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Natural ventilation in High-Rise Residential buildings in Hot and Humid Climate: Malaysia as a Case Study

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Natural ventilation is used as a passive strategy in high-rise buildings to provide the air quality and thermal comfort at the same time saving energy. This study examines the internal lightwell connection to outdoor through different horizontal voids as inlets in high-rise residential (HRR) buildings. A Computational Fluid Dynamics (CFD) technique employing ANSYS Fluent code is used to predict airflow characteristics for alternative ventilation configurations of full-scale building model. The full-scale model was developed in accordance with common configurations of high-rise residential (HRR) buildings in Kuala Lumpur as well as referring to the minimum requirements of Uniform Building By-Law (UBBL). The results show that the existence of a direct connection of the internal lightwell through horizontal void affects the air change per hour (ACH) and thermal comfort in the lightwell space and adjoining units, respectively. Although the existence of double-level voids increases ACH up to 200% along the lightwell, it reduces the air velocity by 78% in both units compared to the lightwell without direct connection. Based on the results of this study a design guideline for naturally ventilated HRR buildings was developed.

Keywords: *Natural Ventilation, HRR Buildings, Lightwell, Void, CFD*

1. Introduction

Natural ventilation is the most effective strategy in naturally ventilated buildings (Jiang and Chen, 2002; Kubota *et al.*, 2009; Zhai, 2006). This strategy plays an important role regarding thermal comfort, air quality and thus energy saving (Kubota *et al.*, 2009). In hot and humid climate building configuration is incorporated with a number of different types of lightwells, either in core or the perimeter of the building that allows opening of windows in different directions and thus providing cross-flow ventilation (Givoni, 1998; Nutalaya, 1999) .

Building codes in some tropical countries such as Australia, Malaysia, Singapore and Hong Kong emphasized providing all habitable rooms in apartment buildings with natural ventilation. In Malaysia the Uniform Building By-Laws (UBBL) of 1984 regulates the minimum size of sky opening as outlet of internal lightwell as well as its adjoining windows to ensure natural ventilation for those rooms that are far from the external facades. However, UBBL did not stipulate the possible direct connection of the lightwell to outdoor through inlet openings such as horizontal voids which is common in practice (Farea and Ossen, 2013; Farea *et al.*, 2012).

Previous studies demonstrate that the lightwell space is subjected to produce suction effect along its space and adjoining indoor spaces (Chiang and Anh, 2012;

Etheridge, 2012; Ghiaus and Roulet, 2005; Ismail, 1996). Thus, in order to provide indoor natural ventilation through the lightwell space, aerodynamics in the lightwell and its effect on the natural ventilation in the adjoining units should be understood and clarify.

This study examines the effect of inlet existence (horizontal void) and its connection with the lightwell on its spaces and adjoining rooms with special focus on Kuala Lumpur. This is beneficial to investigate the performance of the ventilation configuration (connection between the internal lightwell and outdoor) which contributes for developing a design guideline and UBBL for naturally HRR buildings.

2. Wind Climate of Kuala Lumpur

Kuala Lumpur as a tropical city experiences high humidity and small diurnal variation of temperature with heavy rainfall throughout the year. It has a diurnal range of maximum 31.9 – 33.7 °C and minimum 24.0 – 25.1 °C. The mean annual temperature is 27.8 °C over last 10 years and the variation among these years is not more or less than 1.6 °C. The average of relative humidity (RH) is 79.7% and the average of surface wind speed is 1.5 m/s at 10 m height. The annual daily average of the global radiation is 17.19 MJ/m^2. These meteorological data is obtained from Subang weather station in Kuala Lumpur (2003 – 2012) which is located at 16.5 m above sea level with a Latitude 03° 07' N and Longitude 101° 33' E.

3. Description of Ventilation Configuration

The present study configuration is based on the survey conducted in Kuala Lumpur and hypothetical assumptions derived from design perspectives and Malaysian UBBL. A field survey was conducted to gather data on selected HRR buildings in Kuala Lumpur. The method for collecting the data and the results of the survey are presented in Farea *et al.* (2012). The main objective of the survey is to recognize HRR buildings, which include lightwell in selected areas representing Kuala Lumpur. Besides, is understanding of design ideas related to common configuration of the lightwell, e.g. sizes, positions, types and possible connection to outdoor (Fig. 1).

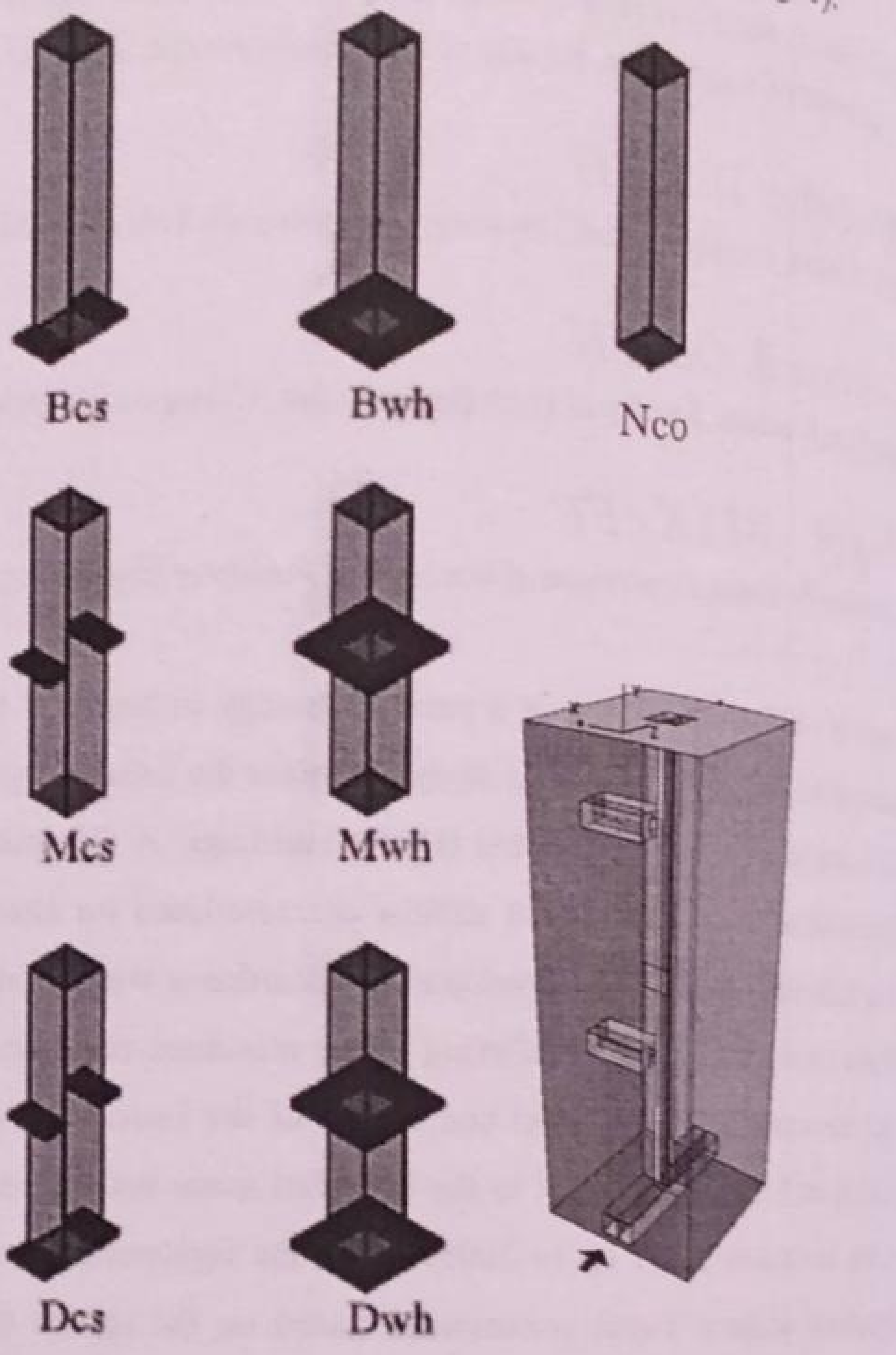

Fig. 1 Alternative Ventilation configurations

This study examines the most common ventilation configurations of HRR buildings. The building configuration is simplified and represents a 20-storey HRR building with square plan. It combined with internal lightwell (in the core of the building) and its spaces connected to outdoor through varied position of void as shown in Fig. 1 the lightwell is without roof and the sky opening left open as outlet for all alternative configurations. Two hypothetical units are placed at lower and upper level of the building. Their position is at lateral facade of the building to avoid the direct effect of the wind direction. This allowed for the examining of cross ventilation through the external windows and internal windows (adjoining the lightwell) in both units. The model represents full-scale model so all dimensions are derived from real practice and followed the minimum dimensions stipulated by UBBL as much as possible. In other word, all minimum dimension stipulated by UBBL are used e.g. the area of the sky opening of the lightwell, size of the adjoining windows and the floor height. However, the rest dimension that are not subjected to UBBL are assumed based on the common practices, e.g. the depth of surrounded blocks (depth of unit) is 8 m from external facade to lightwell surface of the lightwell which could be appropriate for units with three rooms and this common for medium-coat apartment (based on category conducted by authorities in Malaysia).

4. CFD simulations

There are many methods that could be used to predict the natural ventilation characteristics in buildings. The most appropriate and common method is Computational Fluid Dynamics (CFD) (Chen, 2009). Nevertheless, CFD cannot stand alone without assistance and evaluating its performance and results by comparing with analytical and experimental models (Chen and Srebric, 2002; Hussain *et al.*, 2012; Ramponi and Blocken, 2012). Therefore, this study is based on validated Computational Fluid Dynamics (CFD). The validated CFD used to predict the airflow pattern, air velocity and temperature in alternative configurations of lightwell connection to outdoor through horizontal void as inlet in terms of the void existence and positions.

4.1 CFD Validation

The basic model of the present study was validated with small-scale experimental model in wind-tunnel. The CFD code used in the present study was validated by authors in a previous study (Farea et al. 2014). The simulation results confirmed a good agreement with the experimental data. Several parameters and conditions were examined in order to select the most appropriate settings for further simulation i.e. parametric study.

4.2 CFD Settings

The computational model of the full-scale building models that are developed and derived to be applicable to HRR buildings in Kuala Lumpur was reproduced. All alternative ventilation configurations in Fig. 1 are numerically simulated based on coupled approach. The computational domain has dimensions L × W × H = 710 × 570 × 330 m (Fig. 2) that agrees with recommended distances between the building model and all boundaries of the computational domain. The maximum blockage ratio is 0.6 %, which is less than the recommended maximum of 3% (Franke *et al.*, 2007; Tominaga *et al.*, 2008).

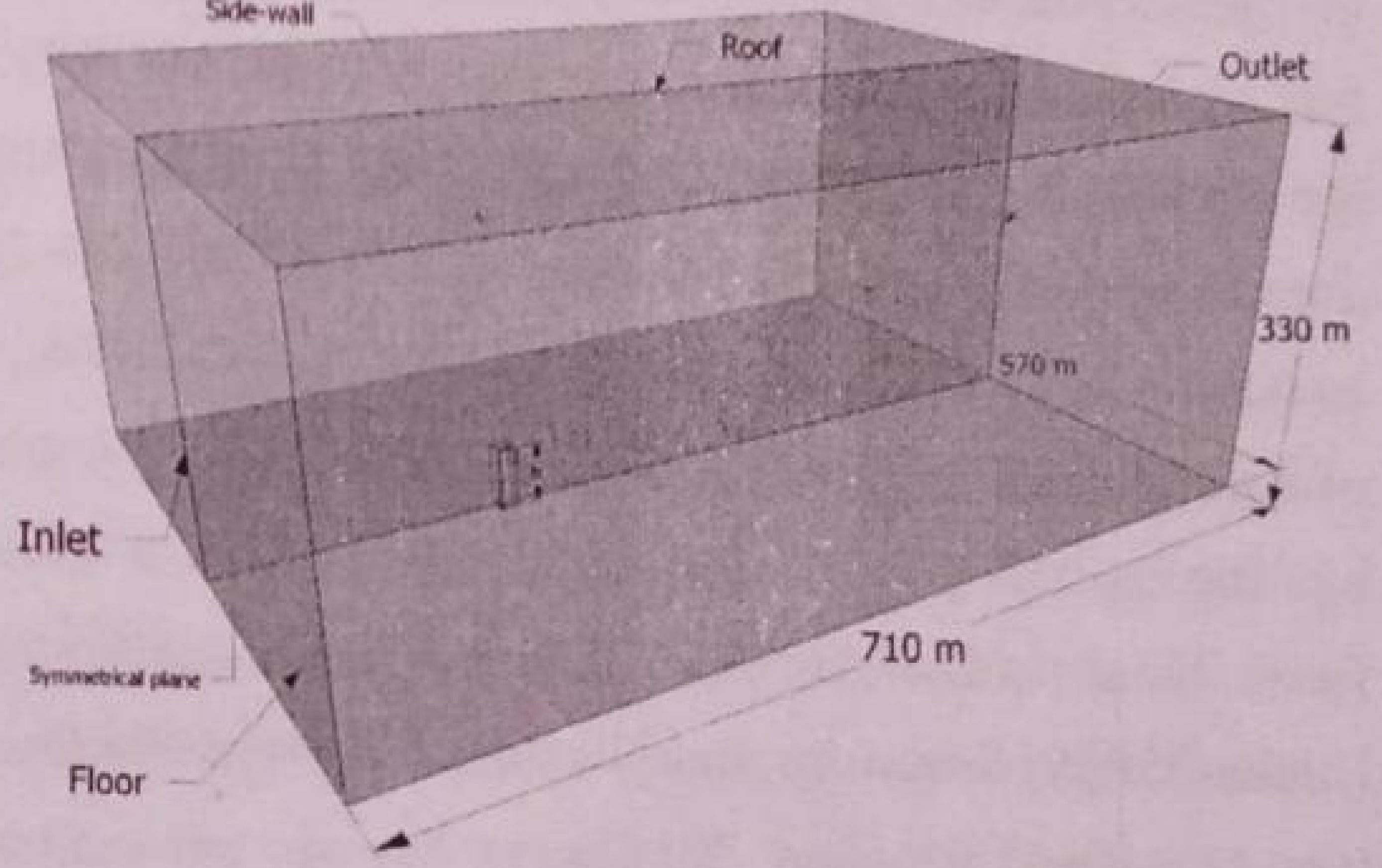

Fig. 2 Computation domain boundaries and size

All models received high quality grid with the same size but different number depending on the configuration of the building model. The grid is automatically generated and higher resolution provided around openings. The proximate minimum size was set at 0.02 m and the number of cells in the smallest element i.e. wall thickness is 10 cells which meets the requirements of the best practice guidelines suggested by (Franke *et al.* (2007); Tominaga *et al.* (2008)). Only the growth rate was varied among all models used to tune the grid size in the fixed range of the minimum (0.02 m) and maximum (10 m) sizes in meeting the acceptable range of grid quality suggested by ANSYS (2012). The spatial domain was purely divided into unstructured tetrahedral grid. Elements grid was constructed from pure elements that allows the airflow movement at all directions smoothly.

The airflow and temperature gradient in the lightwell and hypothetical units are calculated with 3D steady RANS equations. As presented in the validation study, the results of two equations turbulence models (*k-ε*) showed the best agreement with WTE data compared to other models. Although the RNG *k-ε* showed better performance in small-scale simulation in *k-ε* models, the Re-normalize *k-ε* (R *k-ε*) was chosen for the full-scale building model simulations. This is because the RNG *k-ε* in full-scale building model simulations did not converge with recommended scaled residuals. In contrast, the R *k-ε* proofed more powerful in terms of solution converged in full-scale model. The R *k-ε* has the overall good performance for outdoor wind flow and indoor airflow (Franke *et al.*, 2004; Linden, 2009; Sorensen and Nielsen, 2003 as cited in (van Hooff and Blocken, 2010)).

SIMPLE solution algorithm was used for pressure-velocity coupling. The spatial discretization gradient is least square cell based, while pressure interpolation and both the convection and viscous terms of the governing equations are based on the second-order schemes. The Boussinesq approximation is selected for stack-effect because $\beta(T-T_o) = 0.007 \ll 1$, where β is the thermal expansion coefficient and $T-T_0$ the maximum temperature difference between ambient and local temperature.

The convergence criteria were obtained by reducing the scaled residuals which depends on the ventilation configuration. The scaled residuals were set at 10^{-5} for all governing equations. The minimum scaled residuals for each case were limited to 5000 iterations after checking that there is no further convergence. All simulations were performed by high-performance computer (HPC). It has parallel processing on 8 CPU's containing six Nodes – Quad-Core AMD Opteron ™ processor 2376 HE (2.3 GHz) and each Node has 8 GB memory. The time of simulation of all cases ranges between 20 – 40 hours depending on the configuration.

5. Results and Discussion

Fig. 3 (left) illustrates the results of upward air velocity pattern and profile centrally along the lightwell in no-connection (Nco) and double-cross void (Dcs) configurations. In Nco, it is clear that the upward velocity (*v* vector) is between -0.5 to 1 m/s forming large eddies and recirculation flow that leads to greenhouse effect of the air inside the lightwell. This can also be noted in Fig. 3 (right) where the maximum air temperature reaches 34 °C and the minimum is not less than 30 °C. On the other hand, the Dcs configuration shows that the upward airflow velocity along the lightwell is reasonably high, particularly in the upper half of the lightwell spaces (Fig. 4). The average air velocity in the lower half zone is about 0.75 m/s and the rest zone, except the zone close to the void, is 1.75 m/s. there are small recirculation flow near the bottom and middle voids.

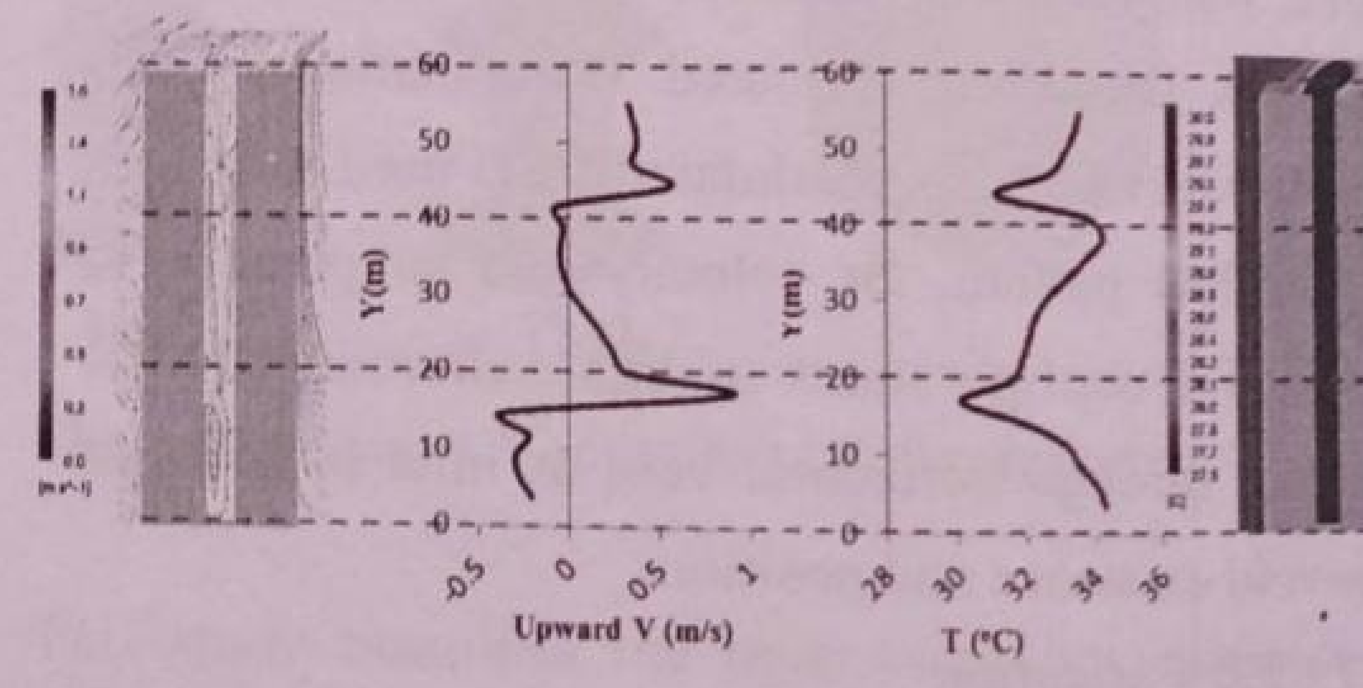

Fig. 3 Upward air velocity (left) and temperature gradient (right) in mid-section of the lightwell of Nco

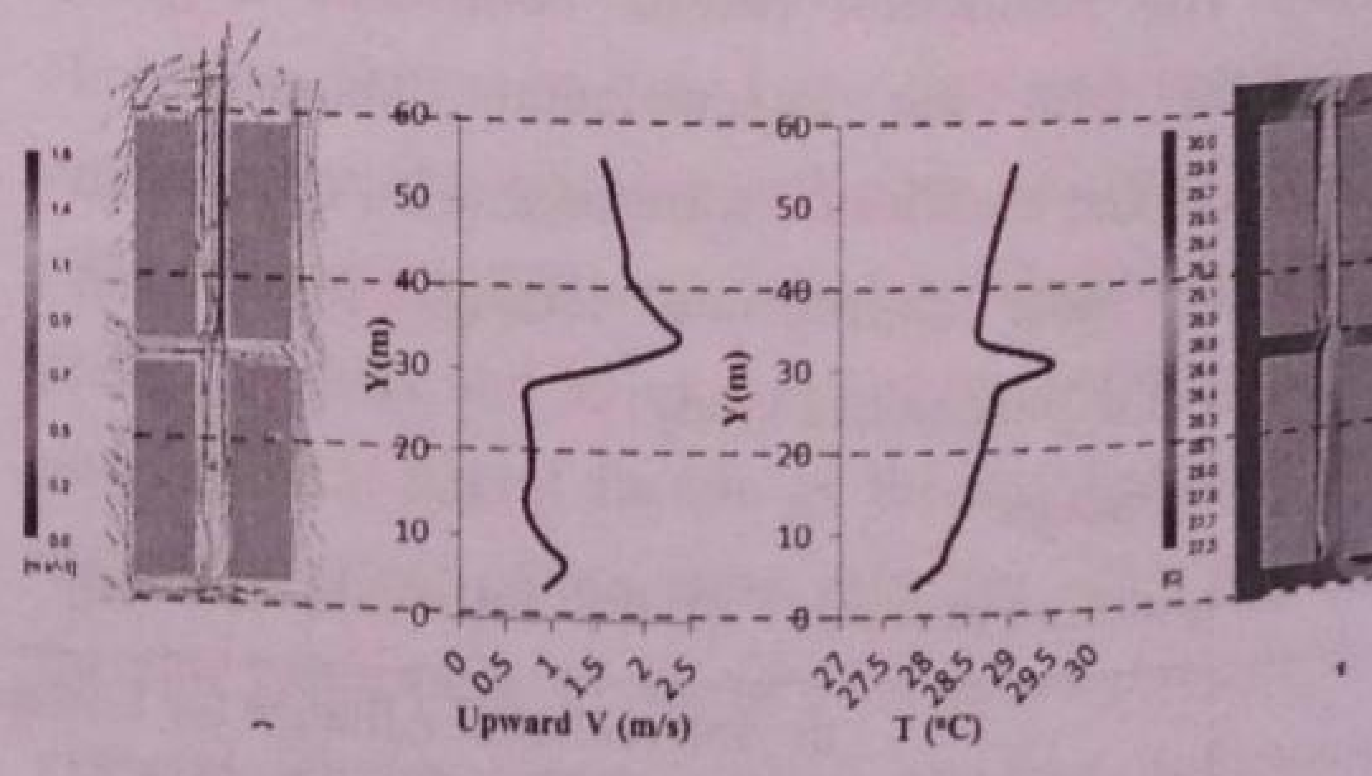

Fig. 4 Upward air velocity (left) and temperature gradient (right) in mid-section of the lightwell of Dcs

The results in adjoining units of the lightwell in both configurations are presented in Figs 5 & 6. It is thus clear, that the air velocity in the lower and upper adjoining units of Nco configuration is higher than both units in Dcs. The air velocity in both rooms of Dcs is poor, ranging between 0.02 to 0.12 m/s and reached to the maximum (0.17 m/s) only close to the external windows (Fig. 6). In Nco configuration the air velocity along both rooms is above 0.15 m/s which represent the minimum acceptable air velocity for thermal comfort in Kuala Lumpur. The air velocity in this configuration contributes to decrease in the average temperature to 28.5 °C instead of 29.5 °C as found in Dcs configuration.

Fig. 7 shows the upward air velocity in the lightwell for all configurations. It is clear that the air velocity in Nco configuration is the lowest from bottom to top. The upward air velocity results of the rest configurations could be categorize under three groups and each one included two configurations. This categorization is based on the vertical position of the void e.g. bottom, middle and double level voids (Fig. 1).

The first group is the middle-void (Mwh & Mcs). Fig. 7 shows that the upward velocity in both configurations of this group are almost the same of Nco results but only in the bottom half part of the lightwell space as elimination of the bottom void. However, the velocity in Mcs is higher than Mwh with about 0.7 m/s in the upper half part of the lightwell (Fig. 7). This difference shows that the connection of the lightwell to outdoor through cross-void is better than using wholly open void, at the middle of the building height. This may be due to the wholly opening void (Mwh) pressure loss from the upper half zone of the lightwell, as it open from the four sides of the building compared to Mcs which only has two side openings. In the bottom void configurations (Bcs & Bwh) the scenario of the cross-void and wholly opening void is different, where the upward velocity in both configurations is almost the same (Fig. 7). However, the result shows that the connection to the outdoor through wholly open void (Bwh) is better than cross-void configuration (Bcs).

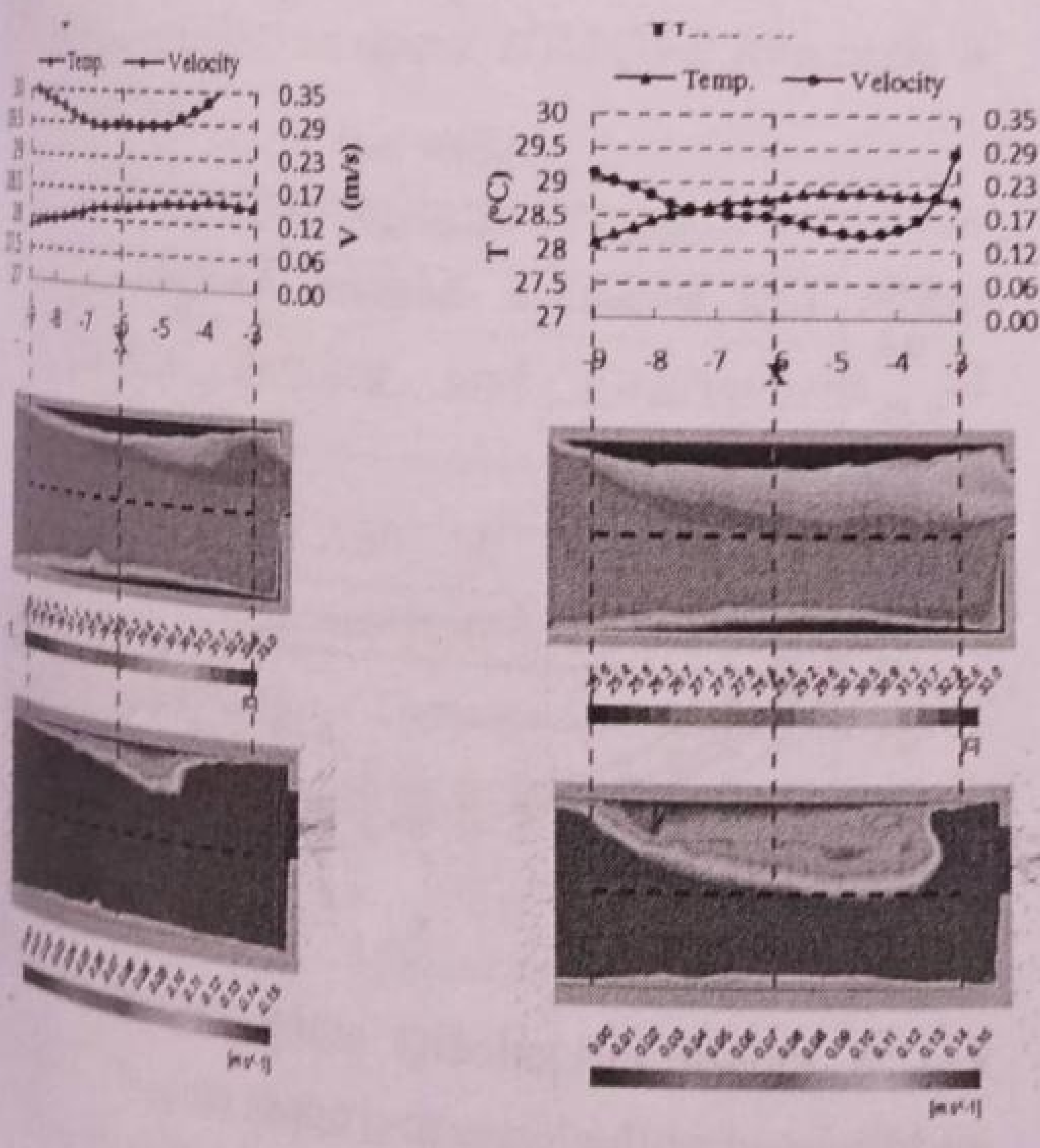

Fig. 5 Predicted indoor air velocity and temperature in mid-section for lower (left) and upper (right) units of Nco

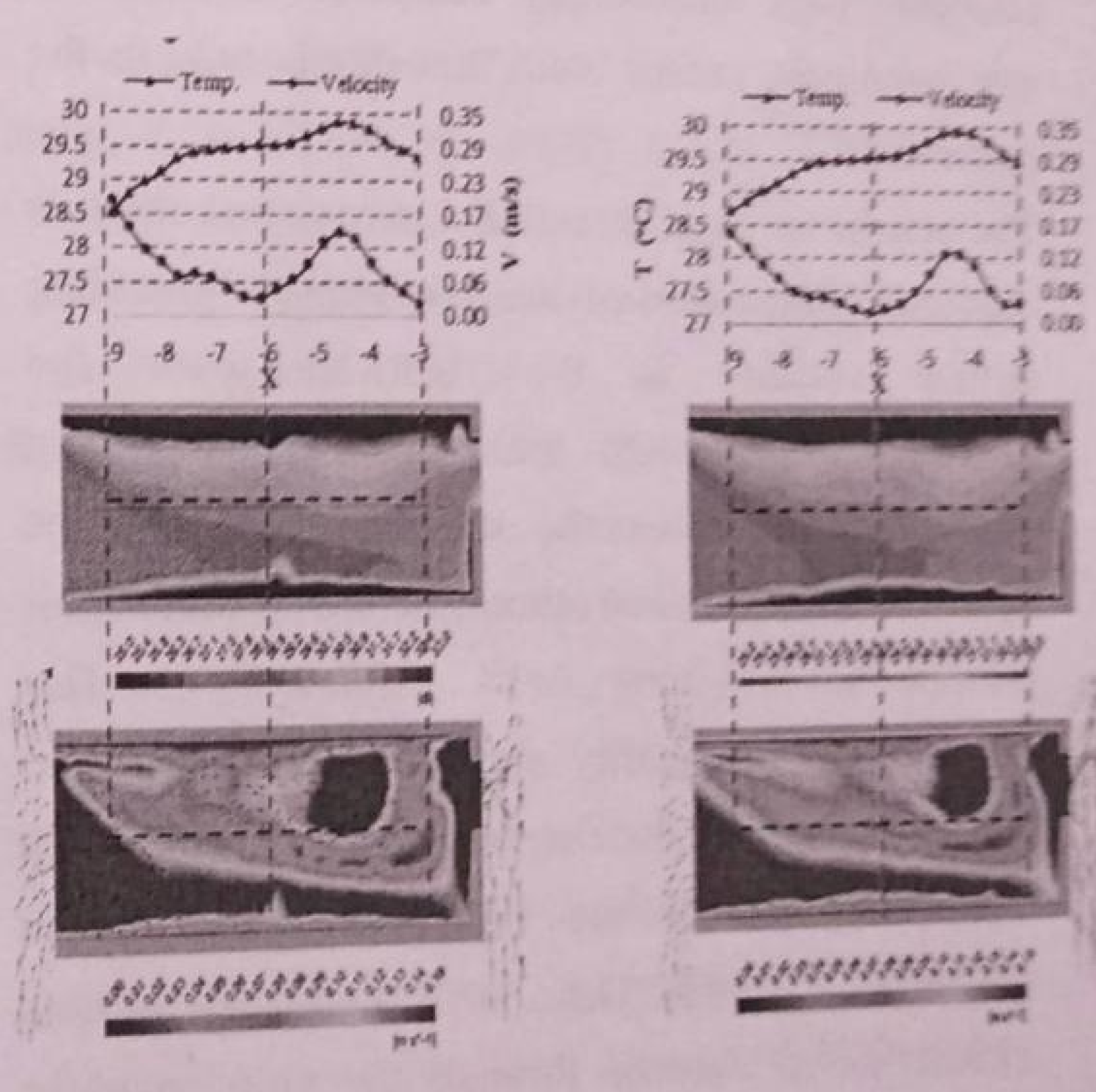

Fig. 6 Predicted indoor air velocity and temperature in mid-section for lower (left) and upper (right) units of Dcs

The results in the double-level void group (Dcs & Dwh) show that the cross-flow void is better than whole-opening voids in terms of providing upward air velocity. In general the results in the three groups demonstrate that the void configuration (i.e. cross-flow and whole opening) highly influence the velocity and pattern of the air flow along the lightwell. Nevertheless, the vertical positions (i.e. bottom, middle and double levels) are superior in terms of the influence on the airflow pattern and air velocity; particularly in the lower half part of the lightwell (Fig. 7).

Fig. 8 illustrates the results of air velocity along the upper and lower hypothetical units which are adjoining of the lightwell through windows. As shown in both figures the difference between the upper and lower units is clear in terms of providing the airflow velocity through the adjoining windows. The lower hypothetical unit demonstrates higher air velocity in all configurations. However, the results show that the lightwell without connection to outdoor through voids (Nco) is the best in terms of providing indoor airflow velocity. As shown in the figures, the air velocity in both units of Nco are above 0.15 m/s (the minimum velocity to provide indoor thermal comfort in Kuala Lumpur). The middle-level void configurations (Mcs & Mwh) also demonstrate relatively high air velocity compared to the other configurations (except Nco), but this is only in the lower unit.

The results in Figs. 7 and 8 indicate that there is opposition of the void existence in terms of providing airflow velocity in the lightwell space and hypothetical units. On the other hand, the void elimination decreases the air velocity along the lightwell at the same time increases indoor air velocity in adjoining units. Although the Dcs increases the air quality along the lightwell up to 200%, it reduces indoor air velocity by 78% in both units compared to the lightwell without direct connection (Nco). Thus, the lightwell without connection to outdoor through the void could be preferred as it provide thermal comfort in the adjoining units and the same time provide reasonable air flow in the lightwell which is enough for air quality based on the standard.

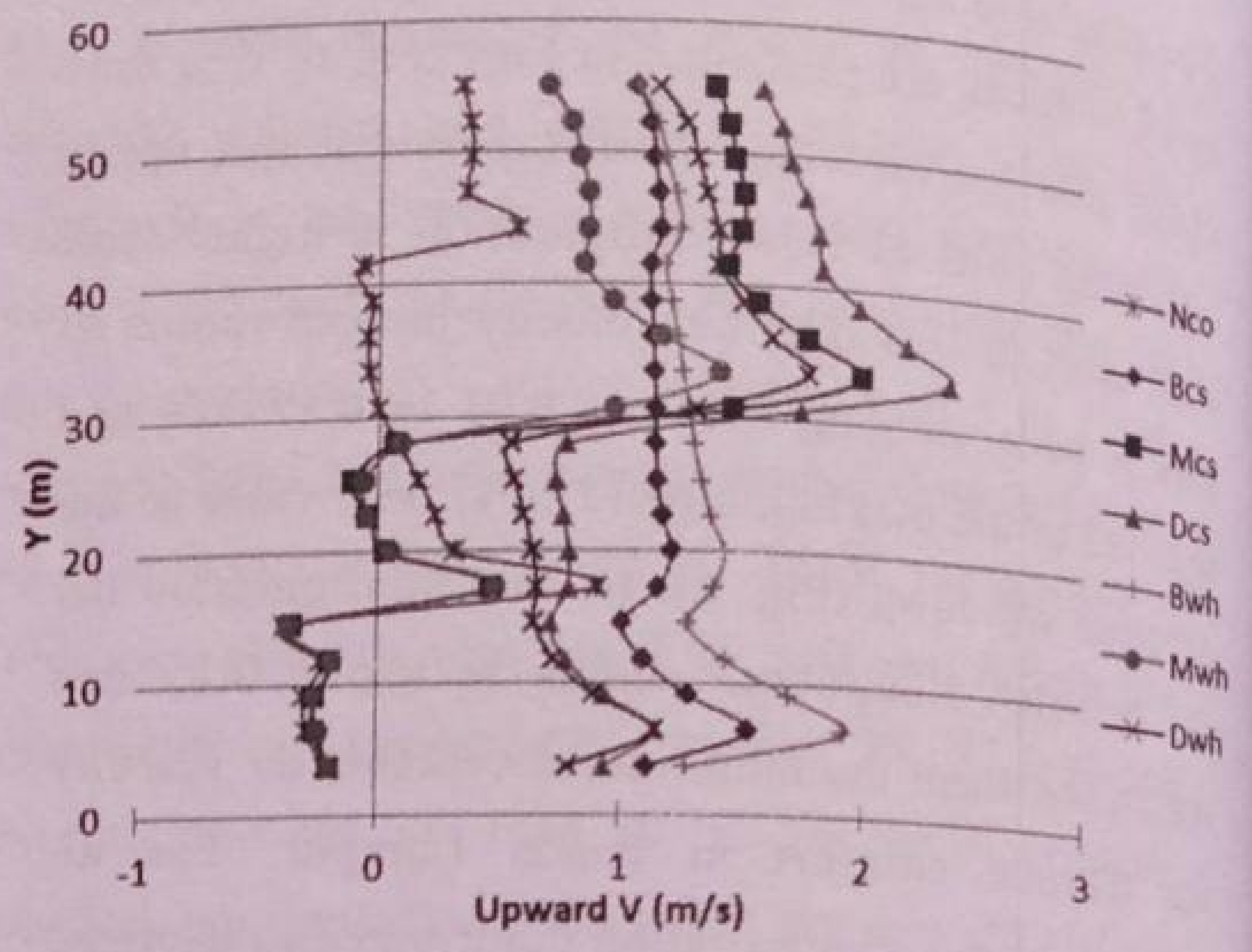

Fig. 7 Predicted upward air velocity in vertical centerline of the lightwell in all configurations

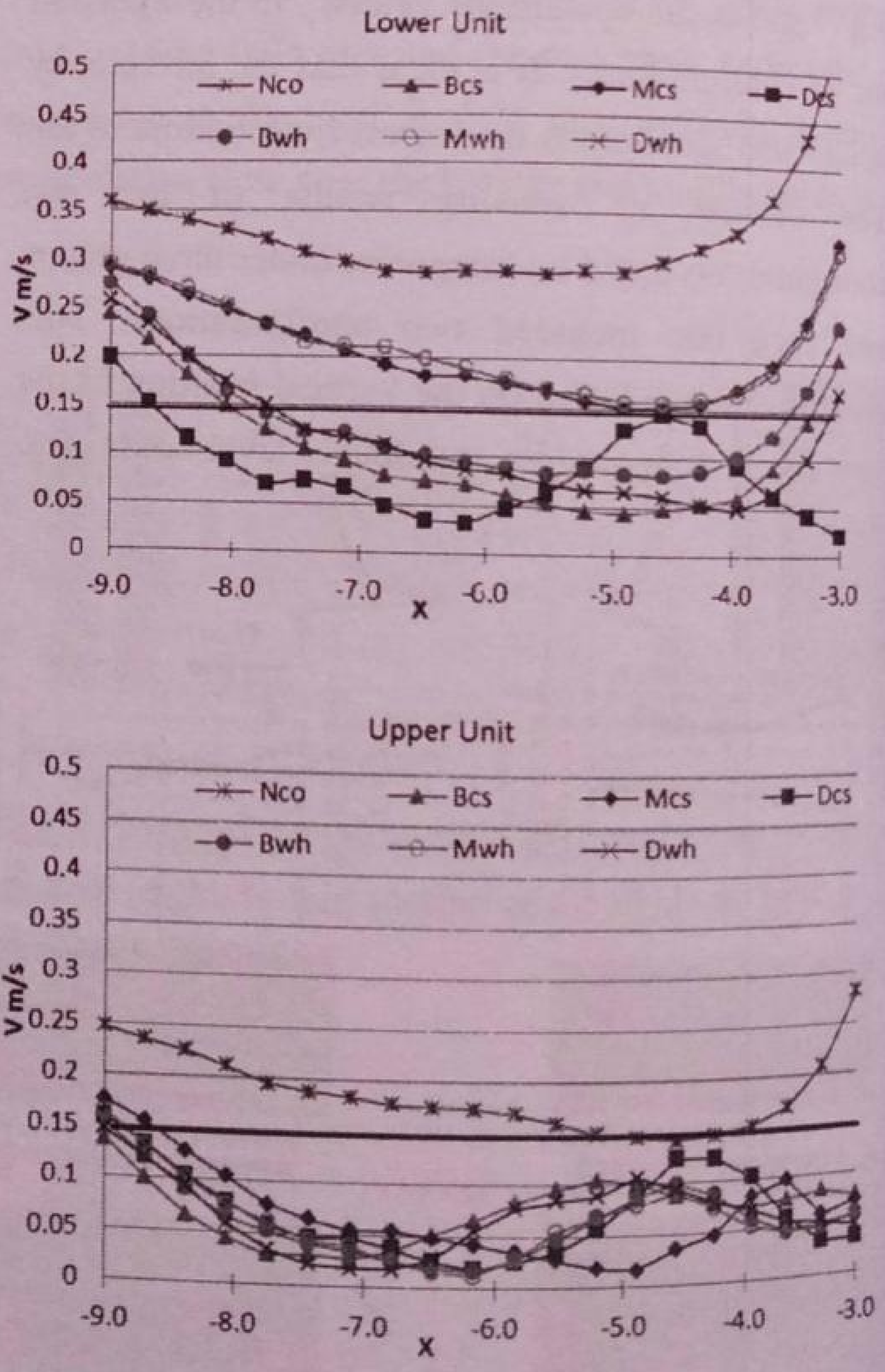

Fig. 8 Indoor air velocity along the x-axis at the middle level of the lower and upper units

6. Conclusion

Based on validated CFD code this study examined different ventilation configurations (connection between internal lightwell and voids). The ventilation configuration was developed based on design perspectives and Malaysian uniform building by-law (UBBL). This study based on 3-D steady RANS CFD model validated with the experimental data for a lightwell in a high-rise building where the lightwell is connected to the outdoor through a bottom void.

The simulation results of this parametric study showed that the inlet existence and its connection with the lightwell are highly effective on the natural ventilation in the lightwell and adjoining rooms. Thus, the study recommended developing design guidance in UBBL regarding the inlet of the internal lightwell in order to improve the air quality and thermal comfort in naturally HRR buildings in Malaysia.

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