by plume equations with a Gaussian profile across the layer.

Because the inner viscous layer is very thin (in the order of 1 cm) according to Wells and Worster [23], the flow rate along the vertical