WIND-INDUCED NATURAL VENTILATION IN TYPICAL SINGLE STOREY TERRACED HOUSES IN MALAYSIA

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ABSTRACT

Natural ventilation in buildings is a well known strategy for energy saving to ensure occupant's thermal comfort without any energy consumption and influence on global warming. In the present study, airflow inside and around two types of terraced house model, one with a porch and another without a porch, have been numerically simulated using Reynolds-averaged Navier-Stokes model to evaluate the effect of a porch on wind-induced ventilation. The results of velocity distribution inside rooms and ventilation rates of openings revealed that the porch has a significant effect on the flow field modification, resulting in the better ventilation rate of the building.

INTRODUCTION

Natural ventilation consists of two parts namely wind-driven natural ventilation and buoyancy effect (stack ventilation) in which no mechanical forces are required to replace room air with the fresh external air through openings for better thermal comfort and satisfy indoor air quality. This technique has repeatedly attracted researcher's intention for decades due to the fuel price hikes and global warming issue. In reality, the application of natural ventilation in buildings is a challenging task because of the complex phenomena affected by various factors such as wind velocity, wind direction, temperature difference, opening design (size, shape, and location), building shape, and adjacent building.

Malaysia is one of developing countries with continuous increase of the population resulting in the expanding of energy demand. The total population in the year 2010 was 28.3 million which has increased more than twofold compared to that in the year 1980[Malaysia, Population and Housing Census, Malaysia 2010 (2010 Census), 2011]. The nationwide energy demand of transportation, industrial, residential, commercial, and agriculture sectors also shows an increase of three times over the past two decades [Malaysia, National Energy Balance, 2011].

The residential sector is the third largest contributor to the electricity consumption in Malaysia consists of 21.5% from the total electricity consumed in 2010 after industrial (44.4%) and commercial (33.6%) sectors [Malaysia, National Energy Balance, 2011]. And space cooling accounts for the largest portion of the electricity consumption in residential sector with 29% contribution including air-conditioner 17%, fan 10% and other 2% [Kubota, Jeong, Toe, Ossen, 2011]. Therefore, development of climate-responsive design of Malaysian residence houses so-called 'passive design' is strongly needed to achieve both thermal comfort and energy conservation by reducing the usage of air-conditioners.

Countries located in tropical region experience high temperatures and high humidity with a small temperature variance throughout the year, and such climate condition sometimes causes thermal comfort problem, thus, utilization of mechanical cooling devices leads to higher energy consumption and increase of green gas emission. However, passive design techniques have not been carefully considered and implemented in Malaysian residence houses, most of them are terraced houses influenced by western designs with less consideration of local climate condition. Building materials with large heat capacity such as bricks and concrete are mainly used in the construction of terraced houses which cause large amount of heat storage during day time and the heat is released into living spaces at night time, thus, occupants have to use mechanical cooling devices to remove the heat in order to obtain acceptable thermal comfort level.

Application of natural ventilation strategies to solve thermal comfort problem in Malaysia's terraced houses have been investigated through field measurements and numerical studies based on computational fluid dynamics, and stack effect has been selected as the main focus to induce airflow inside the building [Nugroho, Ahmad, Ossen, 2007] [Mohammad Yusoff, Salleh, Adam, Sapian, Sulaiman, 2010]. A relationship between air-conditioner usage and opening windows has been also extensively investigated to understand occupant's behavior in order to determine the most suitable energy saving strategy to reduce dependency on air-conditioners [Kubota Ahmad, 2007]. Meanwhile, simulation on the effect of an internal courtyard showed the improvement of natural ventilation and thermal conditions of the surrounding spaces if openings as well as shading devices are adequately and efficiently designed. [Sadafi, Salleh, Haw, Jaafar, 2011].

Most researchers have focused on the application of stack ventilation strategy. In contrast, the aim of this study is to present effective wind induced ventilation strategy for Malaysian residence houses, thus, a typical one-storey terraced house with and without a porch are adopted for the numerical simulation to understand the effect of a porch on ventilation efficiency especially in a living room and a bed room. Detailed information on air flow inside rooms are also provided.

SIMULATION SETTING

Building models

Seven cases with actual size of a typical one-story terraced house with a flat roof constructed in Malaysia are adopted for the simulation target. Figure 1 shows the floor plan of the house, which consists of a living room, 3 bed rooms, a kitchen, and utility space. Each case is named according to the porch geometries (length, L= 3.5 m and width, W= 3 m) as shown in Table 1.

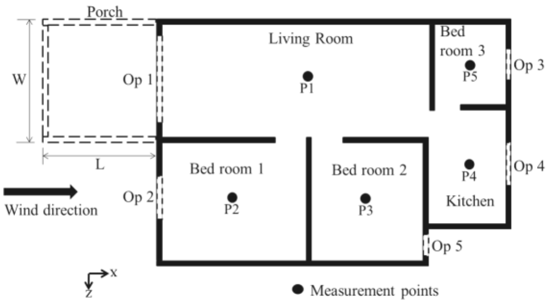


Fig. 1. *Layout plan for terraced house used in the simulations*

The porch is a typical design element that constructed at the front façade of terraced houses for parking and for social purposes as well as avoiding the direct penetration of solar radiation to the building envelope. By comparing the results of the seven cases, we evaluate the effect of the porch on the airflow inside the houses in order to interpret the necessity of porch design for effective wind driven natural ventilation.

Openings are an unobstructed space that constructed at respective rooms purposely to allow free uninterrupted flow of air and area of these openings shall be not less than 5% of such room floor area [Malaysia, Uniform Building by-Laws, 2006]. The center of each opening is located at a height of 2.4 m from the floor with a height of 0.75 m. The width of each opening is varied in order to comply with the area applied in present study, which is 5% from the respective room floor area hereafter Op1, Op2, Op3, Op4 and Op5. Op1 and Op2 positioned at the building front facade work as inlet and Op3, Op4 and Op5 located at the rear of the building work as outlet. Doors with dimensions of 1 m width and 2 m height positioned at each bedroom are kept opened to allow cross ventilation occurs.

Table 1 Simulation cases

Simulation Case	**Porch size (length x width)**
Case NP	No Porch
Case 1L-1W	3.5 m x 3 m
Case 0.5L-1W	1.75 m x 3 m
Case 2L-1W	7 m x 3 m
Case 1L-2W	3.5 m x 6 m
Case 0.5L-2W	1.75 m x 6 m
Case 2L-2W	7 m x 6 m

Governing equations

The simulations were conducted based on Reynolds-averaged Navier Stokes equations (RANS) using standard *k-ε* turbulence closure model. For a steady, incompressible, isothermal and turbulent flow, the continuity equation and RANS equations can be written as:

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) + g_i \tag{2}$$

Two turbulence closure equations for standard *k-ε* are as below:

$$\frac{\partial k}{\partial t} + \overline{u_j}\frac{\partial k}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \frac{G_k}{\rho} - \varepsilon \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + \overline{u_j}\frac{\partial \varepsilon}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{1}{\rho}C_{\varepsilon 1}G_k\frac{\varepsilon}{k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

Where, u_j is the velocity of j-component, t is the time, x_j is the j coordinate, ρ is the air density, μ is the dynamic viscosity and g_i is the gravitational body force. Reynolds stress term can be express as below:

$$-\overline{u_i' u_j'} = \frac{1}{\rho}\mu_t\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}$$

$\mu_t = \rho C_\mu k^2/\varepsilon$ is the turbulent viscosity and G_k is the turbulent kinetic energy production. σ_k, σ_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ and C_μ are the coefficients of standard k-ε model and the values are generally fixed at 1.0, 1.3, 1.44, 1.92 and 0.09 respectively. Open source software OpenFOAM (Open Field Operation and Manipulation) has been used to solve the governing equations at each grid of the computational domain.

Computational domain and boundary conditions

Figure 2 shows the computational domain we used. In each simulation, inlet, outlet and lateral boundaries are treated as periodic condition, and the top boundary of the domain is treated as free-slip condition. In contrast, non slip condition is applied on the bottom boundary and surfaces of building structure. The initial horizontal velocity in the x-direction is set at 5 m/s for all cases which is constant with respect to the height. Wind direction is perpendicular to the front façade in all simulation cases.

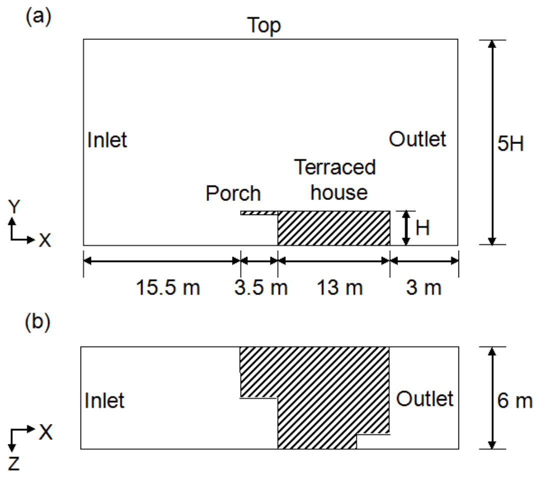


***Fig. 2.** Dimensions of the computational domain (a) sectional view (b) plan view*

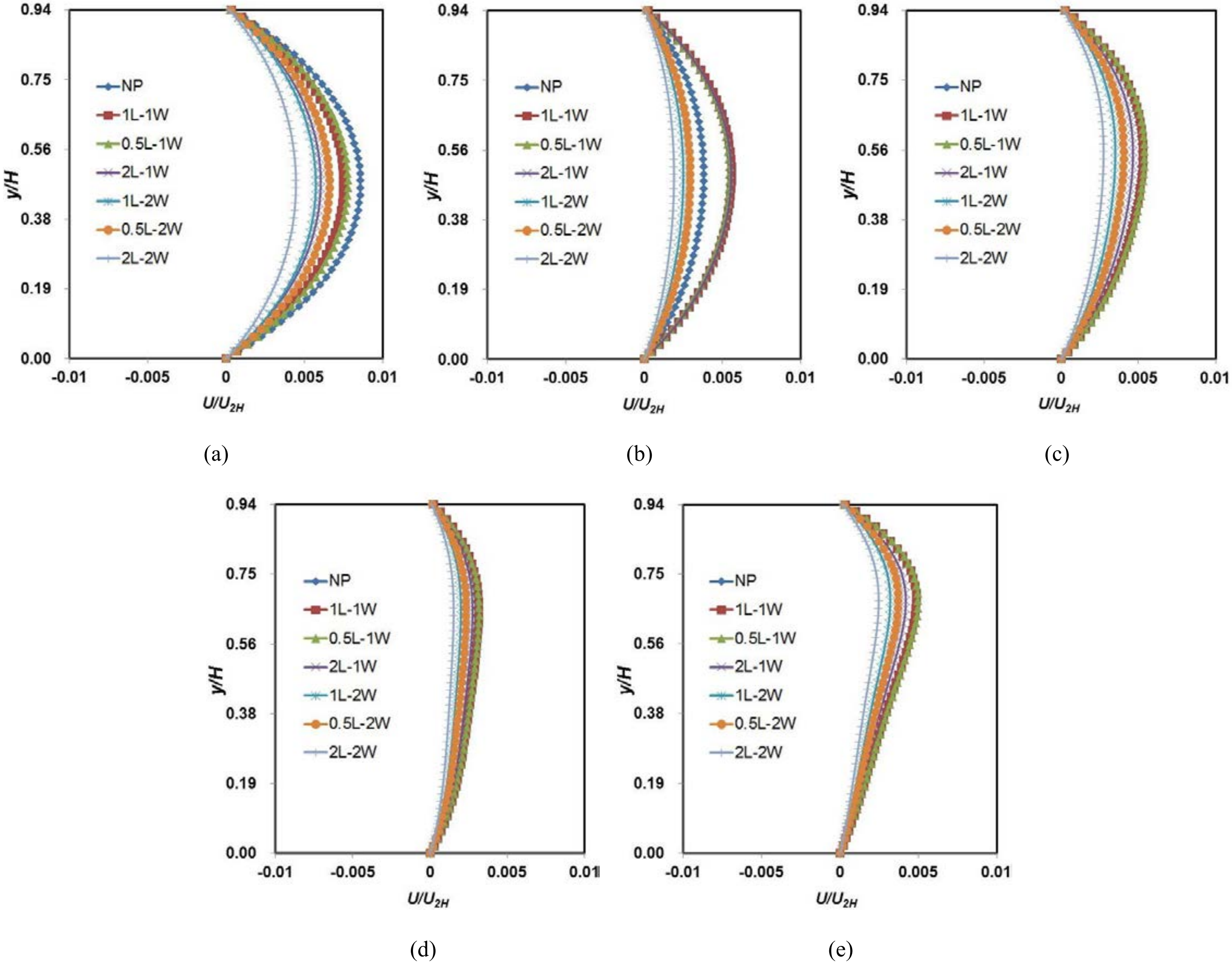
RESULTS AND DISCUSSION

We investigated the simulation results of velocity profile on a central position of each room shown in Fig. 1.

Figure 3 shows vertical distributions of velocity component U for each case. The horizontal axis refers to the velocity normalized by the value at a height of $2H$, U/U_{2H}, and the vertical axis refers to the height from the floor normalized by building height, y/H. It can be depicted that the velocity component U in the building is obviously very small compared to the outside free stream air velocity. Identical trends of air velocity distributions can be observed in each room in the building. In terms of the velocity of living room, the highest value is observed in the no porch (NP) case, in contrast, largest porch case 2L-2W shows the lowest. Contrastingly, in Fig. 3(b) for velocity distributions in the bed room 1 the highest velocity are observed in cases 1L-1W and 0.5L-1W not in the case with no porch, though case 2L-2W (largest porch) still shows the lowest value. These results indicate that the existence of the porch and its dimension significantly modify the incoming flow and affect the velocity distributions inside the building envelope. The velocity is attenuated as the flow travels far from the openings 1 and 2 as depicted in Fig. 3 (c) ~ (e). Even though the internal flow velocity is comparatively small to the free stream, the velocity distribution differs from line to line which show that the flow at the central areas are not stagnant. It implies that the purpose of ventilation is partially achieved.

Fig. 4 (a) ~ (c) compare the cross sectional views of the wind vectors on mid-plane of the opening 1 in order to investigate the flow patterns around the building for cases of NP, 0.5L-1W and 2L-2W. The air flow approaches from left to the right. In case of NP, the velocity at the opening height is relatively higher compared to the other cases. Recirculation is observed at the lower part of the building near the wall which is attributed partially to the flow bouncing back at the wall. For the cases of 0.5L-1W and 2L-2W, the flow is separated at the porch edge, resulting in the development of swirls just in front of the porch before the flow enters the porch area. The flow then attenuated below the porch area due to shear effects induced by the porch ceiling and the floor which causes the weak air velocity approaching to the opening 1, hence, weak flow velocity in the building envelope is observed.

Fig. 5 shows the lateral view of wind velocity vectors for two different heights, 2.4 m (opening center) and 1.5 m height from the floor. Both axes show the horizontal and lateral distance normalized by the building height respectively. Airflow enters the building envelope through openings 1 and 2 and flow out through openings 3, 4 and 5. The air flow velocity near the opening inside the living room at a height of 2.4m of the cases of NP and 0.5L-1W show high velocity approaching into the interior space, however, low velocity were depicted in the case of 2L-2W for both the living room and the bed room 1 respectively. Air flow velocity enters the bedroom 1 of case 0.5L-1W is slightly higher than that of case NP, and it may be due to the existence of porch that modifies the approaching flow resulting in higher velocity entering opening 2. At a height of 1.5 m from the room floor, the case 2L-2W shows low velocity for both horizontal and lateral directions.



(a)

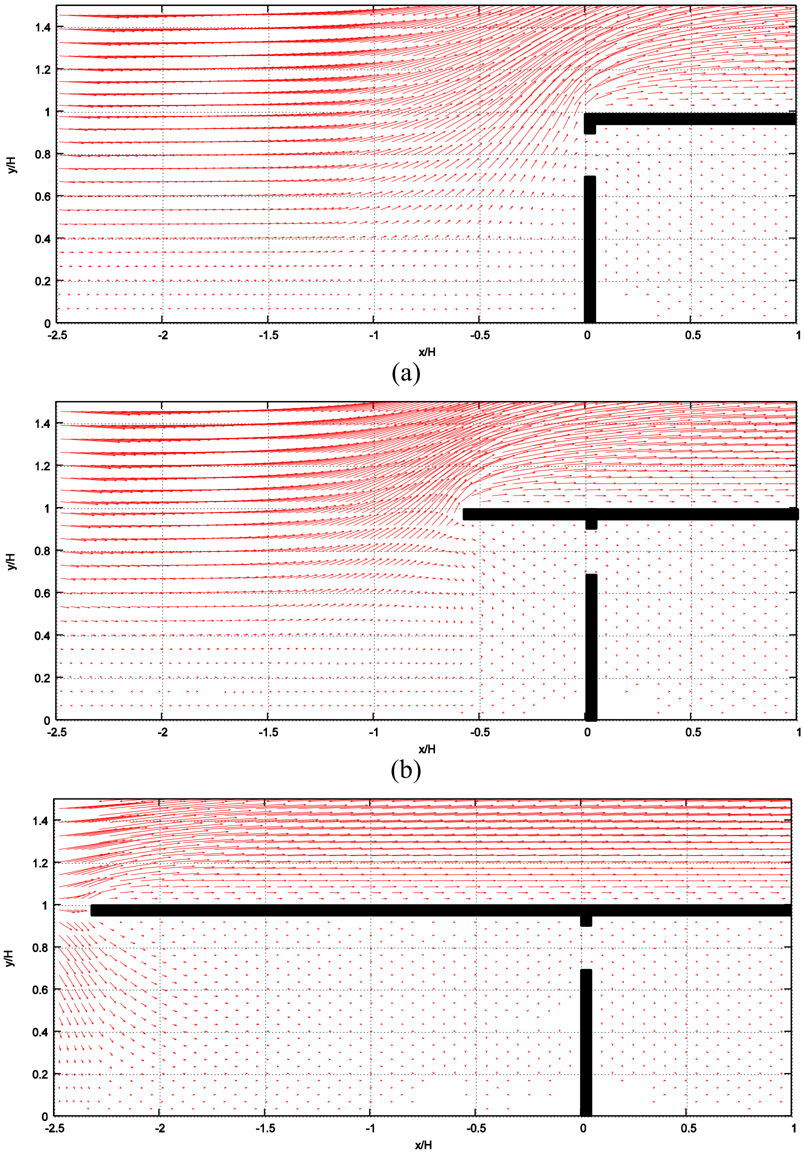
(b)

(c)

(d)

(e)

Fig. 3. *Velocity profiles at (a) living room (b) bed room 1 (c) bed room 2 (d) bed room 3 (e) kitchen for each case*



(a)

(b)

(c)

Fig. 4. *Vertical section view of wind vectors for (a) NP (b) 0.5L-1W (c) 2L-2W*

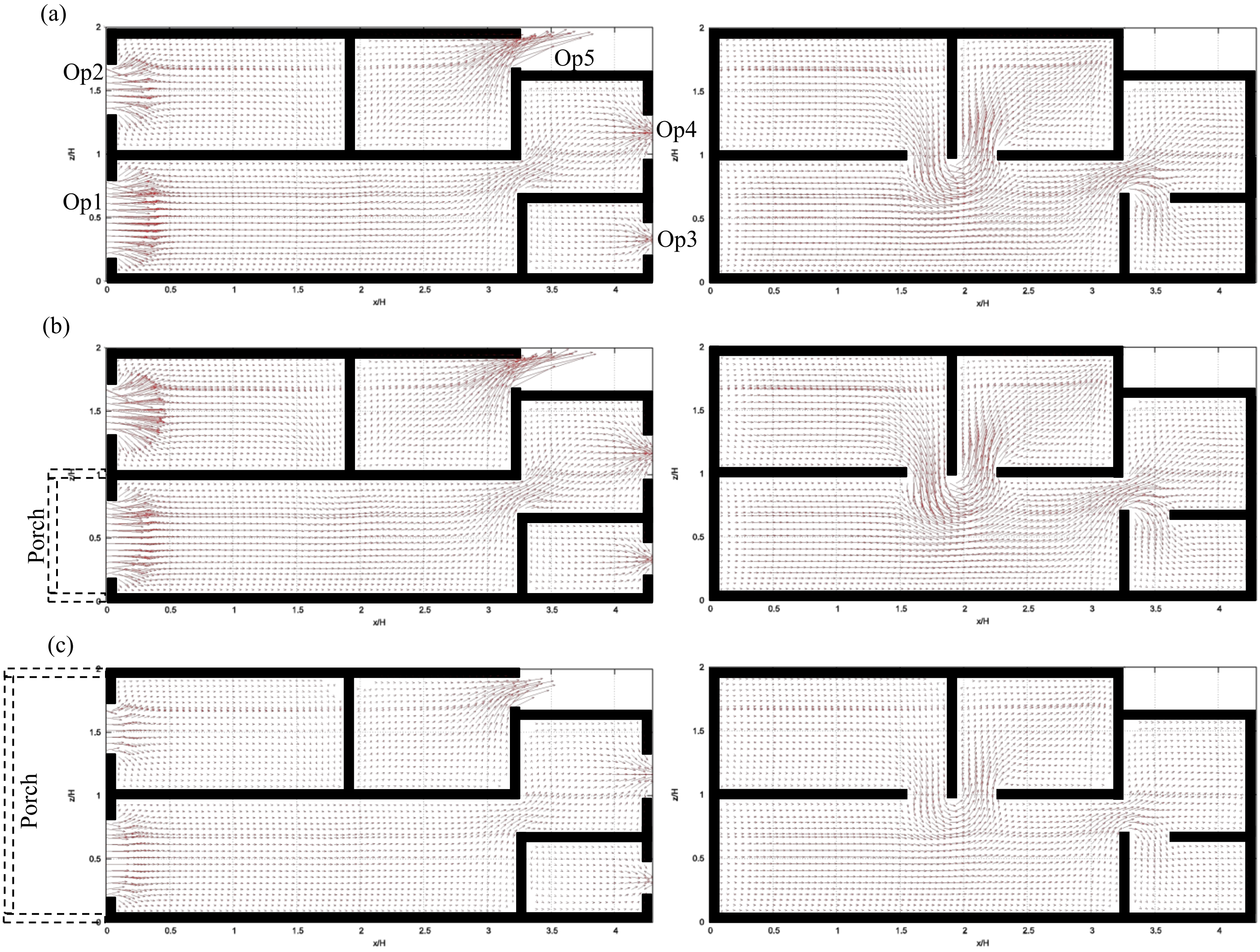
Significant value of lateral direction velocity can be observed in both cases NP and 0.5L-1W especially at door when the flow changes its direction due to the disturbance induced by the room's wall. At the distance far from the openings 1 and 2 (i.e. bed room 3 and kitchen) the velocity is attenuated and become nearly uniform.

Generally speaking, passive design related with wind driven natural ventilation fully depends on the ambient conditions, thus, the building design is necessary to response the unsteady fluctuation of the wind velocity, direction, air temperature and humidity. Based on this fact, the present study predicts the effect of various building designs to the flow rate through building envelope.

Table 2 shows the comparison of the ventilation rate measured at Op1, Op2 and the total ventilation rate for all cases. It is clear that ventilation rate at Op1 of case NP is the highest compared to the other cases due to the high velocity approaching towards opening 1, however, different conclusion can be depicted at opening 2 which cases 1L-1W, 0.5L-1W and 2L-1W show higher values compared to case NP. For both openings, case 2L-2W shows the lowest values and in total, case 0.5L-1W gives the highest ventilation rate. According to this result, external air flow approaches to windward wall of the terraced house with a porch is supposed to be significantly modified at the porch edge before entering Op1 and Op2. As it is expected, the approaching wind speed towards opening has significant effect on the internal flow characteristics as well as ventilation.

CONCLUSION

In the present study, wind induced natural ventilation through a typical terraced houses is investigated by using Reynolds averaged Navier-Stokes equations of standard two-equation *k-ε*



Height = 2.4 m (center of opening)

Height = 1.5 m

Fig. 5. *Velocity vector for plan view for (a) NP (b) 0.5L-1W and (c) 2L-2W cases for different heights*

Table 2
Flow rates in each terraced house (m^3/s)

Simulation Cases	**Op1**	**Op2**	**Total**
No Porch (NP)	0.059	0.025	0.084
1L-1W	0.047	0.037	0.084
0.5L-1W	0.050	0.036	0.086
2L-1W	0.036	0.037	0.073
1L-2W	0.040	0.017	0.057
0.5L-2W	0.046	0.020	0.066
2L-2W	0.031	0.013	0.044

turbulence model. The simulation focuses on the flow fields inside and around a single-storey terraced house under seven conditions with different porch sizes. The velocity distributions inside rooms and windward location of the house as well as ventilation rate through openings were determined. Openings placed at a windward wall and a leeward wall work as inlet and outlet, respectively. Velocity approaches to the openings covered by the porch is attenuated by the shear effect induced by the porch ceiling and the floor resulting in the weak air velocity. In cases with a porch with a width of half of the frontage of the house (i.e. cases 1L-1W, 0.5L-1W and 2L-1W), however, the inlet flow for the opening uncovered by the porch is accelerated due to the effect of flow contraction, and show the larger ventilation rate compared to the case with no porch. The present finding shows some types of porches are possible to either enhance or attenuate wind-induced ventilation according to the size and relative position between a porch and an opening, and suggests the importance of careful design.

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