Hu and Yoshie (2013) investigate the effect of building geometry and they revealed that the ventilation efficiency strongly depended on the level of building aerodynamics. In addition Asfour (2010) investigate the potential of ventilation cooling effect and wind environment on the several group buildings pattern buildings. This study shown a dramatic effect on the formation of airflow behavior was achieved due to the orientation of wind direction and building group arrangement. Despite using CFD method, some studies have been carried out wind tunnel experiment to simulate several aerodynamic effects that may occur around buildings. In example, Kubota, Miura, Tominaga, and Mochida (2008) investigate the relationship between building arrangement of actual residential neighborhoods and average pedestrian wind speed. The study emphasized the strong relationship between the spatially average mean wind of pedestrian space and building coverage; as the building coverage ratio increase the wind speed decreased. Thus, the wind flow profile and pollutant dispersion structure strongly affects air quality in urban areas. Hence, through studies such as this, urban planners and architects could improve the ventilation efficiency, human comfort and the quality of life in a high-density city from the mechanical engineering side.

These previous researches have demonstrated the strong influence of building coverage ratio, layout and wind direction on pedestrian wind environment. However, the holistic knowledge on the effect of the upstream building owing to the diversity of building geometry that located upwind has not yet obtained. In particular the influence of upstream distance has been poorly investigated. The built form affects airflow distribution within a city in terms of building orientation, distances between buildings and group arrangement. Therefore the objective of this study is to identify the effect of the upstream building geometry on mean wind profile in uniform building height.

The structure of the paper is organized as follows: (i) Section 2 provides details of street and building configurations employed in this study and describes the methodology used for estimating the exposures together with numerical modeling set-up, (ii) Section 3 presents the results and discussion, and (iii) Section 4 identifies key research highlights and conclusions.

RESEARCH METHODS

Computational domain

Table 1 shows the four cases of simulation models that consisted of cubical block models arranged in squared and staggered arrays. The entire blocks with aspect ratio (ratio of frontal area to roof area of a block, *hereafter* α_p) $\alpha_p = 1$ had a square based and height fixed at H = 25 mm. The setback distance (x), which is the distance between upstream block arrays and downstream arrays were varied with two main values of *4H* and *6H*. The three-dimensional block arrays were arranged in a square and staggered pattern on the upstream. Whereas, the downstream block arrays consisting of the target area was arranged in a staggered arrangement. Furthermore, the packing density (ratio of building roof to ground surface area, *hereafter* λ_p) of this model was fixed at 25% for all cases. The schematics of the block arrangement and computational domains for both upstream pattern cases are as illustrated in Figure 1.

Table 1: *Summary of computational configuration*

Case	λ_p (%)	Setback distance, x	Computational domain size	Remarks
ST4H	25	$4H$	$13H \times 29H \times 4H$	• Staggered arrays with cubical blocks at upstream and measurement area
ST6H		$6H$	$13H \times 31H \times 4H$	
SQ4H	25	$4H$	$13H \times 29H \times 4H$	• Square arrays with cubical blocks at upstream area • Staggered arrays with cubical blocks at measurement area
SQ6H		$6H$	$13H \times 31H \times 4H$	

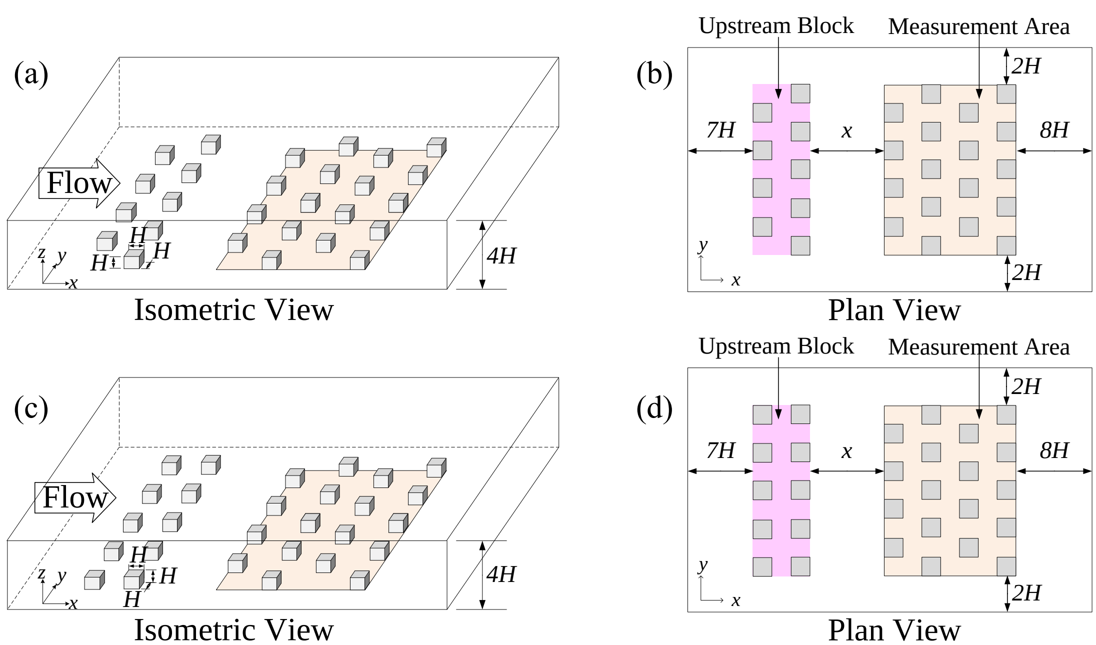

Figure 1: *Schematic diagram of isometric view and plan view of block arrangements and computational domain. (a) and (b) isometric view and plan view of computational domain for case of ST4H and ST6H, (c) and (d) isometric view and plan view of computational domain for case of SQ4H and SQ6H.*

Numerical model and simulation setup

Simulations were performed using the *OpenFOAM* software which is open source computational fluid dynamics (CFD) software. The turbulence model was set as LES Smagorinsky for obtaining a desired decrement in the range of the scales acquired for numerical equation. The boundary limits will guide the computations throughout the simulation. The domain models were set as free stream flow along the horizontal inlet and outlet direction and the lateral direction were treated as symmetrical boundary condition. The domain floor and surface of buildings were applied with a wall function whilst the top boundary were applied with a no-slip condition. Whereas, the grid refinement used was *H/32* achieved by the snappyHexmesh function of the simulation setup. The inlet velocity was set as 3m/s which is the standard value of velocity in a 4 season urban area. If the local wind speed was used there will be complications in terms of obtaining the average wind speed because it differs from place to place. For effective ventilation, the wind speed needs to be in continuous flow of the same speed (Bezpalcová et al., 2009). The simulation were carried out for all case until approximately *200T* (*T=H/U*), to ensure the wind statistic are in sufficient convergence. The time step used to analyze the influence of the upstream building arrangement was *0.00005T*. The steps taken to carry out the simulation and validation process similar with Mohammad et al. (2014).

RESULTS AND DISCUSSION

The numerical results obtained from the simulations are as in the following sub-chapters. The profiles of mean wind speed and mean wind speed ratio will be compared with each other to assess the effectiveness of urban ventilation due to different upstream arrangement and distance.

Vertical Wind Profiles

Figure 2 shows the comparison between spatially-average mean streamwise velocity inside the urban canopy of the four consecutive models, *ST4H*, *SQ4H*, *ST6H* and *SQ6H*. From the numerical data it is observable that case SQ6H gives the highest velocity profile between the four configurations. Although there are several discrepancies among all the spatially average mean wind velocities the results shows that the square patterns gives a higher streamwise mean velocity than the staggered patterns. As a result, it will contribute to the transportation of pollution from the target area.

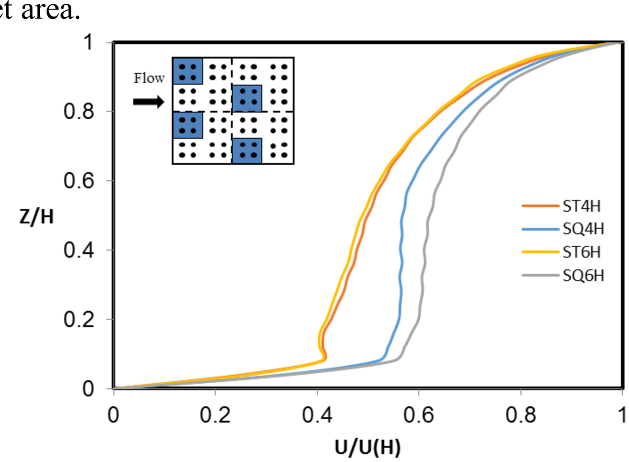

Figure 2. *Comparison between spatially-average mean streamwise velocity*

Figure 3 (a) and (b) shows the comparison of spatially-average streamwise velocity ratio for two different upstream arrangements. The figure depicted that streamwise velocity ratio is higher for both squared cases, SQ4H and SQ6H, than the staggered cases, ST4H and ST4H. Apart from that, it also observable that the wind profile shows a high shear stress at the ground level (z < 0.1). This effect of shear stress on the wind profile begins to normalize by the averaged streamwise velocity at the block height. This is observable in all the wind profiles within the target area. This result proves that a denser building arrangement can strengthen turbulent and adjective transport whilst contributing to the ventilation performance (Kono et al., 2008).

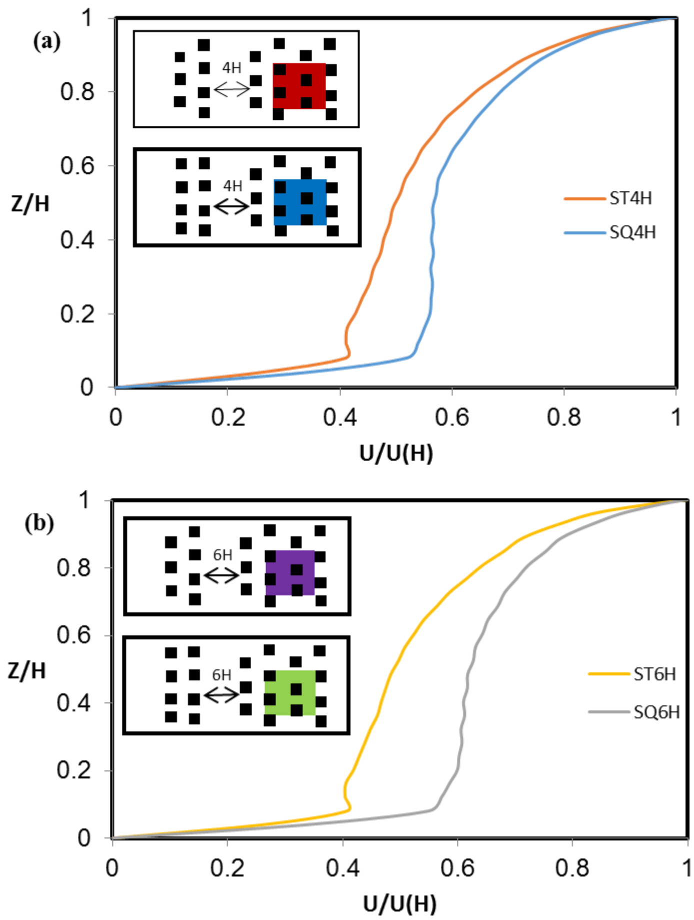

Figure 3. *Comparison between different upstream patterns. (a) 4H (b) 6H*

The effect of setback distance shown in Figure 4. The result of spatially-average streamwise velocity profiles ratio shows that the profiles for ST4H and ST6H almost well agreed. This effect may be due to the difficulty of the air can to flow through around the staggered arrangement then the effect setback distance become smaller compared to the breathability effect. However, the wind profile for squared arrangement shows slight differences between SQ4H and SQ6H. For the setback distance equal to 6*H* (SQ6H) it shows a stronger mean wind flow around the target area. Hence, it can be conclude that a staggered upstream arrangement decreases the capability of removing pollutants from the target area as it prevents a direct flow between the blocks. Due to the present finding it shows that the upstream building arrangement of upstream building arrays and setback distance is very important for square array.

This would contribute to a better air quality at pedestrian level.

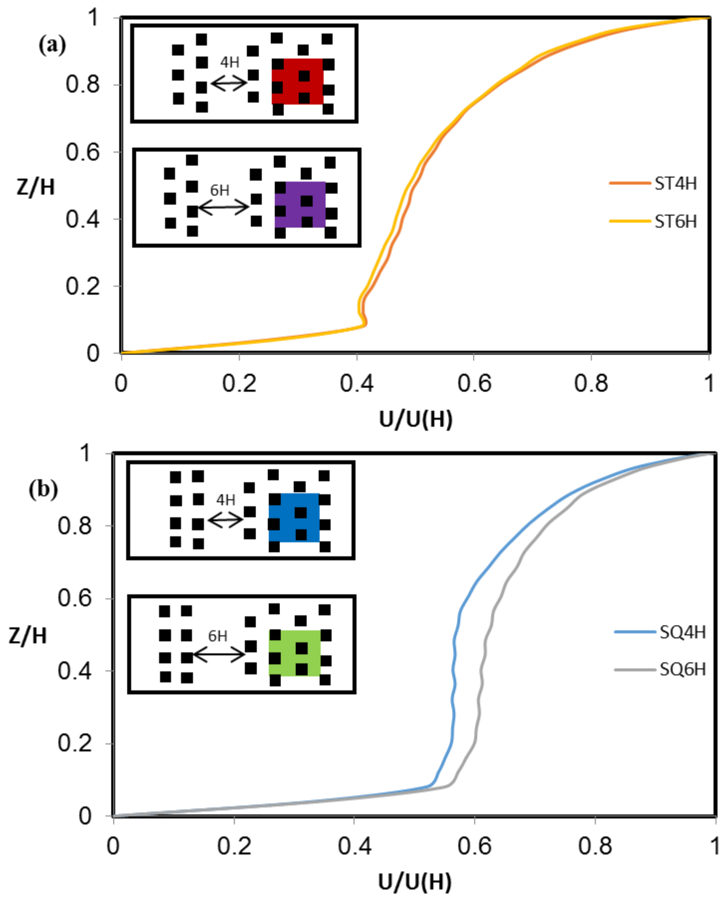

Figure 4.4: *Comparison between different distances of upstream building with test arrays. (a) Staggered (b) Squared*

CONCLUSION AND IMPLICATIONS

Four sets of urban models were simulated with different upstream arrangements and distances between the upstream layer and the test arrays using Large Eddy simulation turbulence model in OpenFOAM. This study investigates the effect of distance and geometry of an upstream building on the breathability of an upwind building arrangement. From the findings we can conclude that by increasing the distance (*6H*) between the upstream and the upwind arrangement will show a wind flow profile that increases the generation of recirculation and isolated vortexes. The recirculation generated at distance 6*H* gave a larger vortex circulation and provided a better transport for the pollutant to be lifted from the target area. Apart from that, the results show that a square wind flow distribution help generate a much better ventilation performance rather than a staggered wind flow distribution. Where, the spatially-averaged velocity ratio of a squared upstream block increased the wind capability in removing pollutants. The wind flow distributions of the staggered upstream pattern are much stronger than the wind flow distribution of the square upstream pattern. It is greatly hoped that the findings of this research may be used as reference for future implications in understanding the geometrical influence of the building in improving the ventilation performance of the urban area.

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REFERENCES

Abd Razak, A., Hagishima, A., Ikegaya, N., & Tanimoto, J. (2013). Analysis of airflow over building arrays for assessment of urban wind environment. *Building and Environment, 59*(0), 56-65.

Asfour, O. S. (2010). Prediction of wind environment in different grouping patterns of housing blocks. *Energy and Buildings, 42*(11), 2061-2069.

Baskaran, A., & Kashef, A. (1996). Investigation of air flow around buildings using computational fluid dynamics techniques. *Engineering Structures, 18*(11), 861-875.

Bezpalcová, K., Ohba, M., & Jaňour, Z. (2009). Influence of building packing density and building height distribution on vertical mass transport. *Proc. ICUC-7, Yokohama, Japan, A5-4*.

Hu, T., & Yoshie, R. (2013). Indices to evaluate ventilation efficiency in newly-built urban area at pedestrian level. *Journal of Wind Engineering and Industrial Aerodynamics, 112*(0), 39-51.

Kono, T., Ashie, Y., & Tamura, T. (2008). *Numerical Investigations of Mean Winds within Urban Canopies Using Large-Eddy Simulation.* Paper presented at the Proceedings of the 4th International Conference on Advances in Wind and Structures (AWAS'08), Jeju, Korea.

Kubota, T., Miura, M., Tominaga, Y., & Mochida, A. (2008). Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. *Building and Environment, 43*(10), 1699-1708.

Mohammad, A. F., Zaki, S. A., Mat Ali, M. S., Abd Razak, A., & Hagishima, A. (2014). *Large-Eddy Simulation of wind-induced ventilation in urban buildings of random staggered arrays.* Paper presented at the 6th International Symposium on Computational Wind Engineering, University of Hamburg, Germany.

Panagiotou, I., Neophytou, M. K. A., Hamlyn, D., & Britter, R. E. (2013). City breathability as quantified by the exchange velocity and its spatial variation in real inhomogeneous urban geometries: An example from central London urban area. *Science of The Total Environment, 442*(0), 466-477.

Zhang, A., Gao, C., & Zhang, L. (2005). Numerical simulation of the wind field around different building arrangements. *Journal of Wind Engineering and Industrial Aerodynamics, 93*(12), 891-904.