and back lane aspect ratio are categorized under urban planning factor and the latter are under building factor. Porch is a typical design element constructed at the front façade with the purposes of solar avoidance, parking and social activities. Its geometries notably modify flow around building and affect the ventilation rate in the terrace house [M. F. Mohamad et al. 2013].These levels are determined based on the ordinary districts of terrace houses in Malaysia.

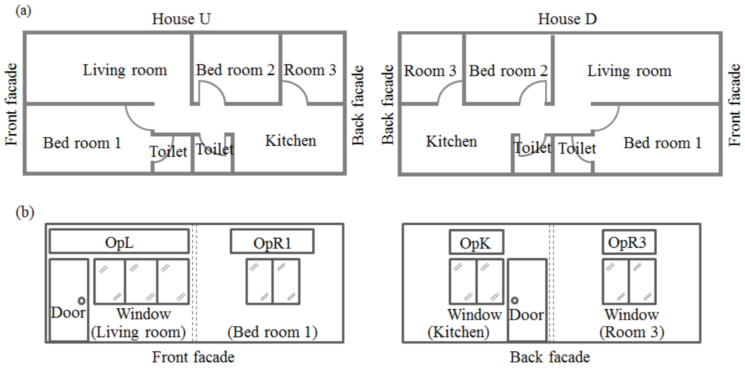

Figure 3. *(a) Room layouts and (b) elevation views of front and back facades of the upwind and downwind houses*

Table 1. *Factors and the levels for the sensitivity analysis*

Factors	**Levels**				
	L1	L2	L3	L4	L5
Main road aspect ratio, W_f / H	5	6	7		
Back lane aspect ratio, W_b / H	1	2	3		
Roof design	Flat	Pitch			
Normalized porch length, P/H	0	0.5	1.0	1.5	2.0

🟩 Standard level

Turbulence model

The numerical simulations using Reynolds-averaged Navier-Stokes with realizable k-ε turbulence closure model [Shih T.H et al. 1995] together with continuity equation were performed using an open source software OpenFOAM 2.1 by assuming that the flow is incompressible, steady state, turbulent and isothermal conditions. The SIMPLE algorithm is employed for pressure-velocity coupling in the governing equations. Each simulation converged after the scaled residuals reached the minimum value of 10^{-5}.

Sensitivity analysis of domain size effect

Prior to the main calculation, a preliminary sensitivity analysis is performed in order to evaluate the effect of domain size on the ventilation flow rates of the buildings. The calculations were carried out for all the 30 cases of the combination of 5 different conditions of the normalized porch length and 6 types of the domain height from *4.8Htop* to *8Htop*. The three factors, front road aspect ratio, back lane aspect ratio, and roof design are fixed at level L2 shown in *Table 1*. The domain length and width are remained fixed.

Figure 4 shows the calculated ventilation flow rate, *Q* of upwind and downwind houses normalized by reference ventilation flow rate, *Qref =A*Uref* based on *Uref* at height of *4Htop.A* is defined as the total opening area at the front façade. Several previous papers suggested that the criteria of the height of the upper boundary of the computational domain should be at least 5 times from building height to prevent the effect of domain size on the simulations result [Tominaga et al. 2008]. The flow rate decreases as the porch length increase in the upwind building but the effect is less significant in downwind building as shown in *Figure 4 (a)* and *(b)* respectively. The results of domain heights *4.8Htop* and *5Htop* at *P/H=1.0* and *2.0* show a significant discrepancies compared to other domain heights for both upwind and downwind buildings. From the result of the simulated cases domain height of *6Htop* seems acceptable minimum height to quantify the effect of porch length on the ventilation late of houses. Therefore, in the following analysis, we apply domain height of *7.2Htop*.

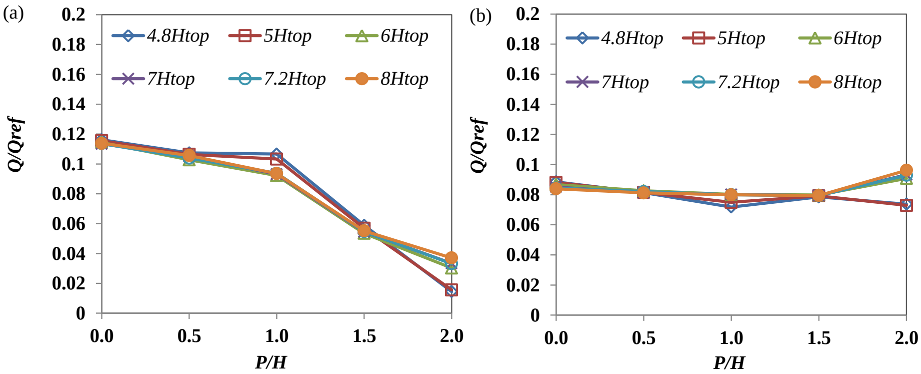

Figure 4. *Normalized ventilation flow rates in domain size sensitivity analysis for (a) upwind building (b) downwind building*

RESULTS

Impact of porch on the flow field around houses

Figure 5 shows the velocity field (normalized by the *Uref*) in the vertical center plane of *OpL* for different conditions of porch length and roof shape. In case of typical two dimensional urban canopy, namely flat roof houses with no porch shown in *Figure 5 (a)*, a wake interference flow regime is observed with the downward flow of the eddy is reinforced by the deflection down by the downstream building façade [T.R. Oke 1988] with dominant vortex center located at x/H=-3.0 and weak secondary vortex is observed at the lower half of building height near upstream building wall.

In contrast to this typical 2D canopy flow, the flow field around flat roof houses with porch shown in *Figure 5(b)* indicates the main vortex being closer to the downstream building façade with the vortex center positioned at x/H=-1.4 and no secondary vortex appears. It might be caused by the fact that the porch at the downstream building enforces downward flow at the porch edge as the airflow enters the area under the porch. It is noteworthy that even though the volume of a porch is much smaller than that of buildings, the flow regime inside the canopy is remarkably different from the well-known 2D urban canopy.

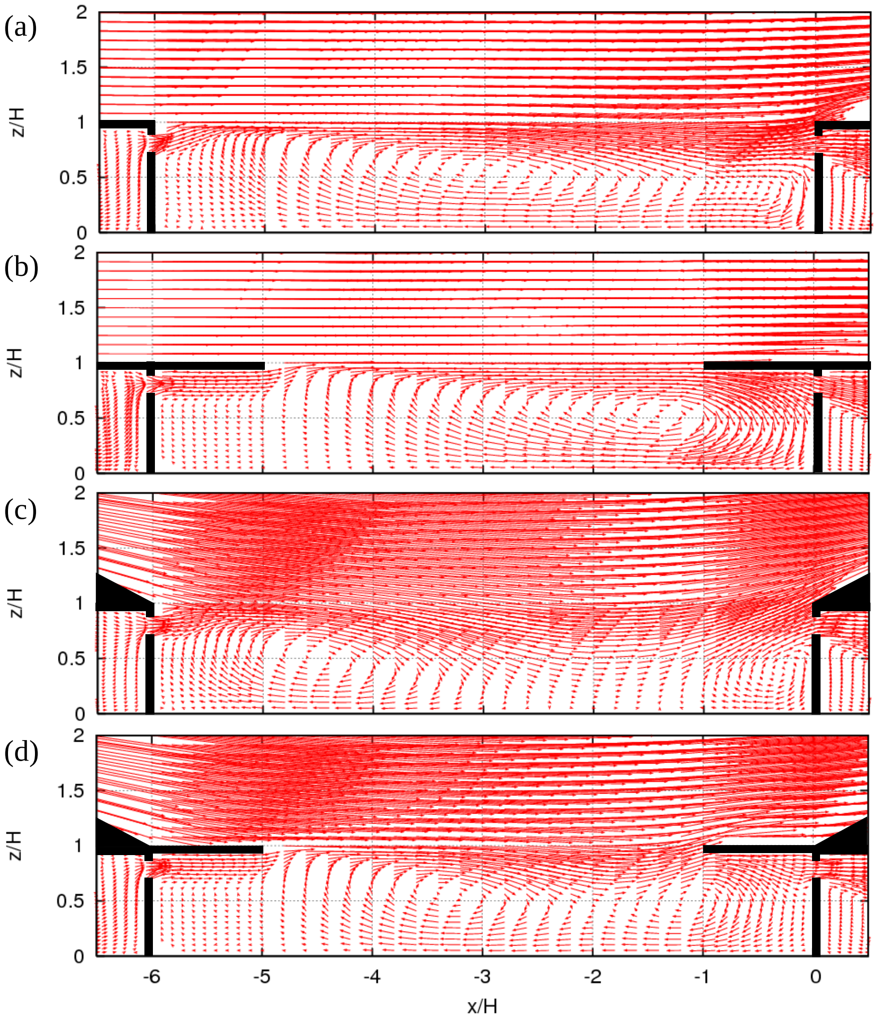

Figure 5. Velocity fields in the canopy of the main road (a) *P/H=0*, flat roof (b) *P/H=1*, flat roof, (c) *P/H=0*, pitch roof (d) *P/H=1.0*, pitch roof for *Wf/H=6*, *Wb/H=2*

In case of pitch roof buildings with no porch (see *Figure 5(c)*), strong downward flow skims over the slope of the pitched roof of the upwind building and reaches to the inside of the canopy, thus, develops significantly different flow features compared to the flow in the canopy of flat roof buildings . A dominant vortex is developed in front of upwind building façade with the vortex center located at *x/H=-4.5*. Furthermore, a secondary vortex is also observed at the vicinity of the downwind building façade. Strong downward flow skims over the pitch roof and entrains the outward flow from the upwind building opening into the canyon. Some of the flow is deflected at the canyon center resulting in the re-circulating flow and some recovers its upwind motion before reaching the downwind building. At the downstream building façade, the flow below the opening flowed downward along the façade caused to the development of secondary vortex as mentioned above. The same features with more bigger recirculation region develops clearly as the flow enters the porch area as shown in *Figure 5(d)* with two vortices are clearly developed within the canyon as the effect of porch existence. The vortex center is shifted to the remote position from the building façade.

Figure 6 shows the normalized ventilation flow rate, *Q/Qref* for all simulated cases comprise the 4 factors shown in *Table 1*. For both type of roof designs (pitch roof results not shown), in the case of no porch condition (*P/H*=0), highest ventilation rate is observed in the *House U* among all 3 main road spacing conditions. In addition, the ventilation rate in the *House U* decreases almost linearly as the porch length increases except for the large reduction from *P/H*=0 to *P/H*=1 as shown in *Figure 6(c)*. Wider spacing between buildings reduces the interaction of the flow around each building and enhances the introduction of upper air to the canopy layer. However, the present of porches at both front building facades have restricted the area of penetration for upper air into the cavity and reduce the velocity of the canopy layer. In such weak condition the ventilation reduction due to the increase of porch length is not significant. It is clearly depicted that ventilation rate in the *House U* strongly depends on the porch length and less dependent on the back lane spacing. For the *House D*, the adverse effect clearly observed as the ventilation rate almost constant despite the porch length is increased. The back lane aspect ratio, *Wb/H* plays important role influencing the ventilation rate in *House D* as the wider spacing allows penetration on the bulk flow into the canyon, hence, increasing the ventilation flow rate.

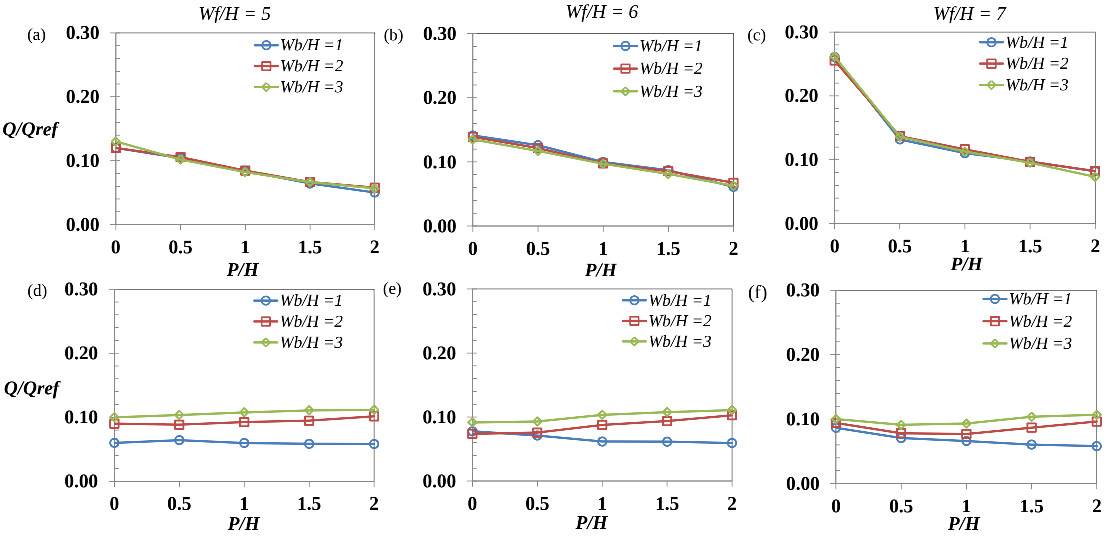

Figure 6. *Normalized ventilation flow rate (a)(b)(c) upwind buildings and (d)(e)(f) downwind buildings for different front road aspect ratios, Wf/H =5, 6 and 7 with flat roof type*

CONCLUSION

Computational Fluid Dynamics (CFD) technique has been applied to systematically investigate the characteristics of the wind-induced natural ventilation of typical terrace houses in Malaysia. A sensitivity analysis has been conducted to evaluate the effect of a porch as well as other external design factors such as front road aspect ratio, back lane aspect ratio, and roof design on the natural ventilation performance. In the upwind building, the ventilation rate strongly depends on the normalized porch length, *P/H* which modifies the position of the standing vortex developed in front of the building facade. The increase of normalized porch length decreases the ventilation rate. However, in the downwind building less effect of porch length is observed. Since the flow enters downwind building through openings located at the back façade, hence, the back lane aspect ratio, *Wb/H* plays a significant effect on the ventilation rate. In addition, flow characteristics within the canyon between buildings with a porch are visualized. Although the porch itself has small volume compared to the buildings, it modifies the in-canyon flow significantly and affects the ventilation performance of the buildings.

REFERENCE

Malaysia. 2011. Population and Housing Census, *Malaysia 2010 (2010 Census)*

T. Kubota, S. Jeong, D.H.C. Toe, D.R. Ossen. 2011. Energy consumption and air-conditioning usage in residential buildings of Malaysia, *Journal of International Development and Cooperation,* Vol.17, No. 3, pp. 61-69.

T. Kubota. 2006. Usage of air-conditioners and windows in residential areas in Johor Bahru city: Planning methods of coastal residential areas in consideration of wind flow, *The 7th International Seminar on Sustainable Environment & Architecture*, pp. 1-10.

Malaysia. 2006. Uniform Building by-Laws.

M.F. Mohamad, A. Hagishima, J. Tanimoto, N. Ikegaya, A.R. Omar. 2013. Wind-induced natural ventilation in typical single storey terraced houses in Malaysia, *Proceedings of 13th Conference of International Building Performance Simulation Association*, pp. 587-593.

Shih T.H, Liou W.W, Shabbir A, Yang Z, Zhu J. 1995. A new $k - \varepsilon$ eddy viscosity model for high Reynolds number turbulent flows, *Computers and Fluids*, 24, pp.227-238.

Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, and T. Shirasawa. 2008. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 96, pp. 1749-1761.

T. R. Oke. 1988. Street design and urban canopy layer climate, *Energy and Buildings*, 11, pp. 103-113.