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Conditions for thermal circulation in urban street canyons

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ABSTRACT

Under conditions of low background winds and high solar radiation, non-uniform heating of building walls and the ground in an urban street canyon may induce thermally driven circulation that competes with inertially driven circulation due to overlying winds. These two types of circulation were studied using a field experiment, wherein a mock building canyon constructed with two rows of north–south aligned shipping containers were subjected to natural differential wall heating and overlying winds of varying magnitude. The site was carefully instrumented, and the measurements and flow visualization were conducted over nine days with varying environmental conditions. A buoyancy parameter, $B = (g\alpha\Delta TH)/(u_0^2[1+(H/L)^2])$, where $g\alpha\Delta T$ is the horizontal anomaly of buoyancy arising from differential heating of canyon walls, H the canyon height, L the canyon width and u_0 the background velocity, was derived to demarcate thermal and inertial circulation regimes. When $B < B_c$, where $B_c(\approx 0.05)$ is a critical value, the inertial circulation prevails, and the canyon velocities scaled by u_0 are approximately constant. When $B > B_c$, the thermal circulation becomes important and at $B \gg B_c$, the flow is expected to be independent of u_0. An intermediate regime is found in the proximity of B_c, where the scaled velocity is dependent both on overlying flow and buoyancy effects.

1. Introduction

Thermally driven flow induced by solar heating of street canyons is an important topic because of its implications in building design, pedestrian comfort, air quality in urban canyons and emergency response planning [1–3]. Understanding of such flows is particularly important in light of recent policy emphasis on urban designs with environmentally friendly and energy efficient buildings [4–6]. Street canyons are in the lowest layer of the urban atmosphere (i.e., urban canopy layer) that exchanges heat and momentum between the ground and the rest of the atmosphere, and hence are critical elements in building and urban flow modeling and conceptual models for urban air quality planning [7–9]. The literature on urban street canyon flows and dispersion is voluminous, but only a few deals with thermal effects in canyons [10–12] and even less studies have dealt with non-uniform heating. The case of non-uniform heating has mainly been studied using wind tunnel experiments [13,14] and numerical models [15–18], but very few field-scale studies have been reported although such studies are imperative for understanding of high Reynolds number flows [19]. Obtaining insights on flow in actual urban canyons is difficult, given the spatial complexity of heating patterns (e.g., sensitivities to the orientation with respect to the sun, internal reflection of radiation), street traffic [20], and intricate flow morphologies (building facades, windows and balconies). These intricacies cause three-dimensional flows of multiple length and time scales [21,22]. While studies with such complexities are certainly important as they represent real situations, it is also useful to study urban canyon flows outdoors using more idealized geometries. Such real-life, high Reynolds number experiments help delineate flow physics and fundamental scaling laws while providing benchmark data for numerical modeling. This was the aim of the original Mock Urban Setting Test, MUST [23–25] dealing with 'man-sized' idealized street canyons, which was a source of inspiration for the present study.

To this end, a mock street canyon was constructed with two rows of shipping containers aligned in the north–south direction (i.e., canyon walls face the sun during certain phases of the diurnal cycle) and was appropriately instrumented with sonic anemometers, weather stations, and thermocouples attached to the building

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surfaces. The canyon circulation was studied under varying environmental conditions, and the effect of buoyancy was analyzed. Considering that this is the first controlled field attempt, the experimental design called for a simplified case of naturally heated walls but without appreciable thermal contributions from the ground surface, with the hope that the extension of this work will encompass such cases [26]. Section 2 presents theoretical considerations in order to determine the conditions for thermal or inertial dominance in a 2D canyon, which is the focus of this study. The experimental setup is described in Section 3, with general results in Section 4. A classification of flow regimes based on a dimensionless buoyancy parameter is discussed in Section 5, and conclusions are given in Section 6.

2. Theoretical considerations

Consider flow past an idealized two-dimensional street canyon, with a characteristic background velocity u_0, as shown in Fig. 1(a). The flow induced within the canyon for this case is inertially driven with vertical and horizontal velocity scales w_m and u_m, respectively. Assuming the skimming (or transition between skimming and wake interference) flow regime [19,27], the horizontal (u) and vertical (w) velocities in the canyon can be related to each other according to the continuity equation as $u/L \approx \beta w/H$, where $\beta \sim O(1)$ is a constant. For mechanically driven flow (denoted by subscript m), $u \sim u_m \sim u_0$, this becomes

$$\beta w_m/H \approx u_m/L \sim u_0/L, \tag{2.1}$$

and experimental results in Section 5 show that $\beta \approx 1$ for both inertially and thermally driven flows. If u_0 is sufficiently small and the walls of the canyon are differentially heated ($T_1 > T_2$), the thermally driven circulation is prevalent (Fig. 1(b)). Assuming that

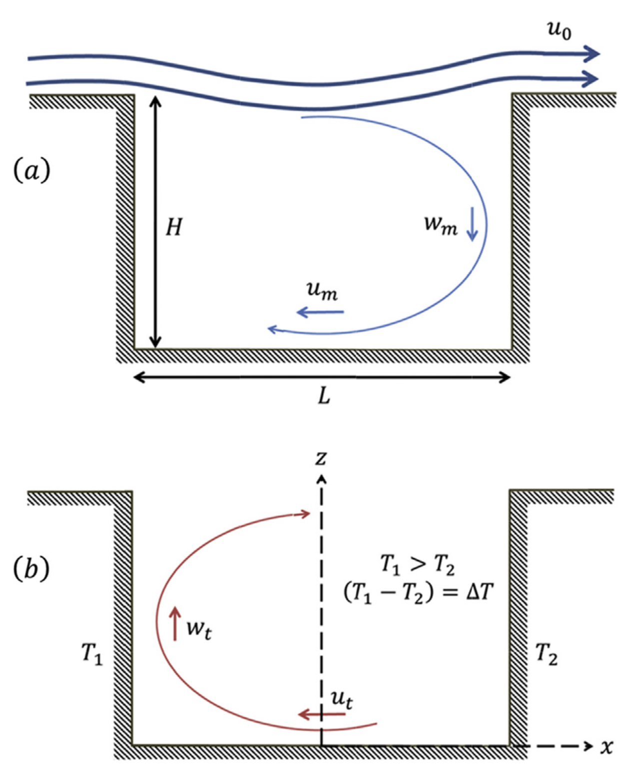

Fig. 1. (a) Inertially driven flow and (b) thermally driven flow in a canyon with aspect ratio $H/L \lesssim 1$.

the flow is driven by the difference in wall temperature, with minimum contribution from the bottom surface energetics, the thermal circulation velocities $\underline{u}_t = (u_t, w_t)$ can be estimated using the vorticity ($\underline{\omega}$) equation with the baroclinic generation term. To the Boussinesq approximation, $D\underline{\omega}/Dt = \underline{\omega}\cdot\nabla\underline{u} + \nabla\times b\underline{k} + \nu\nabla^2\underline{\omega}$, where $b(=g\alpha T)$ is the buoyancy acting in z direction (unit vector $\underline{k}$), g the gravitational acceleration, T the temperature, ν the kinematic viscosity, and $\alpha \approx 1/\overline{T}$ the thermal expansion coefficient where $\overline{T}$ is the average temperature within the canyon. If the amplification of vorticity by vortex stretching ($\underline{\omega}\cdot\nabla\underline{u}$) and viscous diffusion of vorticity ($\nu\nabla^2\underline{\omega}$) are neglected, considering two-dimensionality, and assuming Reynolds number similarity of the flow, only the baroclinic generation of vorticity needs to be considered, $D\underline{\omega}/Dt \approx \nabla\times b\underline{k}$. Considering the y-component of vorticity (along the canyon axis, into the paper) and assuming quasi-steady flow, this becomes, in order of magnitude estimations,

$$\underline{u}_t\cdot\nabla\omega_y \sim -\frac{\partial b}{\partial x} \sim -g\alpha\frac{\partial T}{\partial x}, \tag{2.2}$$

where

$$\begin{aligned} &\omega_y \sim (\partial u/\partial z - \partial w/\partial x)\\ &\sim [u_t/H + w_t/L]\\ &\sim \left[u_t/H + u_t/H(H/L)^2\right]\\ &\sim (u_t/H)\left[1+(H/L)^2\right], \end{aligned} \tag{2.3}$$

where $u_t/L \approx w_t/H$ has been used. Then (2.2) becomes

$$\begin{aligned} &u_t\frac{\partial\omega_y}{\partial x} + w_t\frac{\partial\omega_y}{\partial z} \sim -g\alpha\frac{\partial T}{\partial x},\\ &\sim \frac{u_t}{L}\frac{u_t}{H}\left[1+\left(\frac{H}{L}\right)^2\right] \sim \frac{w_t}{H}\frac{u_t}{H}\left[1+\left(\frac{H}{L}\right)^2\right] \sim \frac{g\alpha\Delta T}{L}, \end{aligned} \tag{2.4}$$

where $\Delta T = T_1 - T_2$. Thus, the scale for thermal circulation is

$$u_t \sim \left(\frac{g\alpha\Delta T\ H}{\left[1+(H/L)^2\right]}\right)^{1/2}. \tag{2.5}$$

When a mean flow and thermal circulation are both present, the latter could dominate when $u_t \gg u_m$,

$$B = \left(\frac{g\alpha\Delta T\ H}{u_0^2\left[1+(H/L)^2\right]}\right) \gg B_c, \tag{2.6}$$

where B_c is a critical value of the buoyancy parameter B. Note that the buoyancy parameter is nominally similar to the traditional bulk Richardson number defined for cavity flows [28], but in this case the B parameter is defined in terms of the horizontal buoyancy difference with inclusion of aspect ratio.

3. Field experiment design and site characteristics

A simplified mock street canyon was constructed in a grassy field on the campus of Nanyang Technological University in Singapore at the location (1°21′22.5″N, 103°41′14.1″E). It consisted of two rows of shipping containers (2.5 m in height and width; total length of each row 24.4 m) aligned in the north–south direction with a 3.75 m separation (Fig. 2), resulting in an aspect ratio of $H/L = 2/3$. Thus, according to the flow classification reviewed by Fernando et al. [19], it is in the transition from wake interference to the skimming flow regime, which is representative of typical cities