The Effects of a Trombe Wall on the Ground Floor Ventilation of Row House

Chhorvy Khat*[1], Angunthip Srisuwan*, Yottana Khunatorn[+]

Abstract

This work studies about the application of passive design by a Trombe wall system to enhance indoor ventilation of Phnom Penh row houses. The system is designed to be installed next to a stair block wall on the top floor of a row house which faces south or west. The current work is investigating the effect of Trombe wall on ground floor facilities compare with the existing design without Trombe wall. CFD program is used as a processing tool. The results indicate that even the Trombe wall system is recommended to enhance indoor ventilation, the side of the system, the distance from the Trombe wall to a target room, the volume of a target room, and the ambient weather are relevant to achieved results. For all cases, the approximate air velocity got at the living room is in an average from 0.12 m/s to 0.16 m/s. At the same time, hot air is brought in by the blowing wind, results in the increase of room temperature around 2°C in the living room, and mostly no effect in a kitchen. Within these ranges of temperature and air velocity, the limited scale of the Trombe wall would not reach comfort standards.

Keywords: CFD program, indoor ventilation, Phnom Penh row house, Trombe wall

1 Corresponding author; Tel: + 66 94 603 0633; +855 77 883 223 E-mail: khatchhorvy@gmail.com

* Department of Architecture, Faculty of Architecture, Chiang Mai University, Chiang Mai 50200, Thailand.

\+ Department of Mechanical Engineering, Faculty of Engineer, Chiang Mai University, Chiang Mai 50200, Thailand

1. Introduction

Row houses has played a major role in the demand of a reasonable housing market in Phnom Penh, the capital city of Cambodia. According to the report published by the department of Planning of Phnom Penh in 2008, 38% of all houses surveyed were row houses (Department of Planning, 2008). The estimation on the increasing numbers of row houses are still in high amount until now and in the future (Municipalité de Phnom Penh, Malrie de Paris, Atelier parisien d'urbanisme, avec le soutien du ministère des Affaires étrangère et eruopéennes de la République francaise, 2009). With this amount, the consideration of comfort living in this kind of house is an essential issue. Gneabheang Lay (Lay, 2013) have done a whole day survey of the air velocity at a ground floor area and other parts inside the row house, showed that there were slightly impact of an outdoor wind velocity to an indoor wind flow, because of the wind direction was not parallel to a house's apertures direction. The survey exposed that the indoor air speed is still less than 0.08m/s in living room area, even the outdoor speed had gained from 1 m/s to 3.5 m/s. The temperature is only 2-3 degree Celsius lower than the ambient temperature which was around 29-33°C. The indoor humidity was very high due to the survey season, thus took longer time to drop though the outdoor humid had already descended. Compared with ASHRAE standard of comfort zone (ASHRAE-55, 2004), which 0.2 m/s to 0.8 m/s of indoor velocity and 23.5°C to 27.0°C temperature is needed, the environment in the house which got from the survey could be explained as a poor comfort standard zone which could lead to insufficient fresh air respiration, chemical microbe and particle growth (SCHER, 2007).

Due to the problems as mentioned, attentions in bringing the fresh air ventilation into the house is a vital factor to meet occupants comfort. Although mechanical and electrical devices could assist comfort for occupiers, the encouragement to apply passive design could reduce the energy assumption and best use from local climate. In the case of wind effect cannot well captured into the house, solar induce ventilation is a good alternative choice. Many researchers gave notions about the good effect of using the advance stack effect by a Trombe wall or a solar chimney to induce ventilation. There are various techniques trying to develop on this advance stack effect to seek for best performance of the system (K. S. C. L. N. A. M. S. Omidreza Saadatian, 2012) such as a zigzag Trombe wall, a water Trombe wall, a solar hybrid wall, a composite Trombe wall, fluidized Trombe wall, and Photovoltaic Trombe wall. All techniques gave both advantages and disadvantages. Moreover, Tengfei Zhang et al. (Y. Z. S. W. Tengfei (Tim) Zhang, 2014) researched on the prediction of airflow rates through the channel by using a two-wall module. J. Hirunlabh (W. K. P. N. J. K. J. Hirunlabh, 1999) took a test on a metabolic solar wall separated with a gap from the glazing panel. The scheme could produce highest air mass flow rates of about 1.01-0.02 Kg/s with 2 m² surface area. Eduardo Krüger et al. (E. S. A. M. Eduardo Krüger, 2013) led test cells using walls and glasses to evaluate the Trombe wall system in a sub-tropic region. The system yielded a high potential in reducing energy consumption for cooling and heating an indoor space of about 30% a year. Others proposed a glass solar chimney wall compare to a single layer glass wall to apply in a tropic region (Ratanachotinun & Pairojn, 2014). The result was found the glass solar chimney had created a lower indoor temperature than one layer glass wall as an average difference in temperature of 2.46-1.80°C, 1.63-1.30°C and 1.36-1.28°C for winter, rainy season, and summer season respectively. Agung N. (M. H. A. T. J. H. Agung Murti Nugroho, 2006) conducted a research to find out the effect of solar chimney geometry for stack induced ventilation strategies which worked the same way as trombe wall. The system could induce the wind velocity up to 0.6 m/s. The study gave the assumption that the use of the solar chimney provided a better indoor ventilation than a non-chimney terrace house in Malaysia. Moreover, some studies investigated the combination of a roof solar collector and a vertical chimney (Wardah Fatimah Mohammad Yusoff, Elias Salleh, Nor Mariah Adam, Abdul Razak Sapian, 2010). The well-known materials of the Trombe wall study are glasses and walls. The wall is normally painted black to be able to store more heat from sun radiation. However, the advance technique also testing on a Photovoltaic (PV) Trombe wall (Kashif Irshada et al., 2014; Ji Jie et al., 2007) . The study revealed that this kind of materials could generate electricity in a range (Ji J, Yi H, He W, Pei G, 2007) but obstruct solar rays to penetrate to the mass wall (Sun W, Ji J, Luo C, He W, 2011). Therefore, in the case of Phnom Penh row houses, the typical glazing Trombe wall should be prior in experiment since this kind of system would not cost much in new buildings and in renovating the existing houses. If this kind of the stake renovated-effect gave satisfy results, it will be seen that those experiments are tested by small-chamber models (Y. Z. S. W. Tengfei (Tim) Zhang, 2014), or used to apply a in target room at the same level of the system or with the floor below the system (K. J. F. K. Milorad Boji´c, 2014; Punyasompun, Hirunlabh, Khedari & Zeghmati, 2009; M. H. A. T. J. H. Agung Murti Nugroho, 2006). The target area which should be first concerned in context of this study is the ground floor plan since these amenities are frequently used more by all members of the family during daytime.

This paper presents an investigation on the effects of Trombe wall on the ground floor facilities of the house. According to the available space to install the Trombe wall and the distance from the Trombe wall to the target area, it is hypothesized that the Trombe wall may or may not influence on the vent flow from the ground floor. Therefore, this research attempts to focus on the impact of the Trombe wall performance to improve stack ventilation and comfort in the house by the comparison of a house model with and without the Trombe wall design. By using the computational fluid dynamic (CFD) program, the consequence could be shown by air flow rates, temperature in specific rooms and outlets, and mass flow rates on which the system could achieve. Meanwhile many scholar articles have proofed the reliability of CFD simulation compared with mathematic theories and real experiments (Gan, 1998; Nitawichit, 2008), so that this program is validated to handle these pilot cases simulation. XFlow CFD program is a new generation of the CFD program which uses Particle-based kinetic algorithm that resolves the Boltzmann and the compressible Navier-Stokes equations (Next Limit, 2014).

2. Methodology

The pilot case models are followed a common model of a Phnom Penh row house which has a dimension of 4.2 m. width and 16 m. length. There are 3 floors linked together by a U-shape stair block that ends up with an opening of cement grills at the top of a stair chamber [Figure1]. The ground floor consists of a living room, and a kitchen with a small toilet. There is also a mezzanine floor with two small bedrooms. First floor could provide two bedrooms separated by the stair block. Thus the second floor exists only a stair block chamber with grill-cement block; and the front of the top floor is decorated with a small triangle roof covering the plain terrace floor. Figure 2 shows an input model to the experiments designed with the Trombe wall. The ratio of the channel gap and the wall height is 0.05, following by the experiment of Phanuphong T. (2006). The inlet and outlet height of the Trombe wall is set equally the channel gap which followed the proportion of the study of Gan (1998). Due to the pilot case, with wall height of 2.4 m. for Trombe wall system, gotten gap of channel was 0.12 m. width. In addition, Figure 3 presents a typical house model with an existing opening on the top of the stair chamber. None relevant elements are cut out to increase the simulation speed. In the drawing, the grills are taken out and maintained only the same hole size for the purpose of reducing the geometry elements and to better see the flow. All openings of the study case are closed except the front door and the aperture over the door which are assumed as inlets. Besides, the opening on the top of the stair chamber and the outlet of Trombe wall are counted as flow outlets. Other openings are closed so as to examine the real capacity of the mentioned outlets.

Figure 1, The opening on top stair chamber of typical house

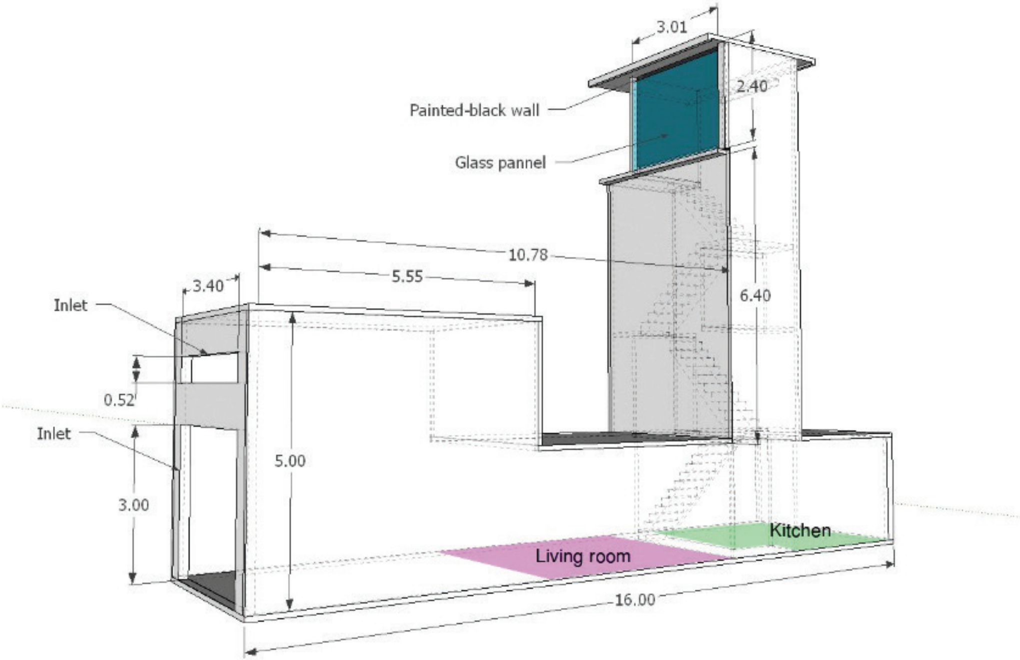

Figure 2, 3D modeling showing the location of Trombe wall (m.)

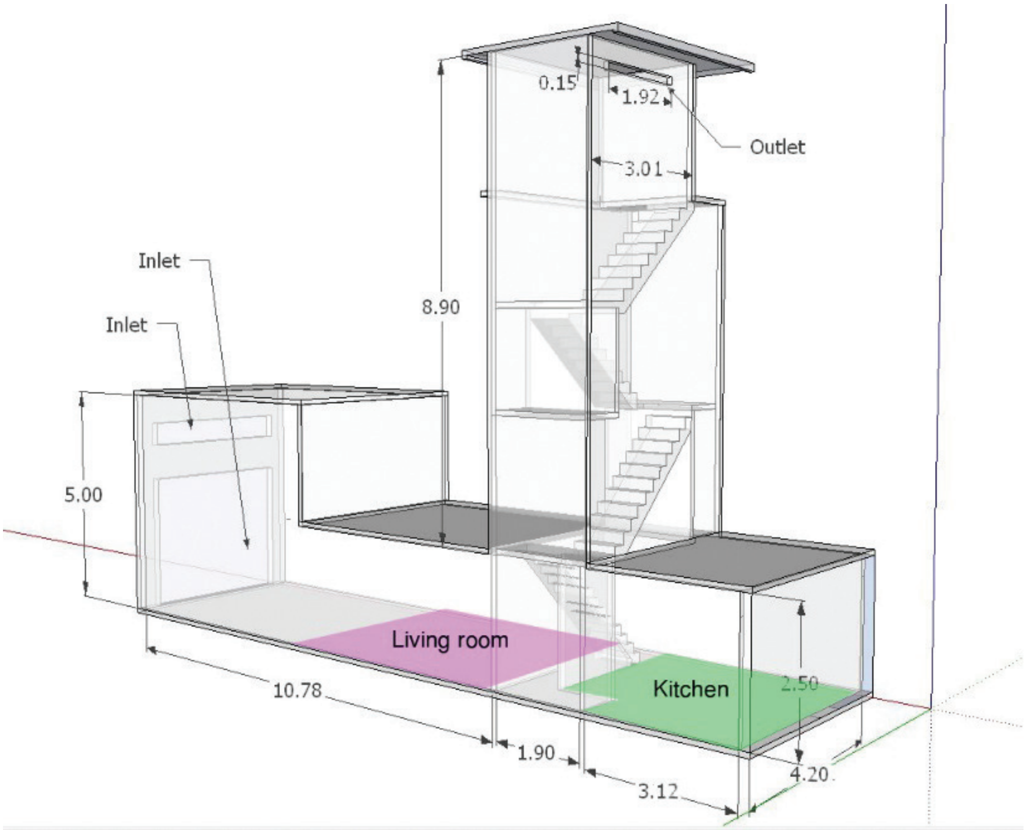

Figure 3, 3D modeling of an existing house with its outlet (m.)

This study is carried out five experiments a typical house with an existing opening without Trombe wall (NTW); a whole house designed with the Trombe wall by heat flux 200W/m² (TW200W/m²) and 1000W/m² (TW1000W/m²); and two other cases which are added temperature on the top ceiling surface and walls of the stair block. One is named as a heated chamber without the Trombe wall (HC-NTW); the other is called a heated chamber with the Trombe wall by heat flux 1000W/m² (HC-TW1000W/m²). In case of the Trombe wall design model, the existing outlet at stair chamber was also blocked like other aperture of the house in order to clearly see the real capacity of the Trombe wall system without any other outlet which could be assumed as leaking point. The temperature on the surfaces of the chamber are added for the purpose of approaching a real situation while non-insulation layers are normally applied, thus the conduction and convection from the sun into the room by the concrete roof and masonry brick wall occur.

Table 1, . Input data for experiments

Input	Unit	Value
Gravity	m/s^2	9.81
Initial temperature (indoor)	K	300.15
Initial wind speed	m/s	0
Operating temperature (ambient)	K	306.15
Glass temp. for heat flux $1000W/m^2$	K	356.35
Glass temp. for heat flux $200W/m^2$	K	325.62
Wall temp. for heat flux $1000W/m^2$	K	334.15
Glass temp. for heat flux $200W/m^2$	K	317.35
Stair chamber ceiling temp.	K	318.15
Inlet pressure	Pa	5
Inlet temperature (effect from ambient temperature)	K	306.15
Outlet		Gauge pressure outlet
Simulation time	s	60

Primary boundary conditions are inputs such as the earth gravity, indoor and outdoor temperature, ambient pressure, wall and glazing temperature. By heat flux inputs, a range of temperature on the internal surfaces of glass and wall is received, according to Phanuphong T. (2006). The temperature is converted from Celsius into Kelvin. To reduce the complexity of the simulation, all surfaces of the domain are considered as isothermal walls and no wall slippery condition is set to the walls which means that the viscosity with wall surfaces was not counted. For the two case studies while the temperature on the top internal surfaces of the stair block are added to be more similar to the real condition, temperature is set by assumption which occurred in around 318.15K as shown in Table 1. Nonetheless, to better see the performance of the scheme an inlet pressure is set 5 Pa. The initial wind speed is neglected because this will affect the performance of the Trombe wall while the main objective is to investigate the real capacity of the Trombe wall during the time without the help of prevailing wind speed. For some real cases, the blowing-in wind cannot be regularly predicted due to house direction or the wind direction. The indoor temperature is set 27°C (ASHRAE-55, 2004), the temperature which starts to give discomfort to occupants without the assistance of blowing wind. Moreover, it is also noted known that from real case, the temperature in the house is not lower than this (Lay, 2013). The outdoor temperature is refered to the Phnom Penh airport weather data station as the average temperature during summer from 2003 to 2012 (Cedar Lake Ventures).

In post processing, the consequences would be analyzed as obtainable air velocity, temperature and mass flow rate. The results was calculated for every 40 cm. grid resolution for general area in the house, and every 1 cm. for area in Trombe wall channel. Later receiving velocity at specific places and outlets, those outputs would be examined to find out the average data and characteristic of the flow at each specific position. Besides, mass flow rate reception would be noticed at outlet of each case to see the quantities of mass which the system can produce. On behalf of the analysis, the output data would be putting into groups in order to compare those 3 elements, velocity, temperature, and mass flow rate at an exact time of simulation. Therefore, the result would be discussed flow characteristic in 3 essential positions: at outlet, in living room, and kitchen. Furthermore, 3D section views and flow vector would be attached as projecting figures.

3. Result

The result reported about the comparison of ventilation, temperature, and the mass flow rate received from 5 simulations as mentioned in the methodology section. First, the outcome was collected from the middle of living room. Second, the measurement location in the middle of kitchen was taken into account. Last, flow result at outlets of each case would be discussed. The simulation was set 60 seconds for running process. As the result, it was noticed that the system started to reach its steady state at 20 seconds of simulation time.

3.1 Simulation result of velocity

Table 2 showed about average velocity at each specific location for all studied cases. The consequences informed that for each case both in living room and kitchen gave slightly different velocity rate. At a cutting surface in the middle of living room, studied case of TW1000W/m² could gain best average velocity. According to human scale of sitting height and standing height (Ernst & Peter Neufert, 2002), from 1.35 m. to 1.8 m. height, the model of HC-TW1000W/m² provided highest air velocity up to 0.33 m/s which could satisfy occupant's comfort (figure 4). Nonetheless, figure 5 displayed that there are mostly no air flow affect within the kitchen. This occurrence could be explained by reason of the kitchen location. Kitchen is at the end of the house without any opened window which could assume as the dead-end. Moreover, the effect of outlet at the top plus the theory of buoyancy force, the air was sucked up, and flowed to the exit.

Table 2, Average velocity at steady state of each specific location (m/s)

	Living r.	**Kitchen**	**Outlet**
NTW	0.123	0.128	1.544
TW200W/m²	0.142	0.100	0.938
TW1000W/m²	0.157	0.113	0.962
HC-NTW	0.144	0.102	1.659
HC-TW1000W/m²	0.146	0.101	1.093

The simulation was also revealed air velocity at outlets of each case. However the average velocity at living room and kitchen were only in range from 0.1 m/s to 0.157 m/s, it was found out that the outlet of HC-TW1000W/m² and HC-NTW created the maximum air speed up to 2 m/s, while the others 3 cases of TW200W/m², TW1000W/m², and NTW could produce the maximum data of 1.45 m/s, 1.63 m/s, and 1.95 m/s respectively. It is supposed that the additional heat applied on the wall and ceiling of the top chamber is the reason for the increasing air speed to move out faster than the normal insulated-surface assumption condition. However, concerning the table 2, the average air velocity of the two cases without Trombe wall system contributed higher rate than cases of Trombe wall application. It is observed that the location of those outlets could affect air flow movement. The existing house design which outlet is located at the top of the chamber enhanced a smoother air flow more than the inlet position of trombe wall which obstructed the flow to turn into the channel.

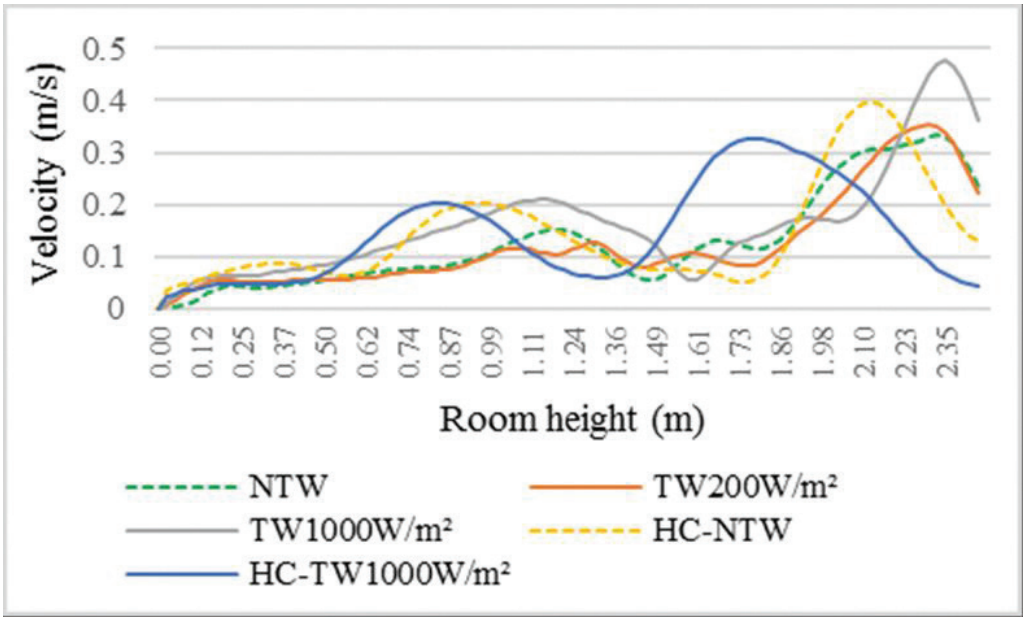

Figure 4, Velocity got at living room from floor to ceiling

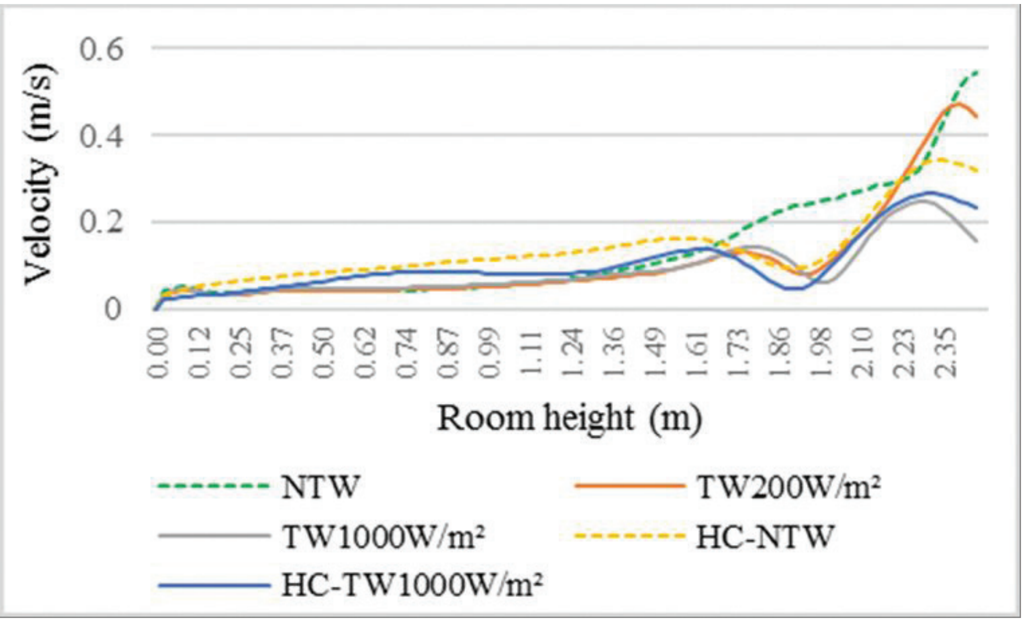

Figure 5, Velocity got at kitchen from floor to ceiling

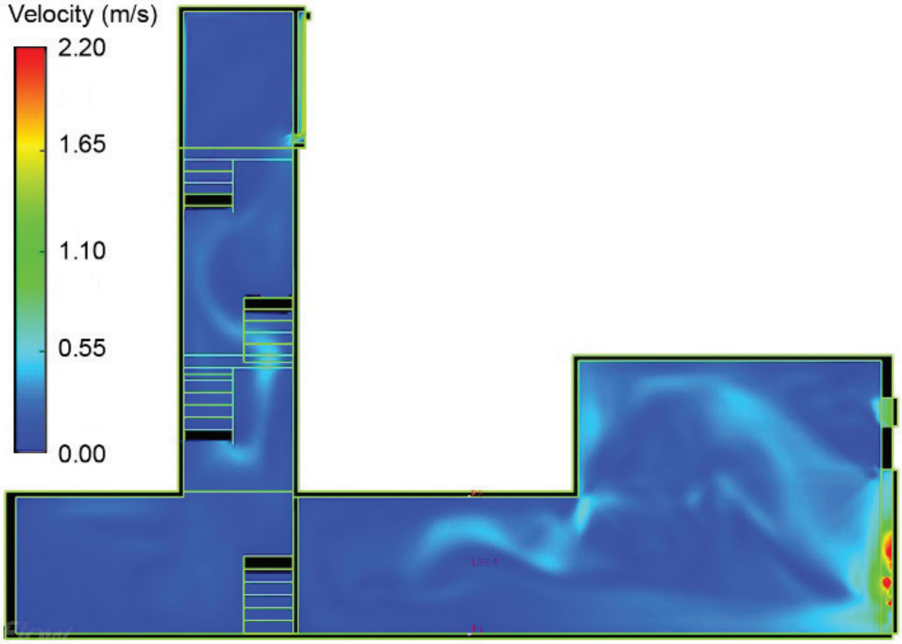

Figure 6, Air velocity simulation of HC-TW1000W/m² case

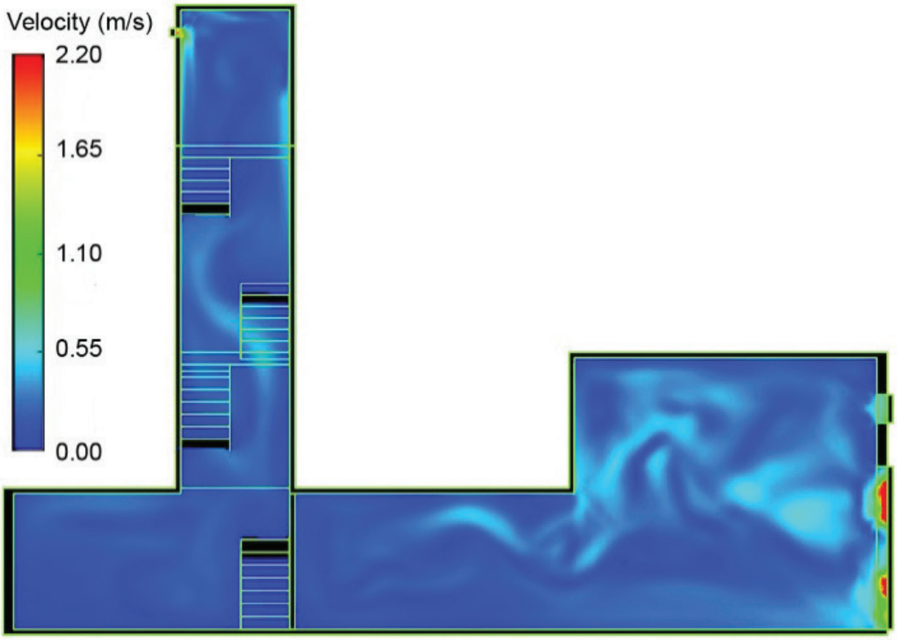

Figure 7, Air velocity simulation of HC-NTW case

Additionally, it could be explained that the available side of Trombe wall was not adequate to induce high capacity of air volume to pull the air from indoor through its outlet. Figure 6 and 7 presented two cases of flow visualization to better comprehend about the air pattern. The cross section were cut in the middle of the house to see both air flow at the middle of living room and outlet channel, so that the relationship of flow from living room area through the corridor were a little bit bothered by wall partition separation from room to the stair.

3.2 Simulation result of temperature

Table 3 notified average temperature in each room. As state in table 2 the average velocity, the temperature of ambient extended its influence by air flow from inlet to the room, resulted the increasing of temperature in living room around 1 to 2 Kelvin. However, the temperature received from every study case is noticed as a merely little different from each other. The result also gave the agreement that in kitchen, there is mostly unchanged in temperature due to a less wind speed. Figure 8 and 9 presented temperature pattern from floor to room ceiling. Higher temperature may store near the ceiling up to 4 or 5 degrees higher than initial room temperature set. Outlets area, in cases of Trombe wall were applied, gave high temperature near glass surface approximately 312.06 K for HC-TW1000W/m²; 318.61 K for TW1000W/m²; and 308.64 for TW200W/m². Temperature in channel dropped owing to the replacement of cool air from inside the chamber.

Table 3, Average temperature at steady state of each specific location (K)

	Living r.	Kitchen	Outlet
NTW	301.33	300.52	300.15
TW200W/m²	301.73	300.50	303.55
TW1000W/m²	302.38	300.57	307.62
HC-NTW	302.67	300.53	302.05
HC-TW1000W/m²	302.49	300.50	307.24

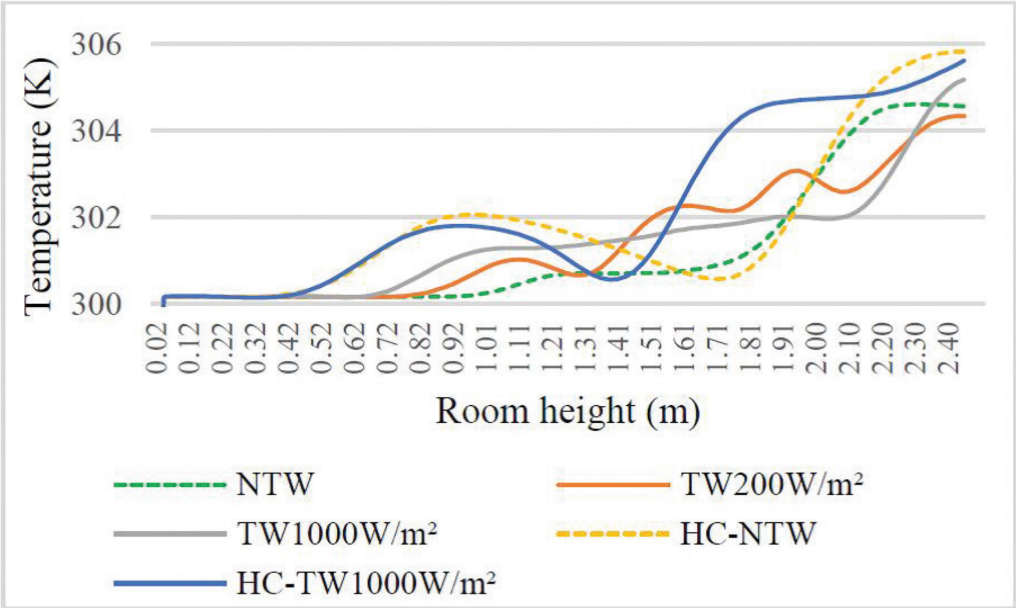

Figure 8, Temperature gotten at living room from floor to ceiling

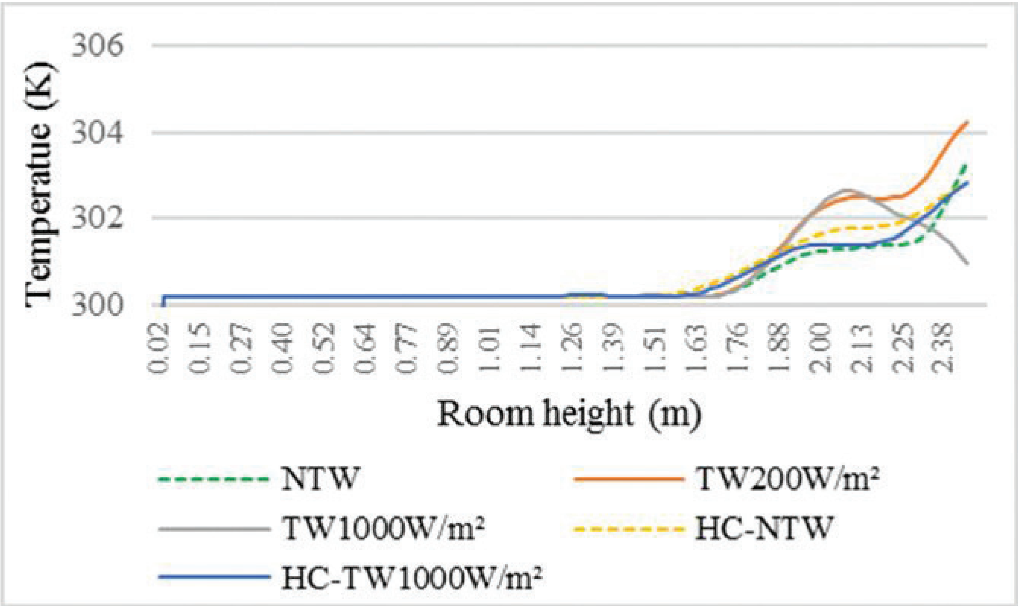

Figure 9, Temperature gotten at kitchen from floor to ceiling

3.3 Simulation result of mass flow rate

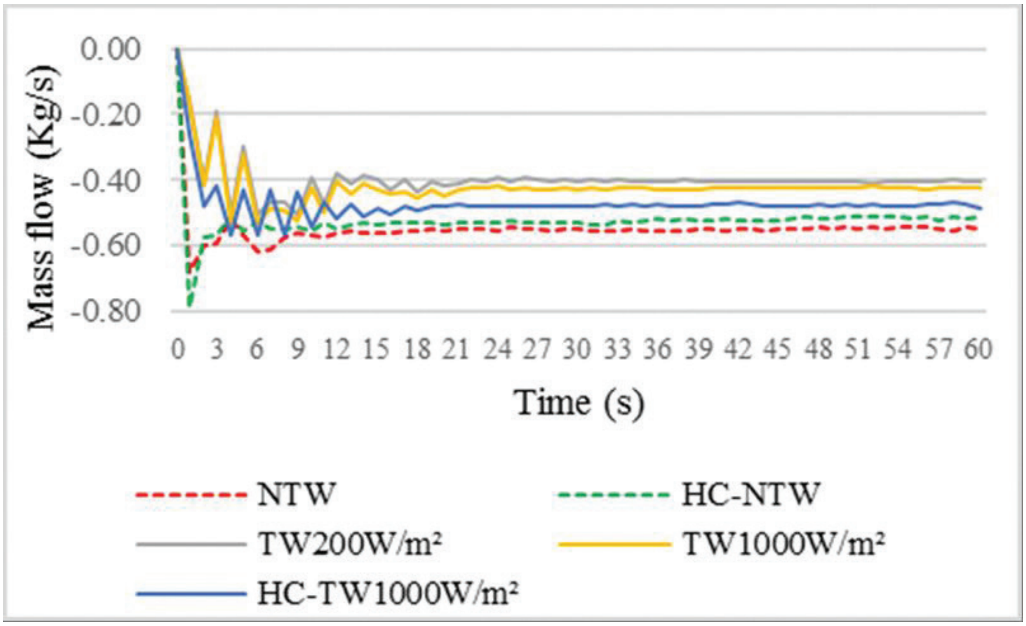

Figure 10, Mass flow rate gotten at outlets of each case at time steps (s)

In steady state condition, NTW and HC-NTW case gave highest mass flow rate than Trombe wall system. Mass flow rate reception for NTW was 0.55 Kg/s, and HC-NTW was 0.52 Kg/s. The others 3 cases of HC-TW1000W/m². TW1000W/m²; and TW200W/m², obtained the rate of 0. 48 Kg/s, 0.43 Kg/s, and 0.40 Kg/s respectively. . It is noticed that the amount of mass flow rate for non-Trombe wall cases could be achieved more than the cases which were designed with Trombe wall. The reason could be from the resistance in the channel of Trombe wall while the size of Trombe wall was too small compare to the supplying air from inlet. Nevertheless, with the amount of air mass flow rate from any case still as little amount compared to target rooms volume. These results explained that, even the design of Trombe wall system produced a remarkable range of velocity, it cannot handle the abortion of air ground floor area, but the air moved out by the pressure different between inlet and outlet height. More or less, the top chamber outlet for each case is the only exit for the ventilation.

4. Conclusion

Even though Trombe wall system are recommended for tropical region to enhance indoor ventilation, it should be considered that size of the system, distance from Trombe wall to target room, the volume of target room, and ambient weather are relevant to the achieved result. Unlike inlet position of the system, and limit size of the system which could produce small capability to drag the air into the channel while the resistance in channel was the obstacle, the existing outlets of the typical house could provide a better favor to push the air to the exit with higher ventilation rate and mass flow rate. However, this result was acceptable in case of the cement grill of existing outlet had been removed out like the simulation case. For all cases, the approximately air velocity got at living room is in average from 0.12 m/s to 0.16 m/s with the increasing of room temperature 1°C to 2°C by the ambient temperature from the blowing-in wind. Anyway, there were mostly same result of air velocity and temperature in kitchen for each case due to the location as dead end of this room. Within these range of temperature and air velocity, this technique cannot satisfy the need of comfort standard. It could be assumed that the installation of Trombe wall on the top of stair block wouldn't influence air flow from ground floor. The flow was automatically moved by the boundary condition of pressure different and interrupt by the resistance in the system while its size is too small compared to the amount of air supplement. However, the assistance of blowing-in wind would help to increase system performance. Last, CFD program contributed as significant tool in comparison between the existing design with the proposed Trombe wall usage. For this method could equally generate the simulation in any cases with the same input conditions while it is hard to make in real model testing, so that cause and effect of each argument is analyzed with reliability reason.

Acknowledgement

This paper was successfully written by the help of research scholarship fund from Chiang Mai Graduate School.

บรรณานุกรม

ASHRAE. (2003). **Ventilation for acceptable indoor air quality**, USA: American Society of Heating,Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE-55. (2004). **"ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy,"** EMA Chicago, Inc., Chicago.

Department of Planning. (2008). **"Phnom Penh's Profile Report,"** Department of Planning, Phnom Penh, Cambodia.

E. S. A. M. Eduardo Krüger. (2013). "Evaluation of a Trombe wall system in a subtropical location," **Energy and buildings**, pp. 364-372.

Neufert E,; Neufert P. (2002). **Architects' Data (Third Edition, 1998)**, B. B. a. N. Walliman, Ed., Wiley-Blackwell, p. 16.

Gan, G. (1998). "A parametric study of Trombe walls for passive cooling of buildings," **Energy and buildings**, vol. 27, pp. 37-43.

Cedar Lake Ventures, I. (n.d.). **"Average Weather For Phnom Penh, Cambodia,"** [Online]. Available: © Cedar Lake Ventures, Inc.

Ratanachotinun, J & Pairojn, P. (2014). "A Feasibility Study of Glass Solar Chimney Wall for Tropical Area, Case Study: Bangkok, Thailand," **International Energy Journal**, vol. 14, no. 2, pp. 95-106.

Ji J, Yi H, He W, Pei G. (2007). "PV-Trombe wall design for buildings in composite climates," **Journal of Solar Energy Engineering**, vol. 129, pp. 431-437.

Ji Jie, Yi Hua, He Wei, Pei Gang, Lu Jianping, Jiang Bin. (2007). "Modeling of a novel Trombe wall with PV cells," **Building and Environment**, vol. 42, p. 1544–1552.

K. J. F. K. Milorad Boji´c. (2014). "Optimizing energy and environmental performance of passive Trombe wall," **Energy and Buildings**, pp. 279-286.

K. S. C. L. N. A. M. S. Omidreza Saadatian. (2012). "Trombe walls: A review of opportunities and challenges in research and development," **Renewable and Sustainable Energy Reviews**, vol. 16, pp. 6340-6350.

Irshada, K.; Habiba, K.; Thirumalaiswamya, K. (2014). "Energy and cost analysis of Photo Voltaic Trombe wall system in Tropical climate," **Energy Procedia**, vol. 50, pp. 71-78.

Lay, N. (2013). **The use of wind-catchers technique to improve natural air movement in row houses**, Bangkok: Chulalongkorn University.

M. H. A. T. J. H. Agung Murti Nugroho. (2006). "Evaluation of parametrics for the development of vertical solar chimney ventilation in hot and humid climate," in **the 2nd International Network for Tropical Architecture**, Jogjakarta.

Municipalité de Phnom Penh, Malrie de Paris, Atelier parisien d'urbanisme, avec le soutien du ministère des Affaires étrangère et eruopéennes de la République francaise. (2009). **Phnom Penh Croissance et Transformation**, Phnom Penh: Municipalité de Phnom Penh, p. 49.

Nitawichit, C. (2008). **"Analysis of thermal comfort and particulate matter dispeersion in a classroom under natural ventilation,"** The graduate school, Chiangmai University, Chiangmai, Thailand.

Thongnut, P. (2006). **"Performance and parametric design of trombe wall,"** Chiangmai University, Chiangmai, Thailand, 2006.

SCHER. (2007). **Opinion on risk assessment on indoor air quality**, Brussels: SCHER, pp. 7-9.

Punyasompun, S.; Hirunlabh, J.; Khedari, J. & Zeghmati, B. (2009). "Investigation on the application of solar chimney for multi-storey buildings," **Renewable Energy**, vol. 34, p. 2545–2561.

Sun W, Ji J, Luo C, He W. (2011). "Performance of PV-Trombe wall in winter correlated with south facade design," **Applied Energy**, vol. 88, no. 1, pp. 224-231.

Next Limit, T. (2014). **"Next Limit"** [Online]. Available: http://www.xflowcfd.com/pdf/XFlow2013_ProductSheet.pdf.

W. K. P. N. J. K. J. Hirunlabh. (1999). "Study of natural ventilation of houses by metallic solar wall under tropical climate," **Renewable energy**, vol. 18, pp. 109-119.

Wardah Fatimah Mohammad Yusoff, Elias Salleh, Nor Mariah Adam, Abdul Razak Sapian. (2010). "Enhancement of stack ventilation in hot and humid climate using a combination of roof solar collector and vertical stack," **Building and Environment**, vol. 45, pp. 2296-2308.

Y. Z. S. W. Tengfei (Tim) Zhang. (2014). "Prediction of airflow rate through a ventilated wall module," **Energy and Buildings**, pp. 651-659.