Urban Canyon Influence on Building Natural Ventilation

K. Syrios[1] and G.R. Hunt

Department of Civil and Environmental Engineering, Imperial College London SW7 2AZ, U.K.
[1] email: constantine.syrios@imperial.ac.uk, phone: +442075945990, fax: +442075945991

ABSTRACT

Natural ventilation driven by the combined forces of wind and buoyancy has been studied experimentally for a building flanked by others forming urban canyons. The steady ventilation established in an isolated building was observed to change dramatically, both in terms of the thermal stratification and airflow rate, when placed in the confines of an urban canyon environment. The resulting ventilation flows and internal stratifications are presented for different combinations of wind speed, opening area and location, and canyon width (building density). Flanking an otherwise isolated building with others of similar geometry in a typical urban canyon geometry is shown to reverse the effect of wind on the buoyancy-driven ventilation. The implications on thermal comfort and design guidance are discussed.

KEYWORDS

Urban canyon, small-scale modelling, natural ventilation

INTRODUCTION

Natural ventilation is the low-energy replenishment of indoor air by naturally occurring pressure differences associated with convection driven by internal heat sources/solar gains and the flow of wind past the building. Achieving the desired airflow rate and comfort levels using natural ventilation is not straightforward due to the variable nature of the driving forces. For urban settlements an additional challenge is determining how the wind flow past the building is modified due to the surrounding built environment. Flows in naturally-ventilated buildings have been studied extensively as a low-energy alternative to mechanical ventilation and air-conditioning. Flows in urban canyons have also been studied extensively often with a focus on air quality issues and the dispersion of pollutants. The two families of flows have been studied in isolation; however, for passive ventilation of buildings in urban canyons, where the ventilation openings (*e.g.* windows and doors) link to a canyon, the ventilation flow is expected to be coupled with the canyon airflow. The need to study the interaction of the two flows provides the motivation and in the current study a naturally-ventilated enclosure that is flanked by streets and buildings, thus, forming a typical urban canyon geometry is considered.

METHODOLOGY

Small-scale experiments were conducted in the fluid dynamics laboratory to study this interaction. The working fluid was water. The technique adopted, termed the

‘salt-bath technique’ is known to provide approximate dynamical similarity with full-scale flows, Baker & Linden (1991). A Perspex box (170 mm170 mm598 mm, internal height H=150 mm) with high-level and low-level vents was used to represent the ventilated building. Low-level and high-level vents are often incorporated in the design of naturally-ventilated enclosures to harness the stack effect arising from heat gains. Urban canyons were formed by positioning plastic boxes identical to the Perspex box parallel to and on either side of it. The canyon model was suspended in a recirculating flume (width 600 mm) generating a mean horizontal flow simulating a wind normal to the canyon (Figure 1). No attempt was made to simulate the atmospheric boundary layer. Convection from a localised heat source at floor level in the building was simulated by injecting salt solution into fresh water through a nozzle in the box (constant buoyancy flux B=133 cm^{4}s^{-3}). Conductive and radiative heat transfers were not reproduced. The vertical inversion of the model does not affect the flow dynamics for the small density differences (Boussinesq flows) considered. Density differences were measured using a density meter and the internal stratification was visualised using a shadowgraph.

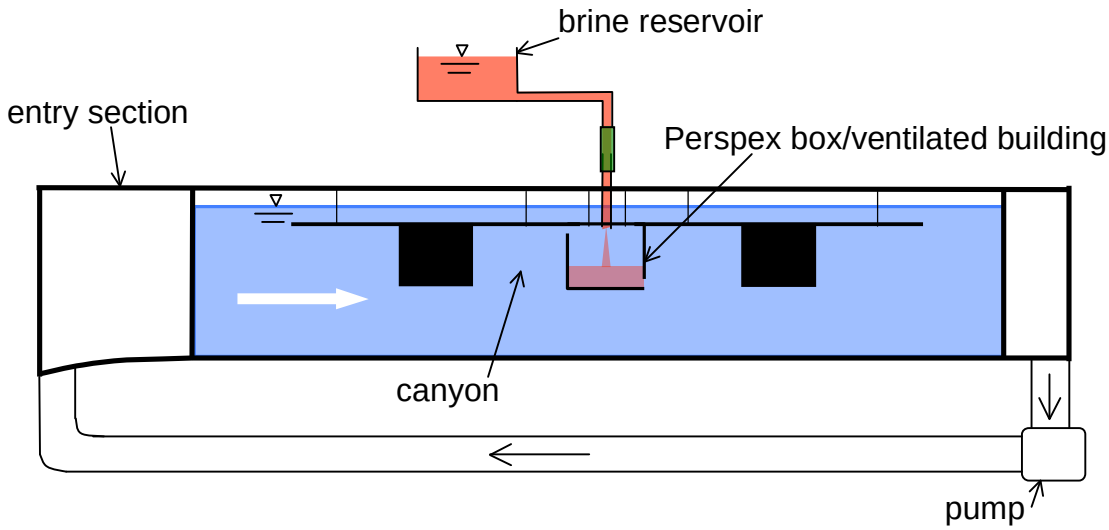


Figure 1: Schematic of flume in elevation and the canyon apparatus.

Two distinct locations for the openings were considered as depicted in Figure 2. By translating the plastic boxes across plastic boards, the canyon aspect ratio H_b/W (building height/street width) was varied between 1/5 and 2. During calibration experiments, the ‘wind’-induced pressure drop Δ across the openings was measured using oil/water U-tube manometers. Apart from varying H_b/W and Δ, the effective opening area $A^* = [(2C_{din}^2A_{in}^2)^{-1} + (2C_{dout}^2A_{in}^2)^{-1}]^{-1/2}$ (Hunt & Linden 2005) was varied by removing (or adding) plugs from the vents in the box. The quantities A_{in} and A_{out} denote the low-level and high-level opening areas, respectively, and C_{din}, C_{dout} are the pertinent discharge coefficients (both taken to be 0.6 herein).

RESULTS

The response of the steady natural ventilation flow to changes in the wind speed, vent area and canyon geometry is now presented for Cases 1 and 2. For the effect of

wind speed and vent area, a square canyon was maintained. Results are shown for A^*/H^2=0.81% and are described in the context of the canyon building.

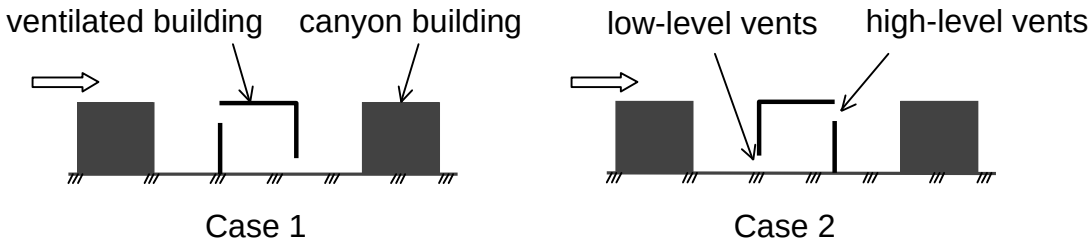


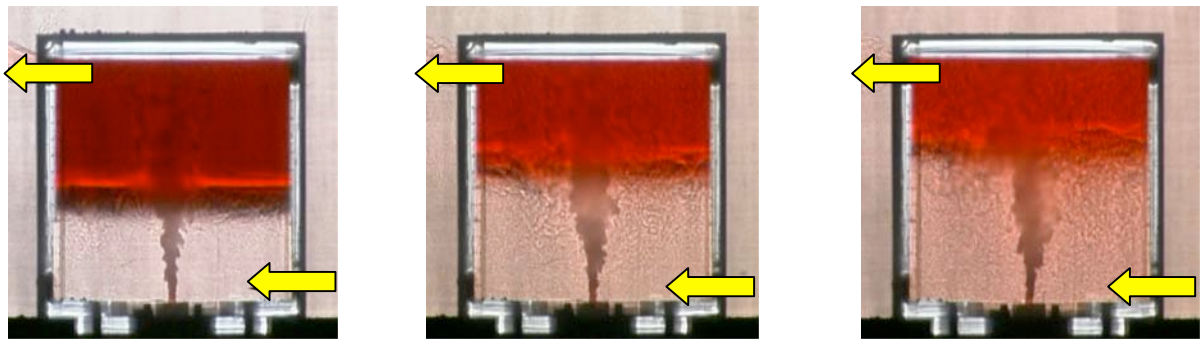
Figure 2: Case 1: high-level vents on the windward façade and low-level vents on the leeward façade, Case 2: vice versa.

Case 1

Displacement flow was observed for the whole range of parameters considered. The rising plume from the localised heat source formed a distinct two-layer 'thermal' stratification – inflow took place through the low-level vents and outflow through the high-level vents as shown in Figures 3 and 4.

Effect of wind speed

Increasing the wind speed, hence Δ, resulted in an upward shift of the interface height *h*, Figure 3. Thus, the external flow tended to drive an upward flow through the space, *i.e.* in the same sense as the thermal force. This assisting wind condition resulted in an increased number of air changes per hour ACH (a small increase in *h* yields a significant increase in ACH, see Linden et al. (1990) for the power law that relates them) and a 'cooler' upper layer (improved comfort) as inferred by the increased dilution of the red dye (compare Figure 3a with 3c).



Δ=0 (no wind), ACH=$1.3\cdot10^{-3}$ Δ=160 $gcm^{-1}s^{-2}$, ACH=$2.4\cdot10^{-3}$ Δ=304 $gcm^{-1}s^{-2}$, ACH=$3.0\cdot10^{-3}$

Figure 3: Case 1. Inverted shadowgraph images showing the effect of increasing wind speed (H_b/W=1). The arrows indicate the direction of flow.

Effect of opening area

Increasing the opening area A^* offered additional area to the flow path and the airflow rate was enhanced. This was verified by an increase in *h* and a reduction in the 'temperature' of the vented 'air'. The same trend with increasing A^* was also

observed for the displacement flows of Case 2 – see Syrios (2005) for details of these results.

Effect of canyon geometry

In the absence of canyons, increasing the wind speed from zero resulted in a decrease in *h* and an increase in the upper-layer temperature, signifying an *opposing* wind condition. However, introduction of the surrounding canyons resulted in *assisting* winds (the upper layer 'cooled'), *i.e.* the canyon reversed the effect of the external flow on the building ventilation flow, see Figure 4.

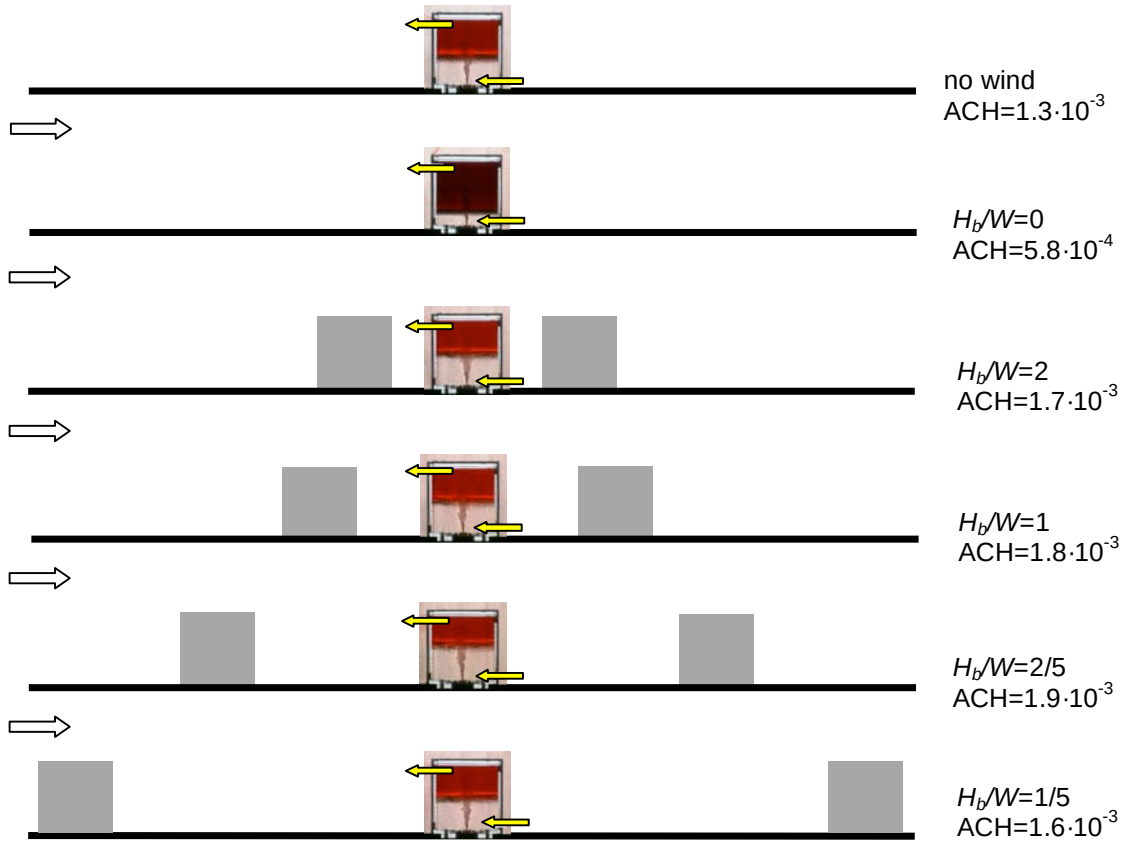


Figure 4: Case 1. Shadowgraph images of the internal stratification are shown for various H_b/W. The mean approaching 'wind' speed was 9.9 cms^{-1}.

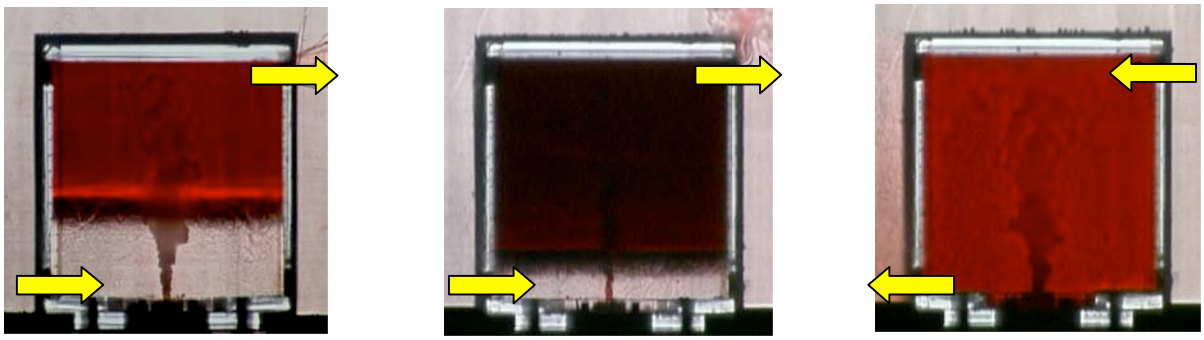
Case 2

Displacement flow was observed for a range of wind speeds, while for sufficiently strong winds mixing flow was also observed, whereupon inflow took place through high-level vents, outflow through low-level vents and the interior was close to uniformly well-mixed (*i.e.* negligible 'temperature' variation with height).

Effect of wind speed

Progressively increasing the wind speed from zero resulted in a decrease in *h* in the displacement flow mode until the stratification broke down. This resulted in mixing (Figure 5). The wind then dominated and drove a downward flow through the space

(*opposing* wind). Increasing the wind speed resulted in decreasing ACH for displacement flow and increasing ACH for mixing flow.



Δ=0, ACH=1.3·10^{-3} Δ=142 gcm^{-1}s^{-2}, ACH=5.3·10^{-4} Δ=246 gcm^{-1}s^{-2}, ACH=2.7·10^{-3}

Figure 5: Case 2. Inverted shadowgraph images showing the effect of increasing the wind speed (H_b/W=1).

Effect of canyon geometry

In the absence of canyons, increasing the wind speed from zero resulted in an increase in *h* and a drop in the upper-layer temperature, signifying an *assisting* wind condition. However, introduction of the canyon resulted in *opposing* winds (mixing flow or displacement flow with deeper and warmer upper layer), *i.e.* the canyon reversed the effect of the external flow on the building ventilation flow, see Figure 6.

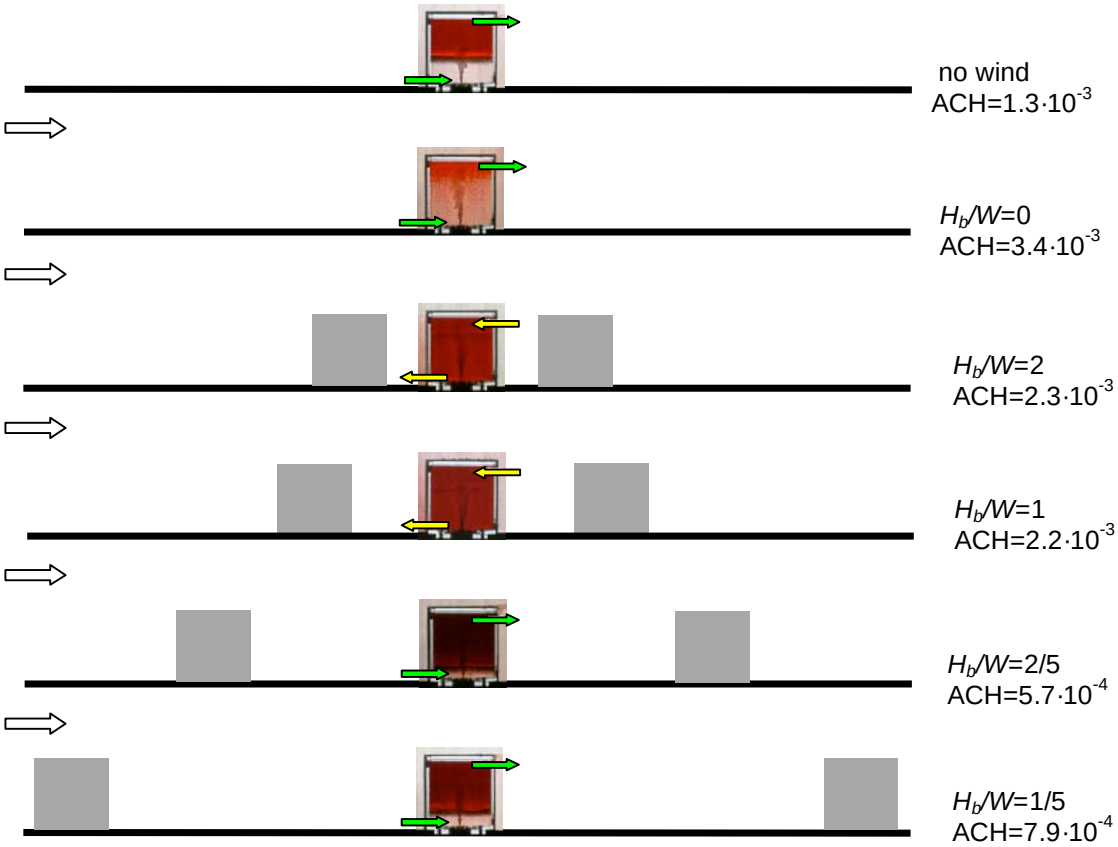


Figure 6: Case 2. Shadowgraph images of the internal stratification are shown for various H_b/W. The mean approaching 'wind' speed was 20.1 cms^{-1}.

CONCLUSIONS

Canyons were shown to reverse the effect of the wind on the thermally-driven ventilation of an otherwise isolated building. Winds that, in general, enhance/oppose the thermally-driven passive ventilation flow through a fully-exposed building were found to oppose/enhance the thermally-driven flow through a canyon building. This reversal was evident for canyons as wide as five times the building height. A design implication is that ventilation openings may have to be positioned counterintuitively, namely, with high-level vents on the windward façade and low-level vents on the leeward façade, if the assisted ventilation flows of Case 1 are to be reproduced for buildings in cities. For Case 2 with the same building geometry and forcing (*i.e.* heat load and wind speed), the resulting ventilation mode[†] was shown to depend upon the width of adjacent canyons.

The reversal of the wind's impact when canyons are present may be explained in terms of the surface pressure on the leeward façade exceeding the surface pressure on the windward façade of the ventilated building. This pressure imbalance arises from the different flow patterns in the upstream and downstream canyon as verified by the dye injection experiments of Syrios (2005).

The outcomes of this study highlight the need for information transfer between the architect and the urban planner: if a passive ventilation technique is to be applied successfully the architect needs to be aware of the surrounding structures as these were shown to influence dramatically the natural ventilation flow. Building designs also need to be flexible regarding the positioning of vents. Vents may have to be rearranged to accommodate changes in the surrounding built environment so that enhanced flows are ensured as the wind blows.

References

Baker, N. and Linden, P.F. (1991) Physical modelling of airflows – a new design tool. In *Atrium Buildings Architecture and Engineering* (ed. F. Mills), 13-22.

Hunt, G.R. and Linden, P.F. (2005) Displacement and mixing ventilation driven by opposing wind and buoyancy. *J. Fluid Mech.* **527**, 27-55.

Linden, P.F., Lane-Serff, G.F. and Smeed, D.A. (1990) Emptying filling boxes: the fluid mechanics of natural ventilation. *J. Fluid Mech.* **212**, 309-335.

Syrios K. (2005) Natural ventilation of buildings in urban canyons, PhD thesis, Imperial College London, University of London.

[†] *i.e.* whether displacement or mixing flow