Pollutant Dispersion inside Re-entrant Bays of Tall Buildings with H-Shaped Sections

K. M. Lam[1], Charles C. K. Cheng[2]

[1]*Department of Civil Engineering, University of Hong Kong, Hong Kong,* kmlam@hku.hk
[2]*Department of Building and Construction, City University of Hong Kong, Hong Kong,* bcccheng@cityu.edu.hk

1 INTRODUCTION

Wind effects play an important role in the structural design as well as serviceability of a tall building. In Asian metropolitan cities, high-rise multi-apartment residential buildings are very common. To provide views and windows to all apartments, these buildings usually adopt an irregular cross-sectional shape with apartments arranged as wing sections extending from a central core. Between adjacent building wings are deeply-recessed re-entrant bays or "light-wells," towards which kitchen and bathrooms windows open. An undesirable effect of this architectural layout is that unwanted matters and heat are emitted into these re-entrant bays. It is thus essential that these emissions can be dispersed out of the re-entrant spaces by wind-induced natural ventilation. In extreme cases, transport of wind-borne matter can lead to disastrous events such as the outbreak of Severe Acute Respiratory Syndrome (SARS) Crisis in Hong Kong in 2003 [1].

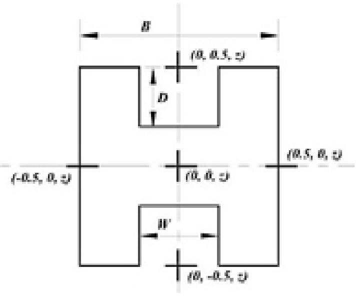
The authors investigate wind-induced flow pattern in re-entrant bays of different sizes in a tall building with computational fluid dynamics [2]. It is found that the induced flow inside a re-entrant bay is not a simple stagnation or skipping flow. In particular, very complex flow patterns are computed inside a side re-entrant bay. The paper continues to investigate how a re-entrant bay is ventilated by the wind-induced flow inside and through the bay. The dispersion of a scalar pollutant initially filling the entire re-entrant bay is computed at successive time instants. The corresponding ventilation efficiency is studied systematically for different geometries of the re-entrant bay.

2 CFD MODEL AND TEST CASES

The CFD technique and computation cases have been described in [2]. Turbulent flow around a tall building is computed using the code ANSYS CFX. The tall building has an H-shaped cross section bounded inside a square envelope of breadth B. There are thus two re-entrant bays (or recessed cavities) on two opposite walls of the building (Fig. 1). Nine different configurations of the H-shape are tested in the CFD computation. In these H-shapes, the horizontal dimensions of the recessed cavity vary in a systematic manner, covering three different widths; $W/B = \{0.25, 0.5, 0.75\}$, and three different depths; $D/B = \{0.125, 0.25, 0.375\}$. In addition, three groups of buildings with different building heights, $H/B = \{4, 6, 8\}$, are studied. Computations are made at two normal wind incidence directions to the building, thus covering re-entrant bays on the windward, leeward and side faces of the building.

In the CFD computations, steady solution of the three-dimensional turbulent flow field is obtained with the RANS (Reynolds Averaged Navier Stokes) approach using the standard k-ε model for turbulence closure. Computations are made at a reduced geometric scale of 1:300 with the building breadth B = 10 cm and undisturbed wind speed U_H = 10.4 m/s at the roof height of a building of $H/B = 8$. The open land terrain wind profiles are used as the inlet boundary conditions to the computational domain. Results of the computed mean flow field around the building and inside the re-entrant bays have been discussed [2].

The focus of this paper is the dispersion of a scalar pollutant from the re-entrant bay. Wind-induced flushing behaviour of the re-entrant spaces is studied for the different test cases. In the computations, a passive and non-buoyant scalar species is used to represent a pollutant and this scalar species is set to fill up the entire volume of the re-entrant bay under study at a uniform concentration at time zero. Afterwards, the scalar is dispersed by the computed solution of wind flow around the building and inside the recessed bay. The concentration field of the pollutant is tracked at successive time steps. The efficiency of pollutant dispersion can be described quantitatively by the retention or residence time [3]. This is the time required for the mean scalar concentration (C), averaged over the spaces inside the re-entrant bay, to decrease to $1/e$ (≈ 0.368) times the initial uniform concentration (C_o).



Case No.	Width (W/B)	Depth (D/B)
1	0.25	0.125
2	0.25	0.250
3	0.25	0.375
4	0.50	0.125
5	0.50	0.250
6	0.50	0.375
7	0.75	0.125
8	0.75	0.250
9	0.75	0.375

Fig. 1. Test cases of building sections and dimensions of re-entrant bays.

3 RESULTS AND DISCUSSION

With wind incidence on the rotated H-shape (Fig. 2a), dispersion efficiencies of the windward and leeward re-entrant bays are studied. The windward re-entrant bay is actively ventilated by the incident wind flow. Wind enters the bay mainly on its vertical opening face and there is flow going out of the bay from and near the roof opening face and near the base of the vertical opening face. This leads to the dispersion pattern of pollutant shown in Fig. 3a for a re-entrant bay of dimensions $W/B = 0.25$ and $D/B = 0.375$ (Case 3) on the windward face of a tall building of $H/B = 8$. At that time $t = 0.05$ s, or non-dimensional time $tU_H/B = 5.2$, the concentration contours of C/C_o on the vertical symmetry plane of the bay show the downwind dispersion of some pollutant from the roof opening and some upwind dispersion along the ground. The dispersion patterns at subsequent time steps show that while the flow through the roof opening disperses the pollutant from the upper part of the cavity quite quickly, the outflow near the base of the cavity is slower in removing the pollutant from the middle and lower part of the re-entrant spaces. The inner base corner of the re-entrant bay takes the longest time to clear out the pollutant concentration.

The dispersion behaviour of all re-entrant bays on the windward face of the building, and also on other faces, exhibit similar pattern of C/C_o decay with time. The decay rate is rapid at the beginning but starts slowing down after the concentration level drops to $C/C_o < 0.1$. Fig. 4a compares the dispersion efficiencies of the 27 test cases of a re-entrant bay on the windward face of a building using the retention times. It is obvious that a taller building (i.e. higher re-entrant bay) always leads to a longer retention time, which means poorer ventilation or slower dispersion of pollutant. This is because the transport paths are mainly from the roof opening and from near the ground (Fig. 3a) so that it takes a longer time to ventilate a taller bay. Fig. 4a also shows that the widest bays (at $W/B = 0.75$) have shorter retention times. For these widest bays, the retention time increases with the depth of the bay in a near-proportional manner. The narrowest bays (at $W/B = 0.25$) are the worst ventilated with the retention time also increasing with the bay depth but as D/B changes from 0.25 to 0.375, the increase becomes very small.

The dispersion behaviour in the leeward re-entrant bays is shown by the example test case in Fig. 3b. The bay spaces are passively ventilated by the wind flow and the pollutant mainly leaves the re-entrant bay from the roof opening face and from the vertical face near the ground. The pollutant leaving the bay near the ground surface keeps flowing along the ground up to about 2.5*B* distance behind the building rear face before it is lifted upwards and slightly upwind, probably due to the recirculation flow behind the building as a whole [4].

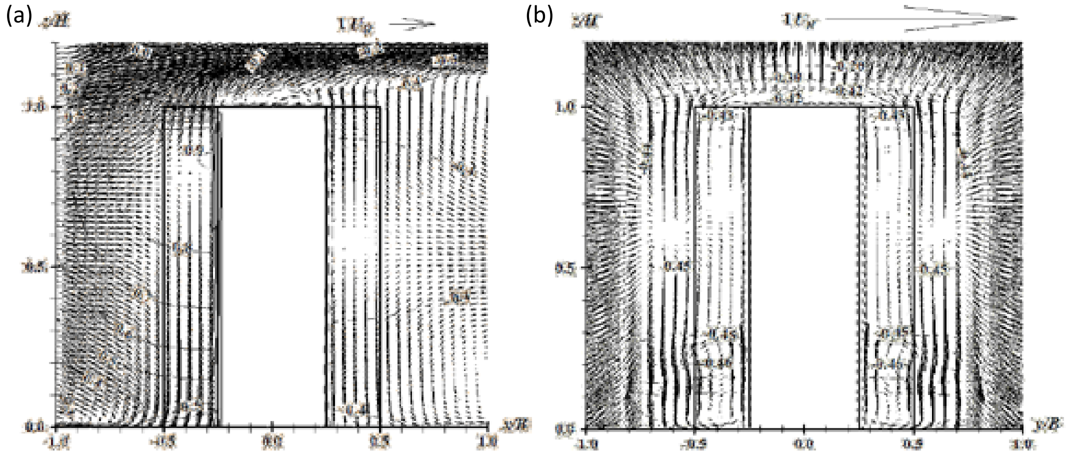


Fig. 2. Wind flow patterns around H/B =8 tall building with Case 9 re-entrant bay on
(a) windward and leeward faces; and (b) side faces of building.
Mean flow vectors on x-z or x-y plane (vertical scale compressed).

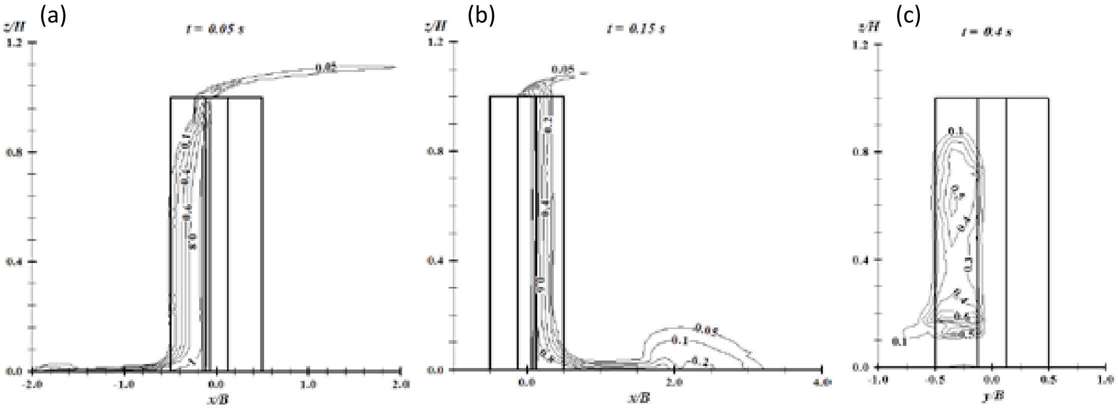


Fig. 3. Pollutant dispersion of Case 3 re-entrant bays on H/B = 8 building.
(a) Windward; (b) leeward; (c) side bay (vertical scale compressed).

Fig. 4b shows that the retention times in the leeward re-entrant bays are longer than those of the windward bays by a factor of about 1.5. Since the air exchange paths are similar to those of the windward bays, that is, from the roof and the base of the cavities, the retention time is also found to increase with *H*. Similar effects of the widths and depths of the bays on the retention time are observed as for the windward re-entrant bays.

With wind blowing across the H-shape, the two side re-entrant bays are passively ventilated and the dispersion of pollutant out of these re-entrant spaces takes a much longer time than the windward or leeward re-entrant bays. The wind flow results have shown the existence of two large-scale vortices inside the bay [2]. The vortex near the ground level brings in clear air from outside and ejects pollutant-laden air at a short height above (Fig. 2b). This leads to the dispersion pattern in Fig. 3c for the side re-entrant bay. For this deep bay, the vortex near the building roof mainly acts to bring in clear air from outside and thus diluting the pollutant concentration near the top of the bay. The CFD results show that a shallow bay is much better ventilated than a deep bay. This is because the small flow out of the vertical opening of the re-entrant bay is sufficient to disperse a larger portion of the pollutant inside the shallow bay.

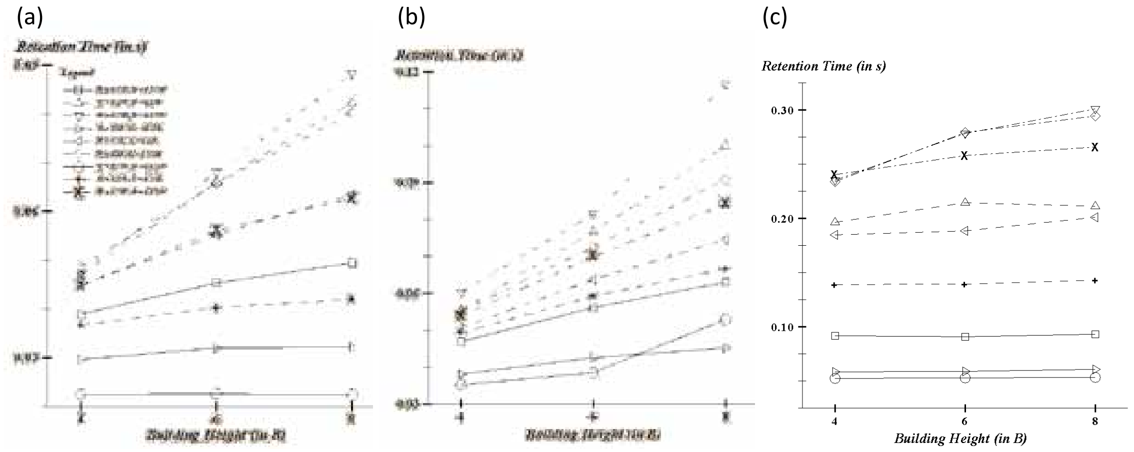


Fig. 4. Retention times of re-entrant bays: (a) Windward; (b) leeward; (c) side bays.

The retention times of the 27 re-entrant bays on the building side faces are shown in Fig. 4c. It is worth noting that the range of retention times is a multiple of those for the windward and leeward re-entrant bays. As contrast to the windward or leeward bays, the retention time in Fig. 4c does not depend on the building height, except for the deepest bays at W/B = 0.375 where a taller height leads to slightly longer retention time. This is because the dispersion of pollutant mostly occurs evenly along the building height. Obviously, the retention time is strongest affected by the depth of the re-entrant bay. The nine curves in Fig. 4c are separated into three groups with the deepest bays at W/B = 0.375 occupying the three uppermost curves of the longest retention times and the shallowest bays at W/B = 0.125 making the three lowermost curves of the shortest retention times. The width of the re-entrant bay also affects the retention time with a shorter retention time for a wider bay but the effect is not as strong as the bay depth. It can also be said that the ventilation efficiency of the side bays depends on their cross-sectional areas ($W \times D$).

4 CONCLUDING REMARKS

Wind-induced ventilation of re-entrant bays on the windward, leeward and side faces of a tall building is investigated with CFD. Dispersion of pollutant is governed mainly by the wind-induced flow pattern through the re-entrant spaces. The ventilation efficiency of the re-entrant bays is studied by the retention time of pollutant inside the bays.

5 ACKNOWLEDGEMENT

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