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# Influence of built form in urban ventilation assessment of tropical cities with weak wind conditions

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Urban ventilation is recognized as effective countermeasure on air pollution and urban heat island, yet most tropical urban areas receive low annual mean wind velocity thus lessening potential for urban ventilation. Effect of built form on resulting mean wind velocity at pedestrian-level was analyzed through computational fluid dynamics (CFD) to assess effectiveness in urban ventilation of tropical cities with weak wind conditions based on three heterogeneous built form of Kampung Baru, Taman Keramat and Pantai Dalam which located in the city of Kuala Lumpur for wind direction from south and west. The urban density for the built form was characterized by using urban packing density parameter of frontal area ratio, $\lambda_f$ and the urban ventilation was assessed based on availability of pedestrian wind which described using wind velocity ratio, *VR*. Influence of built form in urban ventilation was found to be significant in affecting the mean wind velocity, where magnitude of *VR* at pedestrian-level was decreasing as the value of $\lambda_f$ of the built form increases. Suggestions to improve urban ventilation design in major development project are provided based on these findings.

Keywords: urban ventilation; urban canopy layer; wind velocity ratio; frontal area ratio

## Introduction

With increasing rate of global urbanization and growing number of cities around the world, proportion of the world population living in urban area is expected to be 60% by the year of 2030 (United Nations, 2011). Concern on quality of cities environment and comfort is rising due to the rapid urbanization and growth of urban population around the world, especially on problem of heat stress and air pollution within cities. Nonetheless, the discomfort condition can be significantly minimized in a well ventilated city, as ventilation process increases heat lost within the environment

to improve urban thermal comfort, as well as removes airborne pollutant to improve urban air quality. Urban ventilation is defined as the process of ventilation out of and into the urban canopy layer through the openings or the open street roofs of cities (Hang, 2009), including flow and mass or energy transport within and above the urban canopy layer, with assumption that the incoming wind into the urban area is the source of relatively clean air.

Based on global wind velocity collected by Archer and Jacobson (2005), wind velocity is generally low at the tropical region, subsequently causing the urban area in the region to experience low annual mean wind speed. For that reason, residents in tropical cities are highly exposed to discomfort condition in terms of thermal stress and stagnant airborne pollutant, as the capacity of wind to dilute heat and pollutant is not sufficient. Additionally, many studies on urban wind environment used rectangular block arrays since the geometry can be adapted into intended value of urban density parameter, therefore anticipated level of urban density can be generated straightforwardly for further analysis (Macdonald, 2000; Hang, 2009; Hamlyn and Britter, 2005). Not much studies have been done by using complex building geometry based on actual urban area, since realistic urban geometry has complex characteristics and intricate to be assessed.

Built form which defined as shape of buildings as a collective structure is more complex than rectangular block arrays, yet it is more realistic with actual urban area. This paper used computational fluid dynamics (CFD) as research methodology in investigating effectiveness of urban ventilation of tropical cities with weak wind conditions by using wind conditions and built form of three sites in the city of Kuala Lumpur, Malaysia. The three heterogeneous built form was characterized by using urban packing density of frontal area ratio, $\lambda_f$ which is defined as ratio between the frontal area of buildings which facing the incoming wind to the total of ground surface area (Grimmond and Oke, 1999), where wind velocity ratio, $VR$ is used as ventilation indices to examine pedestrian wind environment.

**Methodology**

OpenFOAM was used as solver, where semi-implicit method for pressure linked equations (SIMPLE) algorithm was applied as velocity-pressure coupling for iteration procedure in steady-state airflow. Three-dimensional computational domain was set to correspond with a wind tunnel setup that covered with smooth floor, with aerodynamic surface roughness length, $z_0$ of 0.005m. By defining a length unit $H$ as the height of the tallest building of the built form, the incoming wind entering the domain where the distance from upstream to the built form geometry was $7H$, and the distance from the built form geometry to downstream was $5H$ to allow the atmospheric boundary layer at

the upstream and the wake behind the built form to develop for convergence of the simulation. The vertical height to the top of the domain was set to be 5$H$, and the lateral distance at left and right of the geometry was set to be 2$H$.

RNG $k$-$\varepsilon$ model (Yakhot and Orszag, 1986) which is an improved two-equation models of Reynolds Averaged Navier-Stokes (RANS) was selected as turbulence model as recommended by Franke et al. (2007) and Tominaga et al. (2008) to optimize cost and accuracy in CFD simulation for pedestrian wind, where in some studies like Li et al. (2005) have shown that the RNG $k$-$\varepsilon$ model can predict flow structure inside street canyon reasonably well as to compare to Large Eddy Simulation (LES). Validation analysis for mean wind velocity around built form was done by applying the described CFD setup into a wind tunnel experiment by Kubota and Ahmad (2005) based on a built form of residential area of 410m × 410m that located in Johor Bahru, Malaysia. Mean wind velocity around the built form model were measured at 49 locations in wind tunnel, and results were indicated in term of wind velocity ratio, which defined as ratio of mean wind velocity at 1.5m height with buildings to mean wind velocity at the same height without buildings (see Figure 1(a)).
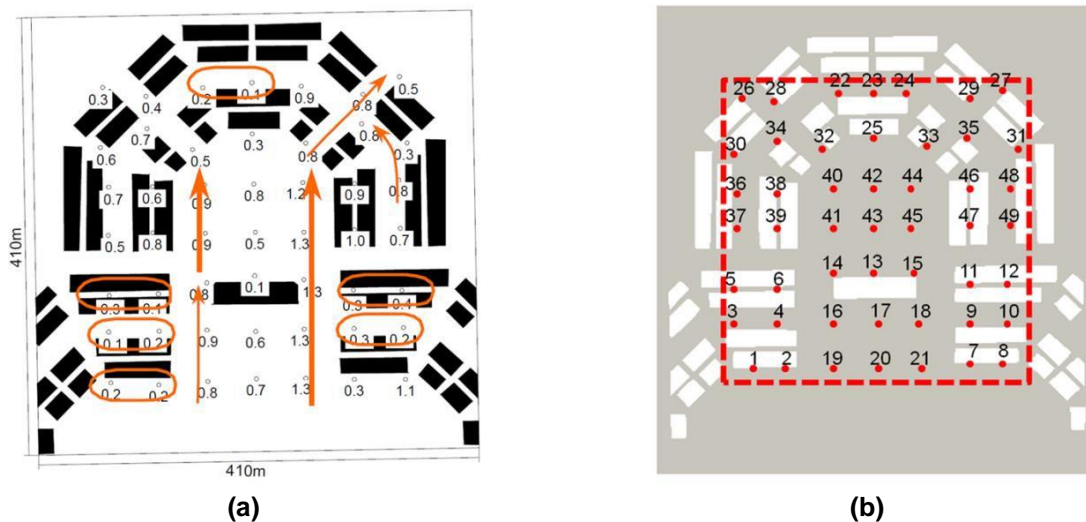


**(a)**      **(b)**

**Figure 1: (a) Test point locations from Kubota and Ahmad (2005) with results of wind velocity ratio for each test points. (b) Test point locations in validation analysis.**

Two simulations were performed for the validation analysis, where the first simulation used the same built form buildings as Figure 1(a). The second simulation was conducted using same set up as the first simulation but without buildings to compare the wind velocity ratio as carried out in the wind tunnel experiment. Atmospheric boundary layer was used as inlet condition for both simulations with reference velocity of 1.8m/s based on climate data of Senai station, Johor Bahru. The values for wind velocity ratio from the CFD simulations were measured at 49 locations

as similar as Kubota and Ahmad (2005) and shown in Figure 1(b), and comparison between results which measured from the wind tunnel experiment and results from the CFD simulations is shown in Figure 2. Hence, it was confirmed that the described CFD setup can predict the distribution of mean wind velocity around built form in sensible agreement with the wind tunnel experiment, also the prediction error for the wind velocity ratio was around 6.7% as to compare to the wind tunnel experiment.
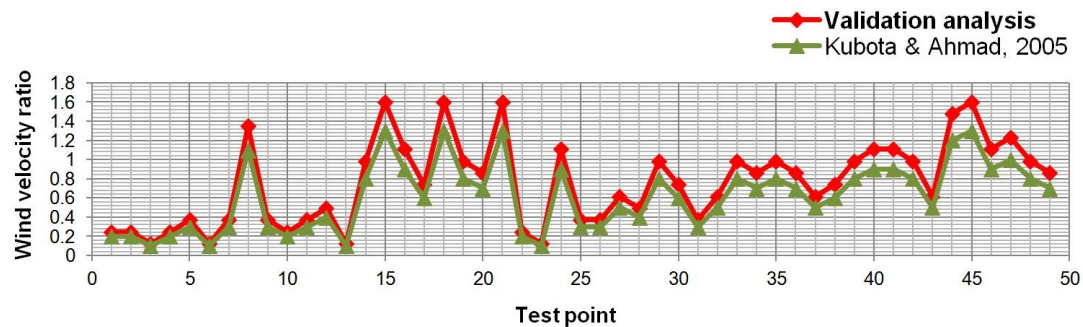


Figure 2: Comparison of wind velocity value for each test point.

## Description of Built Form

The heterogeneous built form of tropical cities with weak wind conditions under investigation are Kampung Baru, Taman Keramat and Pantai Dalam and the built form is based on three sites located in Federal Territory of Kuala Lumpur, which is the most populated urban area in Malaysia. Kampung Baru is a traditional settlement located at the heart of Kuala Lumpur, where low-rise buildings and residential structures are dominating its overall built form due to historical background. Taman Keramat is located at close proximity with Kampung Baru and having similar built form of low-rise buildings but parts of its region are consisting by high-rise residential buildings. Meanwhile, Pantai Dalam is located at the outskirt of Kuala Lumpur city center and the built form of the area is dominated by newly developed high-rise buildings.

Three-dimensional models of the heterogeneous built form for the CFD simulations (see Figure 3) are constructed based on simplified figure of the built form where detail of the buildings was neglected, but height of the buildings was based on actual height at the locations which was obtained from field measurement. Area of interest for each built form is nearly similar, where area of Kampung Baru is 367m × 358m, Taman Keramat is 359m × 343m, and Pantai Dalam is 325m × 336m. Wind direction was applied from south and west for each built form based on local wind rose of Kuala Lumpur, thus creating the total CFD simulations to be six cases. All the cases are characterized by using frontal area ratio, $\lambda_f$ and summarized in Table 1.

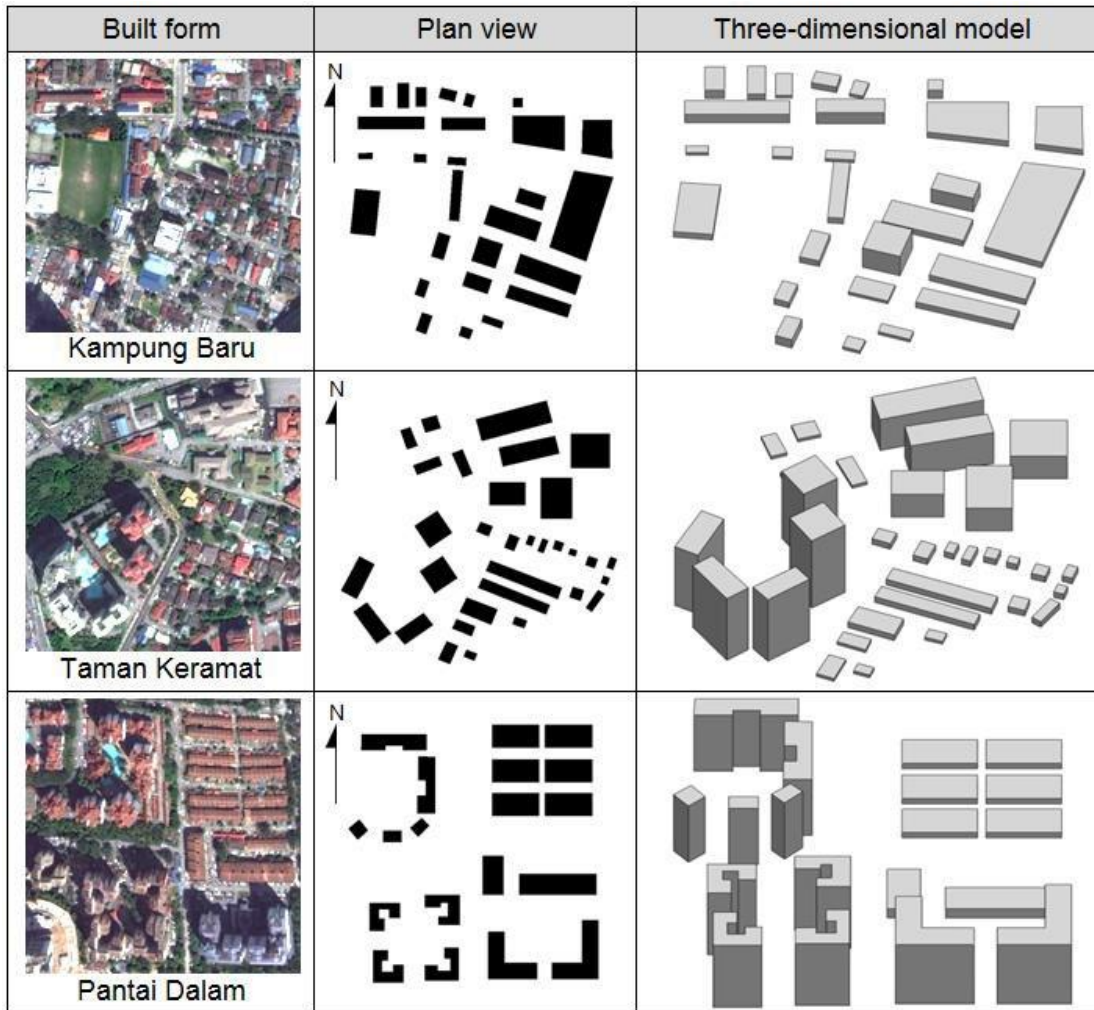| Built form | Plan view | Three-dimensional model |
|---|---|---|
| Kampung Baru | | |
| Taman Keramat | | |
| Pantai Dalam | | |

**Figure 3: Built form, plan view and three-dimensional model for built form of Kampung Baru, Taman Keramat and Pantai Dalam.**

**Table 1: Summary of case analysis with frontal area ratio, $λ_f$.**

| Case | Built form | Wind direction | Total frontal area (m$^2$) | Total ground area (m$^2$) | Frontal area ratio, $λ_f$ |
|---|---|---|---|---|---|
| 1 | Kampung | South | 4,467 | 131,386 | 0.034 |
| 2 | Baru | West | 3,810 | | 0.029 |
| 3 | Taman | South | 18,101 | 123,137 | 0.147 |
| 4 | Keramat | West | 17,978 | | 0.146 |
| 5 | Pantai | South | 20,857 | 109,200 | 0.191 |
| 6 | Dalam | West | 18,782 | | 0.172 |

The wind rose of Kuala Lumpur is influenced by three seasonal periods caused by monsoon as indicated by Figure 4. Two most frequent wind directions of south and west are used for setting up the inlet conditions of the computational domain to replicate the conditions of actual locations in the simulations based on the wind    rose

data, with reference wind velocity of 1.6m/s for the atmospheric boundary layer. Archer and Jacobson (2005) quantified the world's wind capacity into 7 classes, where the lowest global wind capacity is categorized as class 1 with wind velocity less than 5.9m/s. Hence with average wind velocity of 1.6m/s, Kuala Lumpur is categorized into the wind capacity of class 1 and characterized with weak wind conditions, which is observable in most cities in tropical region.
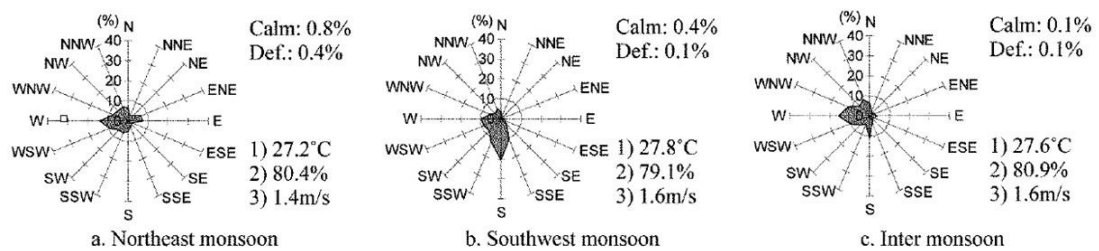


**Figure 4: Wind rose of Kuala Lumpur from 1988-1999.**

### Results and Discussion

Urban ventilation was assessed by using ventilation indices of wind velocity ratio, $VR$ as shown in equation below (Ng et al., 2011):

$$VR = \frac{V_p}{V_{ref}} \tag{1}$$

where $V_p$ is the mean wind velocity at pedestrian-level and $V_{ref}$ is the reference velocity. As the magnitude of $VR$ is increasing, availability of wind captured by pedestrians is higher and considered to be better. In addition, this magnitude is not only indicates the level of comfort to pedestrians, but it is also reflected on the performance of pollutant dispersion since the urban air pollution is mainly concentrates at the pedestrian-level height. The value of $V_p$ is mean wind velocity measured at pedestrian-level height of 1.5m above the ground, meanwhile the value of $V_{ref}$ is based on mean wind velocity of 1.6m/s at upstream free flow to reflect the existence of the built form with the weak wind conditions of Kuala Lumpur.

Effect of frontal area ratio, $\lambda_f$ on wind velocity ratio at pedestrian-level for built form can be seen clearly based on results from the simulation as shown in Figure 5 for Kampung Baru, Figure 6 for Taman Keramat and Figure 7 for Pantai Dalam. The results show that as the value of $\lambda_f$ for built form was decreasing, the mean wind field for pedestrian wind around the built form tends to be dominated by $VR$ with higher magnitude. The mean wind field for Kampung Baru that has the lowest value of $\lambda_f$ among other built form has the highest magnitude of $VR$, mostly ranging from 0.24 to 1.4 for wind direction from both south and west (see Figure 5). The ratio indicates that approximately 1/3 of upstream free flow was captured by most of the pedestrians

around the built form of Kampung Baru, while the lowest magnitude of the ratio ranging from 0 to 0.08 was occurred immediately behind buildings structure.

On the other hand, the wind field of Taman Keramat was found to be fairly critical for pedestrian wind environment where about half of the area around the built form buildings having magnitude of $VR$ below 0.1 for both direction from south and west (see Figure 6). Since the incoming wind to the area was obstructed by high-rise buildings of the built form, the sluggish wind velocity as indicated by the wind velocity ratio potentially causing discomfort for pedestrians and residents around low-rise buildings of Taman Keramat because of insufficient wind to remove heat from the air and to dilute airborne pollutant. Meanwhile, the built form of Pantai Dalam which having the highest value of $\lambda_f$ demonstrated the worst pedestrian wind environment where the wind field for the area was dominated by ratio less than 0.12 for wind direction from south, suggesting that the mean wind velocity available for pedestrians of the area was only around 0.19m/s (see Figure 7). The results implied that as the value of $\lambda_f$ for built form increases, it will reduce the wind availability around the built form, and thus lessening the potential for urban ventilation.
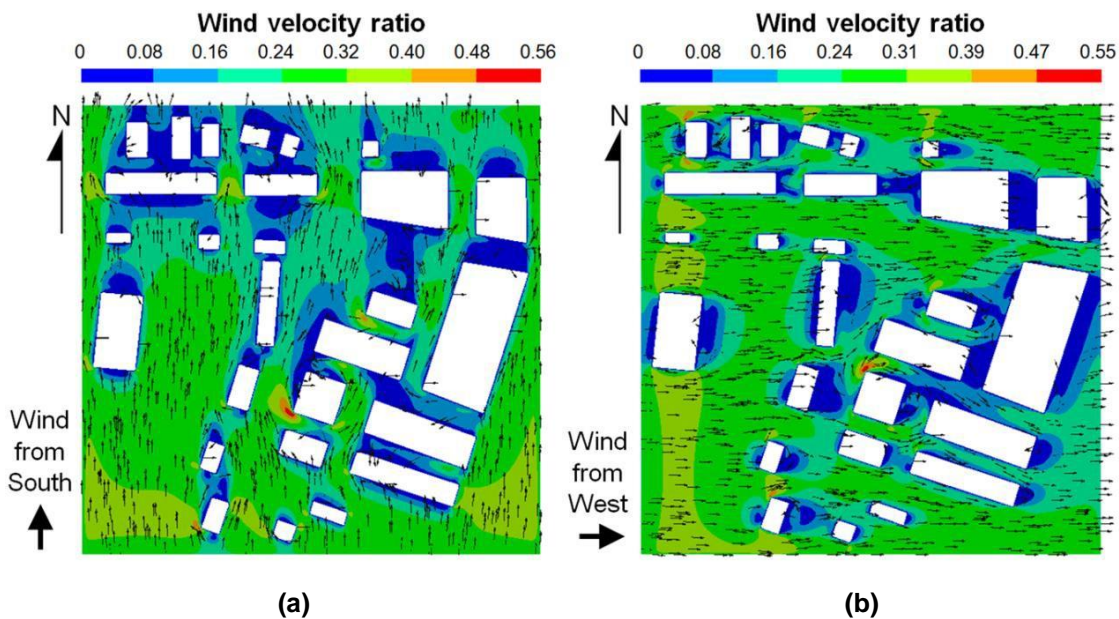


(a)          (b)

**Figure 5: Wind velocity ratio, $VR$ ($V_p/V_{ref}$) at pedestrian-level for built form of Kampung Baru. (a) Wind direction from south. (b) Wind direction from west.**
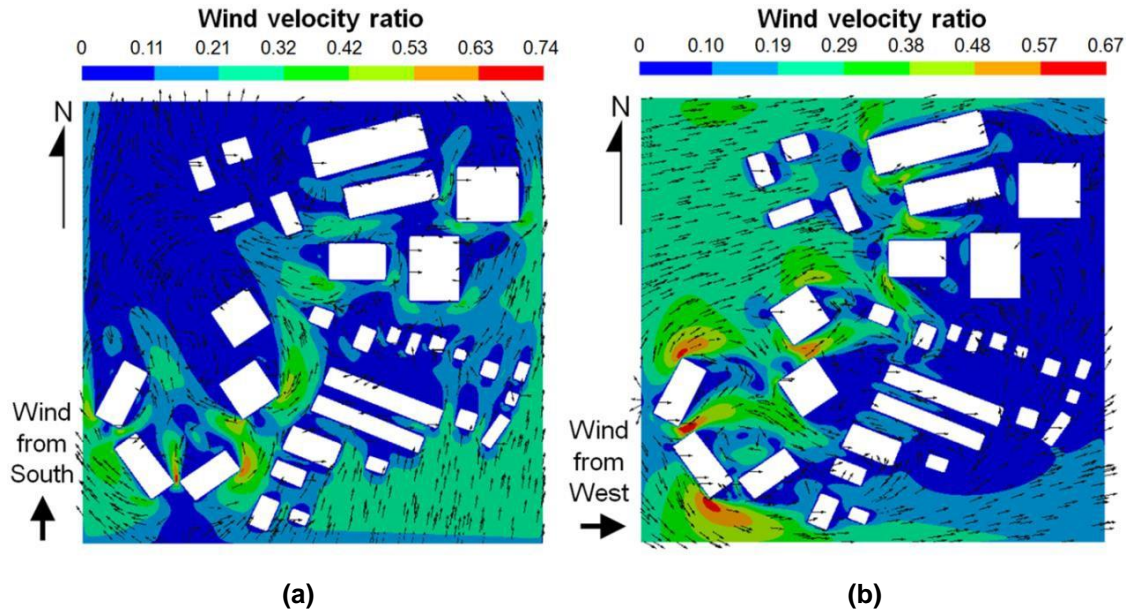
**(a)**                                    **(b)**

**Figure 6: Wind velocity ratio, *VR* ($V_p$/$V_{ref}$) at pedestrian-level for built form of Taman Keramat. (a) Wind direction from south. (b) Wind direction from west.**



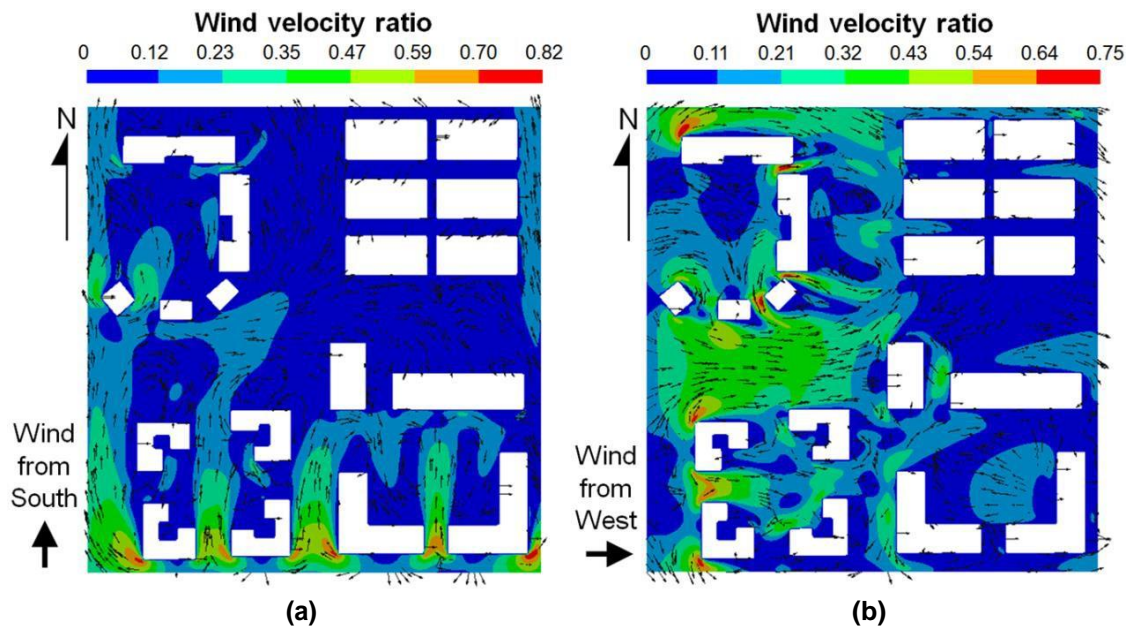**(a)**                                    **(b)**

**Figure 7: Wind velocity ratio, *VR* ($V_p$/$V_{ref}$) at pedestrian-level for built form of Pantai Dalam. (a) Wind direction from south. (b) Wind direction from west.**

Overall, the wind capacity which was captured at the pedestrian-level for the built form of Kuala Lumpur can be considered as critical for urban ventilation based on this analysis since some studies suggested than more wind velocity is needed to provide thermal comfort and to dilute airborne pollutant for urban environment. Ahmed (2003) found that for tropical urban environment at city of Dhaka, Bangladesh, wind velocity significantly increases the upper boundary limit for acceptable relative humidity range,

where the level of humidity for comfort was reported to be improved up to 95% with wind velocity more than 2m/s. Moreover based on field measurement conducted by DePaul and Sheih (1986), they found that the air tends to be stagnated within street canyon for wind velocity below 1.5m/s to 2m/s indicating that pollutants remains within the street and cannot be dispersed.

## Conclusion

This paper investigated influence of built form in urban ventilation assessment of tropical cities with weak wind conditions based on built form of Kuala Lumpur. Six cases with different urban packing density of frontal area ratio, $\lambda_f$ were analyzed utilizing three heterogeneous urban built forms of Kampung Baru, Taman Keramat and Pantai Dalam, with wind direction from south and west. Influence of frontal area of built form that faced on the wind direction was found to be significant in affecting the urban canopy climate as demonstrated from the results, where magnitude of *VR* at pedestrian-level was decreasing as the value of $\lambda_f$ of the built form increases. Therefore, preliminary study on urban design by considering local wind conditions is important especially for major development project to provide good ventilation for hot-humid tropical cities. Optimization on frontal area in buildings design is recommended in order to allow wind to penetrate through the urban built form as much as possible. This can be done by avoiding unnecessary design which can increase the frontal area so that wind blockage can be minimized. As example, large scale of podium structure should be avoided in buildings design to improve wind permeability at pedestrian-level so that air movement can be enhanced and airborne pollutant can be dispersed. Massive projecting obstructions along street canyon which can block the wind flow also should be minimized, such as large horizontal signage and large elevated walkways, particularly for area within narrow street canyon. Moreover, the street canyon can be designed to be functioned as breezeway for better ventilation to let more incoming wind to penetrate into inner parts of urban area, by considering orientation of the canyon to be aligned to the incoming wind direction.

## Acknowledgement

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