PLANNING AND DESIGN TOOLS FOR SUSTAINABLE HOUSING DEVELOPMENT FOR HEALTHY LIVING –

EFFECT OF BUILDING RE-ENTRANT ON VENTILATION EFFECTIVENESS IN HIGH-RISE RESIDENTIAL BUILDINGS

Dr Raymond YAU, Dr Vincent CHENG and Steven LEE
Arup Advanced Engineering
Ove Arup & Partners Hong Kong Ltd
Hong Kong, China
Email: Raymond.yau@arup.com

ABSTRACT

In the design process of a residential development, various site planning and building or layout fine-tuning stages would be involved. The unique high-rise, high-density urban context and the hot and humid climate conditions in Hong Kong are important considerations in designing a comfortable and healthy built environment. Building re-entrants are most popular in high rise and high density residential buildings in Hong Kong, partly due to the Building (Planning) Regulations. Windows of the kitchens and bathrooms as well as living or dining rooms are open towards the re-entrants for sources of natural lighting and ventilation. The quality of the air in the re-entrant will determine the quality of ventilation introduced to the indoor. This paper describes some investigations on variation of the dimension of typical I-shaped re-entrant making use of the powerful simulation tools based on computational fluid dynamics (CFD) techniques on the ventilation effectiveness of the re-entrant. The results show the optimum aspect ratio of the dimension of a re-entrant.

1. INTRODUCTION

Increasingly we need low energy, low pollution and low material waste to produce efficient and healthy buildings. Naturally responsive buildings are more likely to achieve these criteria. Residential buildings in Hong Kong are typically high rise and high density and are governed by Building (Planning) Regulations. The most widespread building layout for an individual residential building is based upon a "cruciform" plan. In this plan, public space including lift lobbies and corridors is usually squeezed to a minimum at the building core. With its four wings radiating out from the core, typically, a residential building consists of eight apartments on a single floor, with two at each wing. This arrangement has typically resulted in a deep and narrow "I-shaped" re-entrant at each wing between the neighbouring apartments. The quality of the air in the re-entrant will determine the quality of ventilation introduced to the indoor. The ventilation effectiveness in the I-shaped re-entrant is therefore the subject of this study.

2. NATURAL VENTILATION IN BUILDING RE-ENTRANT

According to the building regulations, the horizontal minimum dimension of re-entrants varies from 1.5 m to 2.3 m wide. Where re-entrant is for the purpose of lighting and ventilation of bathrooms and toilets, it needs to have a minimum width of 1.5 m. In the case of kitchens with windows not facing the street, the width should be of a minimum of 2.3 m. Windows of the kitchens and bathrooms are open towards the re-entrants for sources of natural lighting and ventilation. According to a survey on residential buildings in Hong Kong that are served with split-type air-conditioners, about 40% of their re-entrants are in I-shaped, 18% are in T-shaped, 14% are in L-shaped, 2% are in Y-shaped and 26% are in irregular shapes (Chow et al, 2000).

The study of natural ventilation in residential buildings is of significant importance as it directly affects human health, comfort and well-being. In a hot and humid city like Hong Kong, natural ventilation is the most cost-effective way to minimize the physiological effect of the high humidity to achieve acceptable indoor thermal comfort condition. In residential buildings, potential of good cross ventilation should be provided. In most layouts, living room or dinning room typically has windows open to the re-entrant and the front fascia, providing a good path for cross ventilation if the windows are open. The exhaust from the kitchen and toilet also often discharges into the re-entrant area. In addition, external drainage pipes are often located inside the re-entrant. Therefore, the ventilation performance of re-entrant is important in affecting the quality and hygiene conditions attained for the tenants. This study presents the findings on the dimensions of re-entrant and the resulting ventilation effectiveness occurred at the re-entrant and those of the indoor ventilation of rooms facing to the re-entrant.

Better ventilation rate could help dilute pollutant released to the re-entrant, improve the cooling performance of air conditioning units and shorten the time needed for drying clothes. However, the ventilation effectiveness of re-entrant geometry dimension (such as width, W and depth, D) to the ventilation rate is not well understood. A typical logarithmic wind profile in city terrain was used with a mean wind speed of about 2ms^{-1} at 10m from ground surface. Two wind directions have been investigated: 1) head-on wind blowing perpendicularly to the studied re-entrants; and 2) wind blowing from sideway (Figure 1).

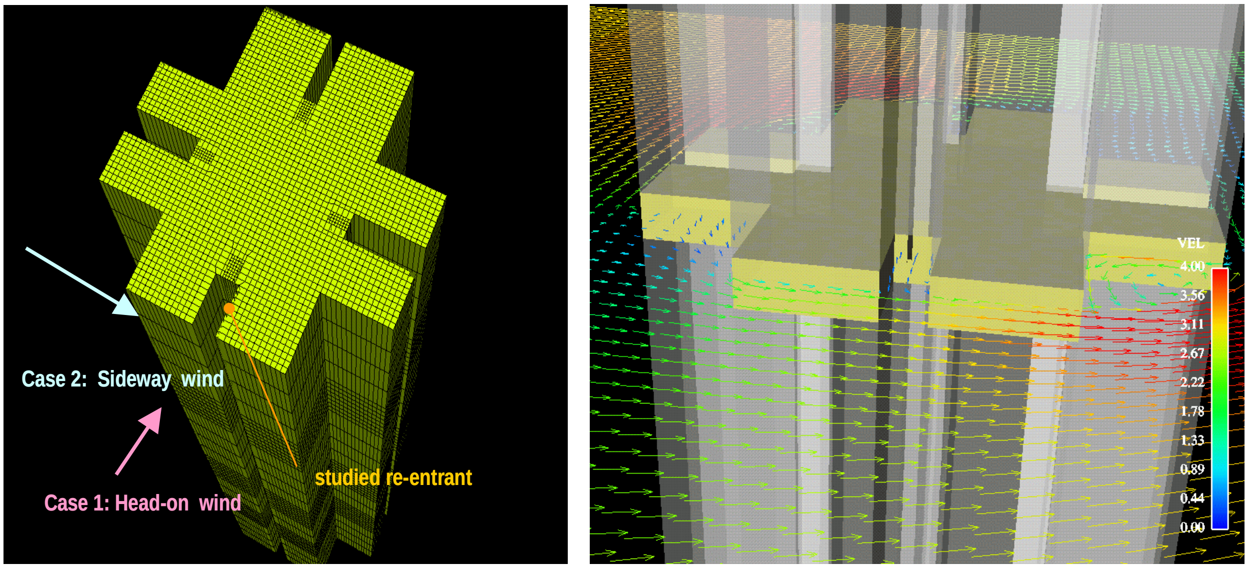


Figure 1. CFD model for studying parameters of re-entrant and the ventilation performance with head-on and sideway winds

3. COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

For the study of natural ventilation and wind microclimate, CFD is most widely used and perceived as an appropriate tool with reasonable accuracy (Yau et al, 2002 & 2003). It can be applicable to architectural or engineering fluid dynamics and transport phenomena including airflow inside and outside a building (Versteeg & Malalasekera, 1995). It can handle calculations involving temperature, velocity, pressure and particle dispersion such as exhaust from kitchen and bathroom.

The driving effects of air movement at a re-entrant are the wind and the thermal buoyancy. In this study, only the wind effect is considered as the effect due to thermal buoyancy resulting from the heat dissipated from air-conditioning condensers have been examined previously (Chow et al, 2000). CFD is carried out to investigate the airflow rate of building re-entrant with variations of width and depth.

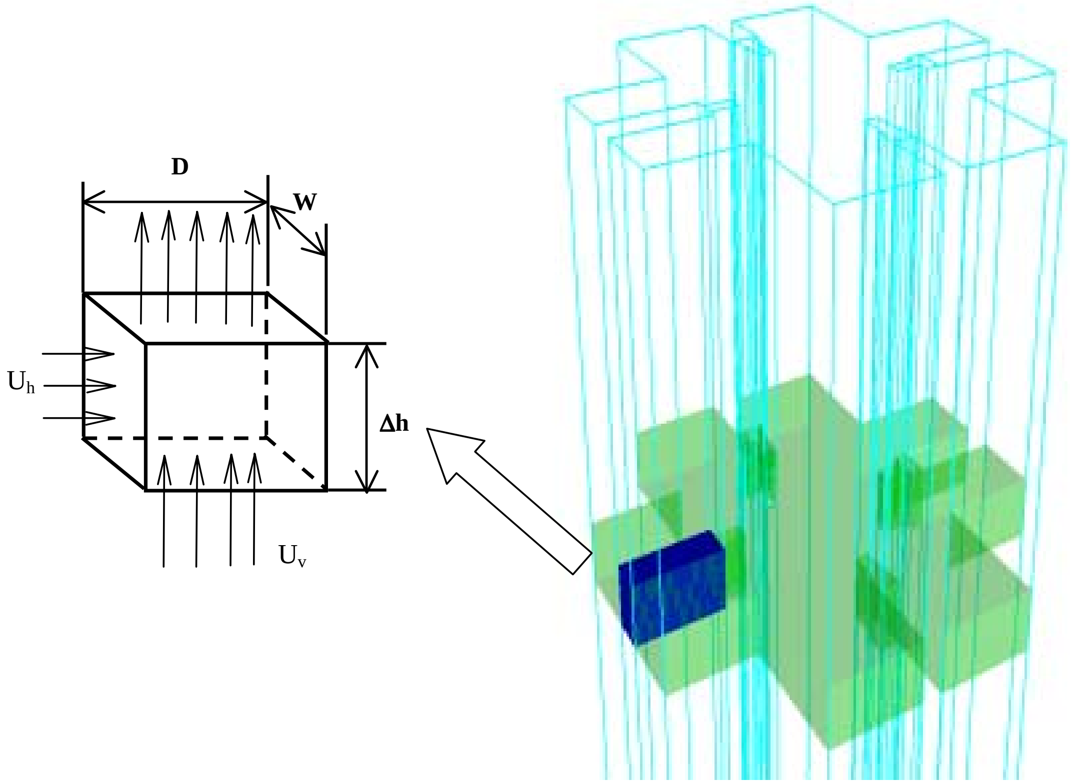


Figure 2. Mass flow rate considerations in a re-entrant

Simplifications and assumptions were adopted to form a steady state computational model to enable the analysis. These include:

1. no obstruction such as air conditioning condensing units are assumed inside the re-entrant;
2. all wall surfaces of the re-entrant are flat;
3. no kitchen and toilet air exhausts nor heat dissipated from air conditioning condensers are assumed.

Two different wind conditions had been evaluated. First, a head-on steady wind condition was examined. The wind was assumed to be approaching at a horizontal speed of 2m/s at a reference height of 10m above the ground, and at the 180-degree with the front of the re-entrant facing the upwind. Second, a sideway steady wind condition was examined. The wind was assumed to be approaching at a horizontal speed of 2m/s at a reference height of 10m above the ground, at a zero-degree with the front of the re-entrant facing the upwind.

The STAR-CD version 3.150A software was used in the CFD study. Numerical simulations were based on the two-equation k-ε turbulence model. In the analyses, the entire I-shaped conditions were modelled. Taking one typical floor of re-entrant for consideration, the airflow pattern is simplified based on the CFD simulation result, as shown in Figure 2. The mass flow in through the studied re-entrant is:

$$\dot{m} = \rho u_h \Delta h \cdot w + \rho u_v \cdot w \cdot D \tag{1}$$

where W and D represent the width and depth of re-entrant

Then the mass flow rate across the horizontal plane of re-entrant could be written as:

$$\ddot{m} = \frac{\dot{m}}{A} = \rho \frac{u_h \Delta h w + u_v DW}{D \cdot W} = \rho (u_h \frac{\Delta h}{D} + u_v) \tag{2}$$

If all the conditions are unchanged, the horizontal velocity component is proportional to the wind velocity, and the vertical velocity component is the contribution of the airflow drawn into the re-entrant from below, so it could also be proportional to the wind velocity:

$$u_h \propto u_0^{\alpha} \quad and \quad u_v \propto u_0^{\beta} \tag{3}$$

In an urban area, the wind speed is proportional to the elevation above the ground floor

$$u_0 \propto h^{0.33} \tag{4}$$

Then the mass flow rate could be written as:

$$\ddot{m} \propto (\frac{1}{D} + \sigma) h^k \tag{5}$$

where σ is a parameter, which has a relationship with the studied re-entrant width W and height h.

The equation declared that the re-entrant mass flow rate of re-entrant is proportional to its elevation, and is inversely proportional to the depth of the re-entrant.

4. NUMERICAL SIMULATION RESULTS

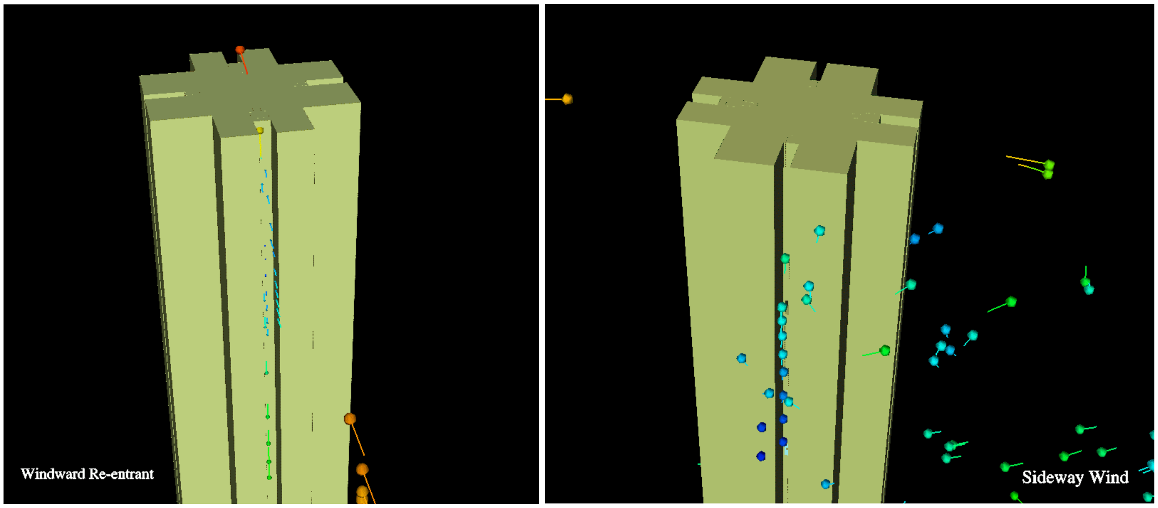


Figure 3. CFD model for studying parameters of re-entrant and the ventilation performance

4.1 Ventilation Performance at the Re-entrant

4.1.1 Airflow rate of re-entrant Vs Depth of re-entrant, D

Numerical CFD simulations had been carried out on a typical high-rise building with variations of re-entrant width and depth. The simulated building was 100m high. The elevations at 30 m, 50 m and 75 m were selected to represent three typical levels, low level, mid level and high level respectively. The ventilation performance of re-entrants was studied by considering the airflow rate of a re-entrant volume with height Δh (See Figure 2) per unit horizontal area. This was similar to the quantification of the ventilation rate of a room using Air Change rate per Hour (ACH), i.e. the airflow rate divided by the room volume.

The following diagrams show the relationship of the mass flow rate per unit horizontal re-entrant area with the depth of re-entrant for the two wind directions studied

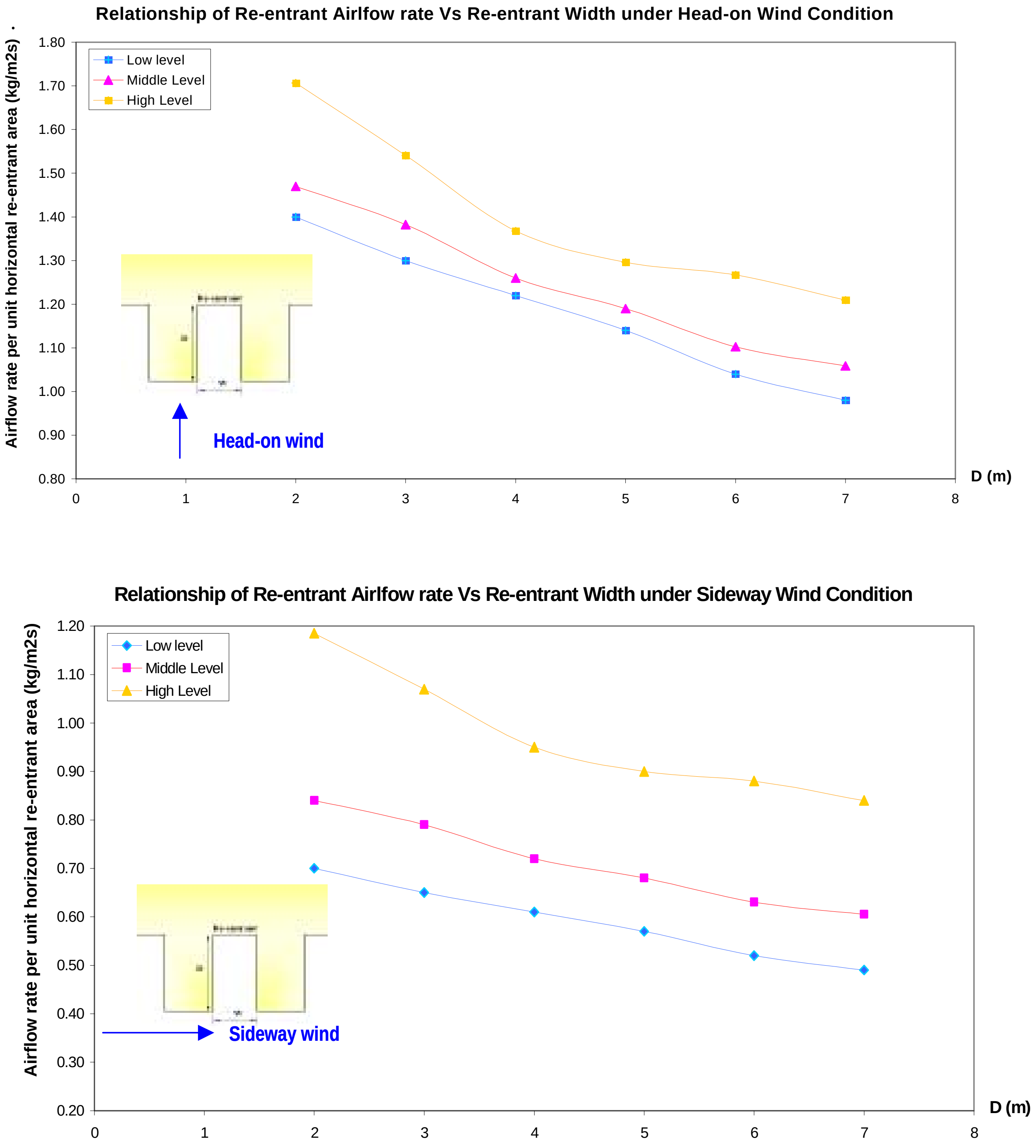


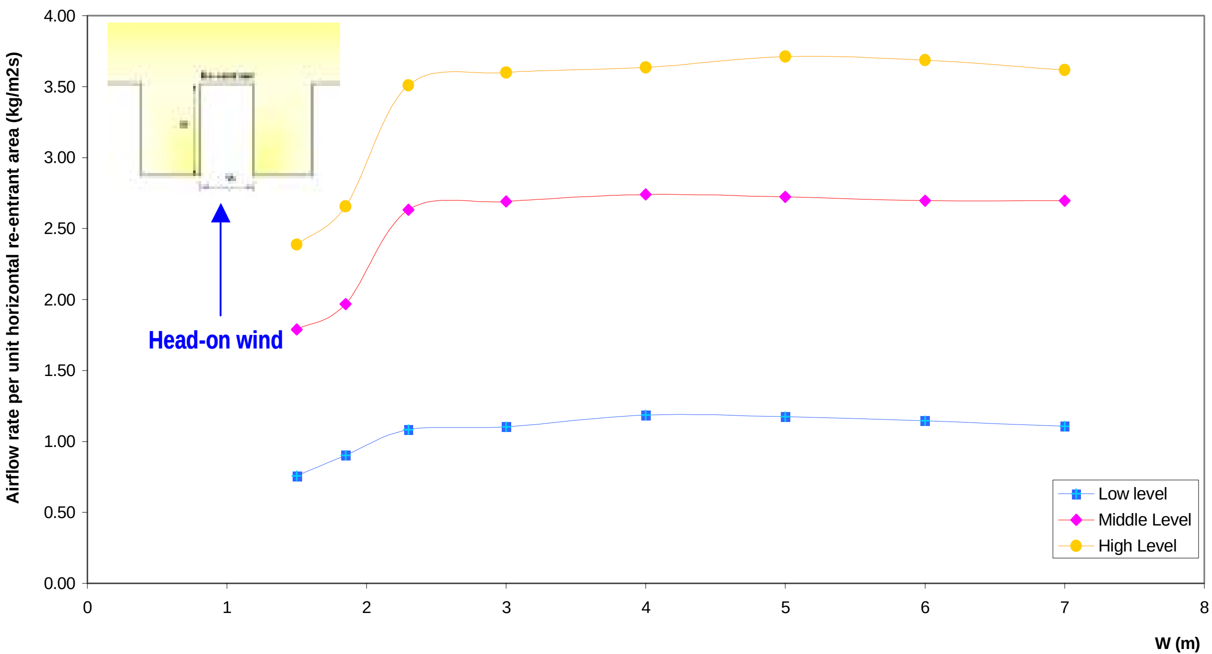
Figure 4. Relationship of airflow rate per unit horizontal re-entrant area with the Depth of re-entrant (D): (upper) head-on wind and (lower) sideway wind conditions

It is found that for both head-on and sideway wind conditions, the ventilation rate at re-entrant decreases with the increasing depth of re-entrant, i.e. the deeper a re-entrant, the less effective ventilation is obtained at the area. Notwithstanding, the ventilation rate for a windward re-entrant is higher than that obtained under sideway wind, whereas it is about 30-50% higher in this scenario. Since the ambient wind speed at a higher elevation is faster as indicated from the logarithmic wind profile, a higher ventilation rate at re-entrant is achieved when compared with a lower elevation.

4.1.2 Airflow rate of re-entrant Vs Width of re-entrant, W

In the same CFD simulations conducted with variations of re-entrant width and depth, the relationship of airflow rate at the re-entrant (i.e. ventilation at re-entrant) with the width of the re-entrant is investigated for the three typical levels at low level, mid level and high level for both head-on and sideway wind conditions. The following diagrams show the findings from simulations.

Relationship of Windward Re-entrant Airlfow rate Vs Re-entrant Width



Relationship of Re-entrant Airlfow rate Vs Re-entrant Width under Sideway Wind Conditions

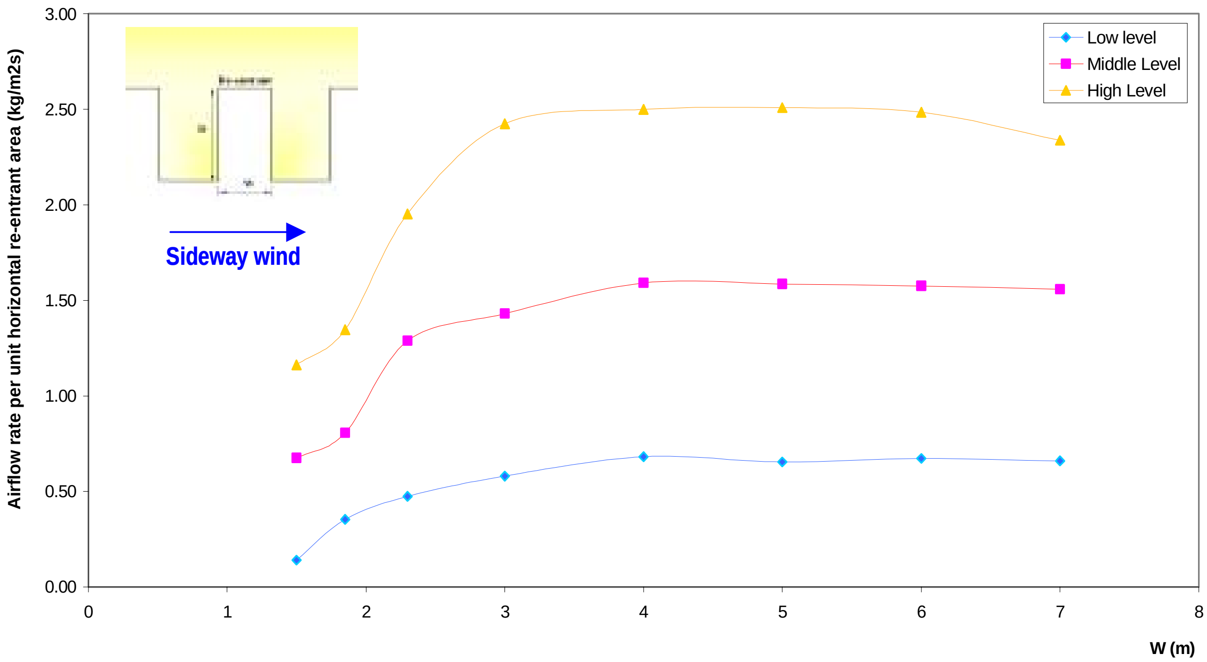


Figure 5. Relationship of airflow rate at re-entrant with the Width of re-entrant (W): (upper) head-on wind and (lower) sideway wind conditions

From the above diagrams, it could be seen that the airflow rate of the re-entrant (i.e. mass flow rate per unit horizontal re-entrant area) increases with the re-entrant width and then fades out at around 3 to 4 m, i.e. no significant enhancement of airflow rate is seen when the width is larger than 4m, for both windward and sideway wind conditions. This phenomenon indicates an optimum re-entrant width for building designers in considering ventilation at re-entrant. For instances, the hygiene conditions when toilet exhausts are disposed to the re-entrant or drying racks are placed at re-entrant. Notwithstanding this, a wider re-entrant would induce better indoor ventilation performance. This will be discussed in the next Section.

Again, the ventilation rate for a windward re-entrant is higher than that obtained under sideway wind.

4.2 Ventilation Performance of a Room facing to Re-entrant

Other CFD simulations were also conducted with variations of re-entrant width and depth to investigate the relationship of indoor ventilation rate of a room at the middle level facing to the re-entrant. The openable area of the windows at the room is set to be one-tenth of the floor area of the room, which satisfies the existing local Building Regulations in terms of ventilation requirement.

It is found that ventilation rate of the room would decrease with a deeper re-entrant, which is consistent with the previous finding for studying the airflow rate at the re-entrant. A wider re-entrant would also induce a higher ventilation rate at the room studied, but the effect of increasing re-entrant depth would dominate the ultimate indoor ventilation performance obtained and this phenomenon is more outstanding when the re-entrant depth increases from say, 2m to 5m.

5. CONCLUSIONS

Investigations were carried out on the ventilation effectiveness in the I-shaped building re-entrant with variation of the width and depth of the re-entrant under two wind conditions – head-on and sideway steady winds. The analysis showed that, with the assumed conditions, the ventilation rate at re-entrant decreased with an increasing depth of the re-entrant while the ventilation rate increased with an increasing width until an optimum size of around 4 m. The analysis also showed that the ventilation rate of an adjoining room to the re-entrant would decrease with a deeper re-entrant but increase with a wider re-entrant. However, it was found that the effect of increasing re-entrant depth would affect the ultimate indoor ventilation performance achieved.

The present study has however not considered the other contributory factor to air movement due to thermal buoyancy. This is particularly relevant to the ventilation re-entrant study for periods where the air conditioning condensers located inside the re-entrants are in operation. Further investigation on this is recommended.

REFERENCES

Chow, T T, Z Lin & Q W Wang; Effect of building re-entrant shape on performance of air-cooled condensing units; Energy and Buildings; Vol 32; 2000.

Yau, R; Building environmental and sustainable design approach to housing developments; Housing Conference 2002; Hong Kong Housing Authority.

Yau, R & Lee, S; Building environmental and sustainable design by advanced simulation techniques; Proceedings of Shandong-Hong Kong Joint Symposium 2003.

Versteeg, H K & Malalasekera, W; An introduction to computational fluid dynamics – the finite volume method; Longman, 1995.

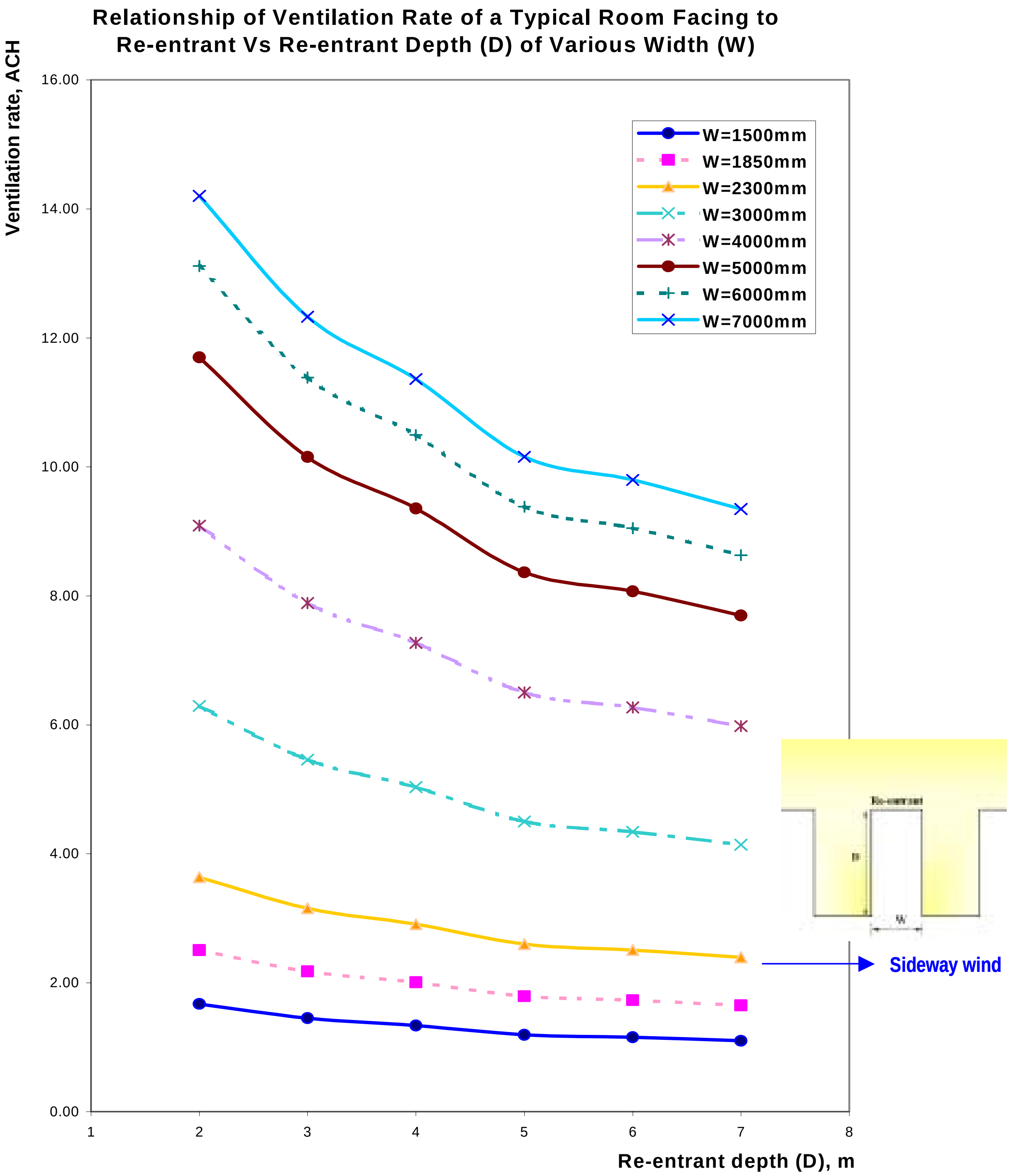


Figure 6. Relationship of indoor ventilation rate of a room facing to re-entrant and the Depth of re-entrant (D) for various Width of re-entrant (W)