Building and Environment 107 (2016) 215–225

Contents lists available at ScienceDirect

Building and Environment

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

# Natural convection flows along a 16-storey high-rise building

Yifan Fan [a, *], Yuguo Li [a], Jian Hang [b], Kai Wang [a], Xinyan Yang [a]

[a] *Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong Special Administrative Region*
[b] *Department of Atmospheric Sciences, School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou, 510000, PR China*

ARTICLE INFO

*Article history:*
Received 10 June 2016
Received in revised form
1 August 2016
Accepted 2 August 2016
Available online 4 August 2016

*Keywords:*
Natural convection
Wall flow
City ventilation
Building wall
Buoyancy-driven flow

ABSTRACT

The flow caused by natural convection adjacent to a heated vertical wall (wall flow) is an important mechanism in the creation of wind flows in a city when the background wind is weak. The wall flows along a 16-storey building were measured in Guangzhou, China. Fourteen three-dimensional ultrasonic anemometers were installed on three floors to study the boundary layer structure. Continuous measurements were taken during three test periods. The Rayleigh numbers were approximately $10^{13}$, $10^{13}$ and $10^{14}$ at the height of the 5th, 10th and 14th floors, respectively. The diurnal changes in the velocity of the wall flows, the wall surface temperature and the ambient air temperature were analysed.

Our new experimental data support the theory that the natural convection boundary layer has a three-layer structure, i.e. an inner viscous layer, a transition layer and an outer turbulent layer, as first proposed theoretically by Wells and Worster. The outer turbulent layer is governed by the law of plumes with a Gaussian profile. The vertical velocity changes with $g'^{4/9}x^{1/3}$ along the vertical wall, where $g'$ is the buoyancy force and $x$ is the coordinate along the vertical wall. It was noted that only the building's roof was significantly cooler than the ambient air at night, due to the sky radiation effect, so no downward flow adjacent to the wall caused by the cooling plate effect was found in our field measurements.

## 1. Introduction

Urban air quality and the thermal environment are largely dependent on a city's ability to remove heat and pollutant via ventilation; see Refs. [1–7]. Natural convection along building walls (wall flows) in a city becomes crucial when the background synoptic wind is absent, and it is an important mechanism in the creation of wind flows in a city in such a situation. The term “wall flows” is proposed in analogy to “slope flows” (e.g., [8]). In cities with high-rise buildings, such as Hong Kong, both the average building height and the total vertical surface areas are relatively much larger than the plan area. For example, in the Central district of Hong Kong, the total vertical wall surface area is about 10 times the plan area. Hence, the natural convection flows along the building walls are expected to play a more important role than slope flows in city winds, as hypothesised by Yang and Li [9]. However, unlike slope flows, which have been extensively studied [8,10–18], wall flows have not been well studied.

The free convection flows along building walls are important for urban canopy layer ventilation [8,9,19], and they can even dramatically influence the flow above the urban canopy layer [20–23], especially in conditions with no background synoptic wind regarding the whole city scale (see Fig. 1). Wall flows also affect the natural ventilation of buildings [24–33]. A good understanding of the strength of wall flows and its governing parameters is needed to study ventilation in cities [9]. Natural convection along a vertical heated plate is a classical topic in convective heat transfer that has been studied both theoretically and experimentally for decades. However, the turbulent free convection flow along a vertical heated plate has seldom been explored on a large scale, such as that of the urban canopy layer depth, probably due to the spatial scale limitations in a laboratory setting. The difficulty lies in the extremely large Rayleigh number ($>10^{13}$) and the uncertainty of whether the existing theory of turbulent natural convection applies to flows with such high Rayleigh numbers. $\mathrm{Ra}_x = (g\beta\Delta T x^3)/\kappa\nu$ is the Rayleigh number, changing with distance $x$ from the leading edge of the wall, where $\beta$ is the thermal expansion rate, $\Delta T$ is the temperature difference between the wall and the ambient air, $\kappa$ is the thermal diffusivity and $\nu$ is the kinematic viscosity.

Eckert and Jackson [34] first analysed the turbulent free convection boundary layer on a vertical flat plate by assuming a 1/7 power law profile for the velocity and temperature in the near wall

---

* Corresponding author.
*E-mail address:* u3002019@connect.hku.hk (Y. Fan).

http://dx.doi.org/10.1016/j.buildenv.2016.08.003

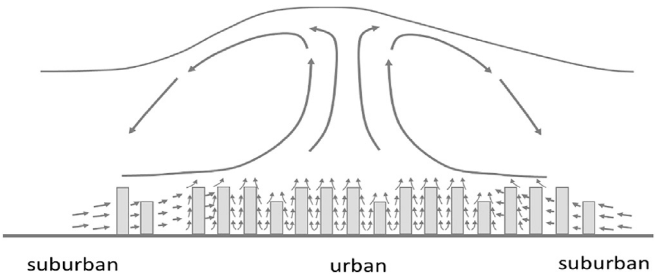

**Fig. 1.** Speculative illustration of the manner in which wall flows may contribute to city winds and city ventilation when background wind is weak or absent. As driven by urban-scale plume flow, there may be horizontal flow to ground level across the urban edge.

region. Ostrach [35] derived a similar solution for the laminar free convection flow adjacent to a vertical heated plate. Szewczyk [36], Nachtsheim [37] and Hiebert and Gebhart [38] analysed the stability and transition process of the free convection layer along a vertical flat plate. Cheesewright [39] investigated the vertical plane turbulent natural convection over a range of Grashof numbers from $10^4$ to $10^{11}$ and compared his results with those of other studies. He pointed out that the data in the laminar region were in good agreement with the existing theory, whereas the velocity and temperature profiles in the turbulent region did not agree well with theoretical predictions. Kuiken [40] obtained an asymptotic solution for very large Prandtl number in the vertical wall free convection boundary layer. Ruckenstein [41] also studied the free convection heat transfer for different Prandtl numbers. Smith [42] investigated flow development with Grashof numbers as high as $10^{10}$. He suggested that the flow had the characteristics of forced convection in the fully turbulent region. Tsuji and Nagano [43–45] carried out significant measurements in the turbulent natural convection boundary layer along a heated vertical plate. Inagaki and Komori [46] specifically focused on the transition region.

George and Capp [47] compared the existing experimental data and first proposed the idea of the so-called two-layer structures with an inner layer in which the convection of momentum and heat is negligible and an outer layer in which the conduction and viscosity effects can be neglected. Hölling and Herwig [48] divided the boundary layer into three layers, a viscous sublayer, a transition layer and an outer layer, and presented an asymptotic analysis of the near-wall region of turbulent natural convection flows. Based on the three-layer structure model, Wells and Worster [49] developed vertical natural convection boundary layer solutions for the geophysical scale, for which the Rayleigh number can reach $10^{20}$.

Our study was inspired by the original theoretical analysis of Wells and Worster [49], as we sought to understand city ventilation by means of thermal buoyancy [9].

## 2. Analyses of wall flows

### 2.1. Different scales of natural convection flow adjacent to a vertical plate

Different scales of the natural convection flow along a vertical flat plate are compared in Table 1. The high-rise building scale turbulent flow has a large length scale (usually between 10 and 100 m) and a relatively small temperature difference $\Delta T$ (usually less than 30 °C); see Supplementary material (Fig. S.1). The laboratory-scale turbulent flow has a small length scale (usually less than 3 m) and a relatively large temperature difference $\Delta T$(usually less than 30 °C). The laboratory-scale laminar flow has a small length scale (less than 1 m) and a small temperature difference $\Delta T$ (usually less than 30 °C). The small-scale laminar flow has a small length scale (several millimetres to centimetres) and either a large or small temperature difference. The flow along the heat exchanger fins of electrical devices is an example of this scale. The natural convection flow along a vertical flat plate in the form of laboratory scales and small scales has been extensively studied in theory and also in laboratory experiments, as reviewed above. Hattori et al. [50] extended the wall temperature in their experiment up to 300 °C; however, because the Rayleigh number is only a linear function of the temperature difference, the increase in it is limited.

### 2.2. The Wells and Worster theory

A schematic of the Wells and Worster [49] theory for the natural convection flow along a high-rise building wall, i.e., wall flow, is shown in Fig. 2. The natural convection flow adjacent to a heated vertical wall is divided into three regions. Region I is the laminar and transition region from laminar to turbulent. Regions II and III are the turbulent regions. $\mathrm{Ra}_x$ is the Rayleigh number. Region II is governed by buoyancy instability and $\mathrm{Ra}_{\delta i}$ is a constant. $\mathrm{Ra}_{\delta i}$ is the Rayleigh number based on the width of the inner layer, and $\delta_i$ is the width of the inner layer. Region III is consistent with shear instability and $\mathrm{Re}_{\delta i}$ is a constant. $\mathrm{Re}_{\delta i}$ is the Reynolds number based on the width of the inner layer. $\Delta T = T_w - T_\infty$, where $T_w$ is the wall surface temperature and $T_\infty$ is the ambient air temperature. $U_0$ and $T_0$ are the mean vertical velocity and mean temperature, respectively, in the outer turbulent layer.

Wells and Worster [49] suggested that the boundary layers along a vertical heated plate could be divided into the outer turbulent layer, which can be described by plume equations, the near-wall laminar flow layer and the transition layer between the two layers. However, no experimental data of flows with such high Rayleigh numbers were available for verification.

Wells and Worster [49] obtained the mean velocity across the plume in the vertical direction $U_0$, the outer plume width $b$ and the non-dimensional temperature $\theta_0 = (T_0 - T_\infty)/(T_w - T_\infty)$ in Region II ($10^9 < \mathrm{Ra}_x < 10^{16}$) and in Region III ($\mathrm{Ra}_x > 10^{16}$) by combining the analytical solution in the inner viscous layer and the plume governing equations in the outer turbulent layer, which are shown in Eqs. (1)–(3) and Eqs. (4)–(6). respectively.

The solution in Region II is as follows.

$$b = \frac{3}{4}E_2 x' \tag{1}$$

$$U_0 = \left[\frac{4\beta_1}{5E_2(1+\beta_1)(\mathrm{Pr}\mathrm{Ra}_{\delta c})^{1/3}}\right]^{1/3}\left(g'\kappa\right)^{1/9}\left(g'x'\right)^{1/3} \tag{2}$$

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

where $x' = x - 700\,\nu/(g'\kappa)^{1/3}$ is the distance from the leading edge after virtual origin correction. $E_2 = 0.135$. $\beta_1 = 0.34$. $\mathrm{Ra}_{\delta c} = 11$ is the Rayleigh number based on the inner viscous layer depth in Region II. $Pr$ is the Prandtl number. $g' = g\beta\Delta T$ is the reduced gravity, $g$ is the acceleration of gravity and $\beta$ is the thermal expansion rate. $\Delta T = T_w - T_\infty$ is the temperature difference between the wall and the ambient air. $\kappa$ is the thermal diffusivity, and $\nu$ is kinematic viscosity.

The solution in Region III is as follows.