Air Changes and Extraction Flow Rate Analysis of Wind-Induced Natural Ventilation Tower under hot and humid climatic conditions

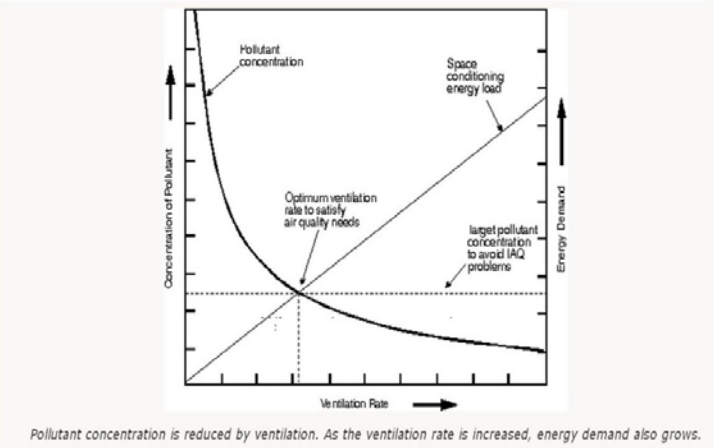
Chin Haw Lim*, Omidreza Saadatian, M. Yusof Sulaiman, Sohif Mat, K. Sopian

***Abstract*—**Wind-induced natural ventilation tower is not a common architectural features in countries located under the hot and humid climatic conditions. It is more commonly found in countries with hot and dry climatic conditions like Iran and other Middle Eastern countries. There are mainly two methods for inducing natural ventilation; namely stack ventilation and wind-induced ventilation. Due to the relatively lower difference between the indoor and outdoor temperature in hot and humid climatic conditions, stack ventilation method alone is rendered insufficient to create desirable air flow in the indoor building environment to achieve comfort and indoor air quality for the building occupant. Hence, wind-induced ventilation tower application has potential to create desired air flow rates and improve the indoor air quality for the building. The results of this research revealed that at external wind speed of 0.1m/s, the aerodynamic design of the inverted airfoil roof on the wind-induced natural ventilation tower is able to generate extraction air flow rate of 10,000m^3/hr with average of 57 air changes per hour (ACH). This paper presents the viability of the application of wind-induced natural ventilation tower in hot and humid climatic conditions.

***Keywords*—**Air movement, air changes per hour (ACH), hot and humid climatic conditions, wind-induced natural ventilation tower.

I. INTRODUCTION

Supply of acceptable air is one of the main factors that determine the comfort and indoor air quality of a building [1]. Natural ventilation is a strategy for achieving acceptable indoor air quality, thermal comfort with reduced energy consumption [2]. It is essentially based on the supply of fresh air to a space and the dilution of the indoor pollution concentration [3]. This is shown in Fig. 1. Standard requirement for a minimum ventilation rate is required to dilute odour and concentration of CO$_2$ to an acceptable level, and to provide sufficient oxygen for occupant needs [4]. Another vital purpose of ventilation is also to provide thermal comfort though air motion. Thermal comfort is achieved when the air motion that passes the human skin enhances the sweat evaporation. This comfort ventilation is effective especially in hot and humid climatic conditions. Air motion or air speed is vital to determine the evaporation rate. The higher the evaporation rate, the better is the thermal comfort.



Pollutant concentration is reduced by ventilation. As the ventilation rate is increased, energy demand also grows.

Fig. 1 Dilution of pollutant concentration with ventilation rate [3]

There are mainly two fundamental principles of natural ventilation; namely stack effect and wind driven ventilation [5]. The stack effects are caused by temperature differences between indoor and outdoor of buildings. This phenomena occurs when the inside building temperature is higher than the outside and the warm indoor air will rises and exit replacing the cooler and denser air from below.

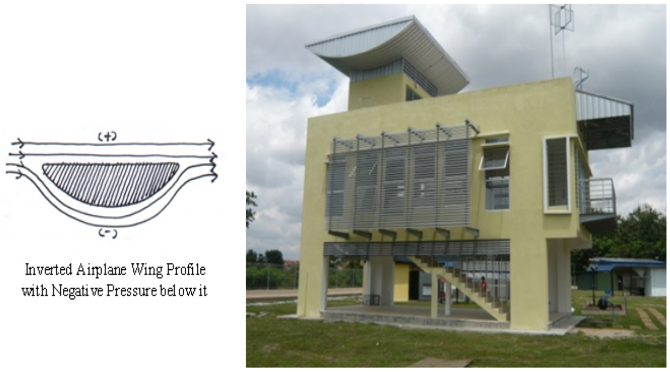
Naghman K. et al. [6], observed that the stack effect reduces when the temperature differences between the indoor and outdoor of buildings are small. Because of the relatively lower difference between the indoor and outdoor temperature especially in hot and humid conditions, stack ventilation alone is rendered insufficient to create desirable air flow to achieve thermal comfort for the building occupants.

Wind-induced natural ventilation is based on pressure differences created by wind. These pressure differences between the two opposite points on the building geometry are the driven force of the wind-induced natural ventilation strategy. Although wind towers are not commonly found in hot and humid climate conditions, according to Givoni B., wind-induced natural ventilation design has a great potential and can be used to achieve the desirable air speed in the indoor building environment to improve the evaporation rates and cooling effect for the building occupants especially in hot and humid climatic conditions [5].

There is another phenomenon that influences the performance of the wind-induced natural ventilation tower which is the aerodynamic roof geometry design of the wind tower. This is because the roof of a building is often the most exposed part to the oncoming wind in particular the roof geometry. The phenomenon at work is the Bernoulli Effect that occurred at the inverted airfoil roof of the wind-induced natural ventilation tower.

In the Bernoulli Effect, when there is an increase in the speed of a fluid, it decreases its static pressure. Due to this phenomenon, the negative pressure occurred underneath the inverted airfoil is used to extract out the air out from the opening at the top of the tower of the building.

Recent research projects conducted by both B. Blocken et al [2] and Van Hooff T., et al [7] revealed the effectiveness of Venturi-shaped roofs in providing significant negative pressure to induce air movement.



(a) (b)

Fig. 2 (a) Inverted Airplane Wind Profile; (b) Experimental House with wind-induced natural ventilation tower

Fig. 2(a) shows a profile of an inverted airfoil with positive pressure above and negative or low pressure below the inverted airfoil. Based on this principle, the experimental building's wind-induced natural ventilation tower is designed with an Inverted Airfoil geometry design as its roof as shown in Fig. 2(b).

II. RESEARCH METHODOLOGY

There are numerous methods in conducting studying on wind-induced natural ventilation. The research methods that are commonly used are the followings:

i. Reduced-scale atmospheric boundary layer wind tunnel experiments,
ii. Numerical simulation with computational fluid dynamics (CFD),
iii. Reduced-scale water tank experiments,
iv. Analytical and semi empirical formulae,
v. Full-scale empirical study.

Full-scale empirical study method is rare due to time consuming and high cost of measuring equipment and full-scale experimental building. According to Van Hoof T., et al [7], the full-scale measurement method is very valuable in giving insight to the wind-induced natural ventilation study.

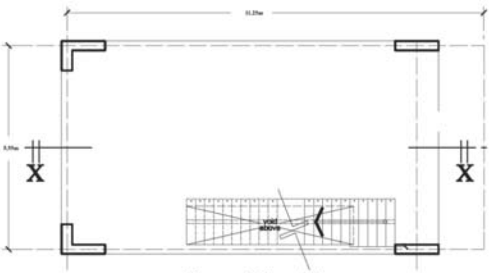
The main objective of the empirical study was to evaluate the performance of the wind-induced natural ventilation tower in hot and humid climatic conditions to provide air movement and air change per hour (ACH) for the indoor environment.

A full-scale wind-induced natural ventilation tower was built on an experimental house at the Green Technology & Innovation Park National University of Malaysia, Bangi, Selangor, Malaysia as shown in Fig. 2. The purpose of the full-scale wind-induced natural ventilation tower is for onsite data collection and measurement.

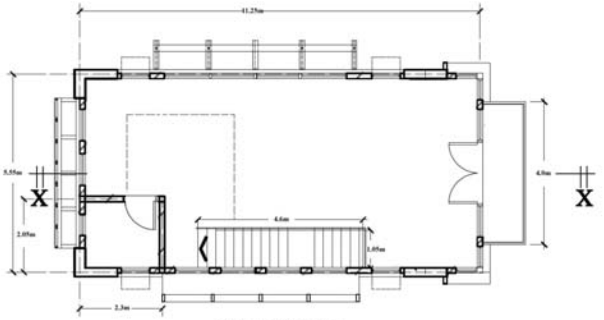
A comprehensive data acquisition and monitoring system is installed for data collection on the experimental house and wind-induced natural ventilation tower. The data acquisition and monitoring system is designed based on parameters like external and internal air movement, pressure, relative humidity and ambient temperature for analysis. The details of the data acquisition and monitoring system are discussed on the following section of this paper.

III. THE FULL-SCALE EXPERIMENTAL HOUSE WITH WIND-INDUCED NATURAL VENTILATION TOWER

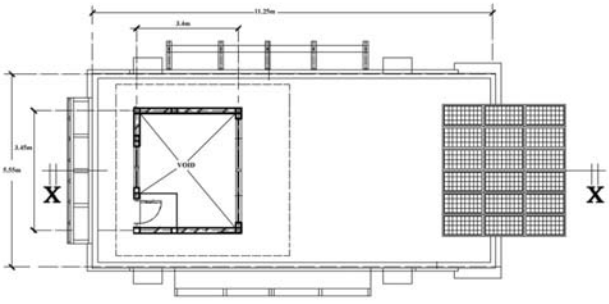
The experimental house is a two-storey detached building with a flat concrete roof. The total volume space of the experimental house is 232.76 m^3. The ground floor is an open area concept with a concrete staircase that leads to the first floor as shown in Fig. 3. The first floor is raised at 3.2 meters on 4 columns above the ground level. This open area concept allows a free flowing of air movement. The ground and first floor dimensions are 11.25m length by 5.55m width and 3.2m height. The wind-induced natural ventilation is located at the flat roof floor level of the experimental house. The total height of the wind-induced natural ventilation tower is 2.81m with inverted airfoil roof geometry of 5.56m width by 5.20m length as shown in Fig. 3. The total volume of the experimental house with wind-induced natural ventilation tower is 232.76 m^3.



Ground Floor Plan



First Floor Plan



Roof Plan

Fig. 3 Ground, first and roof plans of the experimental house

IV. DATA ACQUISITION AND MONITORING SYSTEM

The experimental house is installed with data acquisition and monitoring system for onsite measurement and analysis. Figure 4 shows that there are a total of 6 different locations of monitoring points, namely the front entrance window openings, middle indoor area, below the wind-induced ventilation tower, middle of the tower, upper window openings of the wind-induced ventilation tower and bottom of the tower's roof. The parameters identified for the data acquisition and monitoring are as follows:

i. air speed (m/s),
ii. pressure (Pa),
iii. Relative humidity (%)
iv. Ambient temperature (^{0}C)

The data logger installed is of Graphtec GL800 with 20 channels. The pressure sensor is of Piezo-resistive sensitive element type with measuring range of -500 Pa to +500 Pa and a resolution of 1Pa. The air speed sensors are of hotwire type with measuring range of 0 m/s to 20 m/s with a resolution of 0.01 m/s. The temperature sensors are PT100 class 'A' element with measuring range from 0^0C to 50^0C with a resolution of 0.1^0C. All sensors installed on the wind-induced natural ventilation tower were calibrated by KIMO instruments, France and the calibration certificates were delivered before installation.

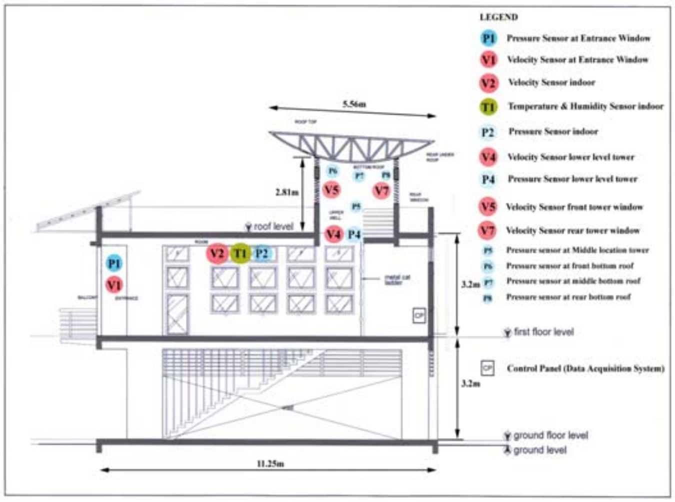


Fig.4 Dimensions of the experimental house & locations of the monitoring points & sensors

Fig. 4 shows all sensors are connected via RS232 system to the data logger. The Graphtec GL800 is equipped with USB memory slot. All data are logged and stored in the USB memory drive. All data are automatically logged every 10 minutes intervals and 24 hours per day. The data is retrieved every 2 to 3 weeks for analysis.

The data were taken from October 2010 to January 2011. All the measurements were taken with both the windows opened at the front of the experimental house and top windows of the wind-induced natural ventilation tower. Figure 5 also shows a weather station that was installed on flat roof of the experimental house to record the wind speed (m/s) and wind directions within the vicinity of the experimental house. The total height of the weather station from the ground level to the top of the anemometer is 11.4m.

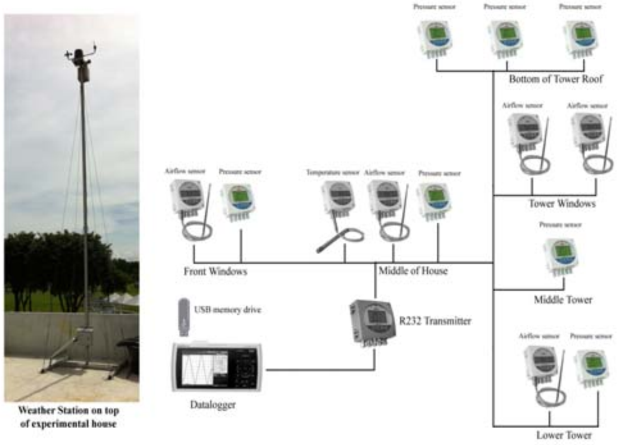
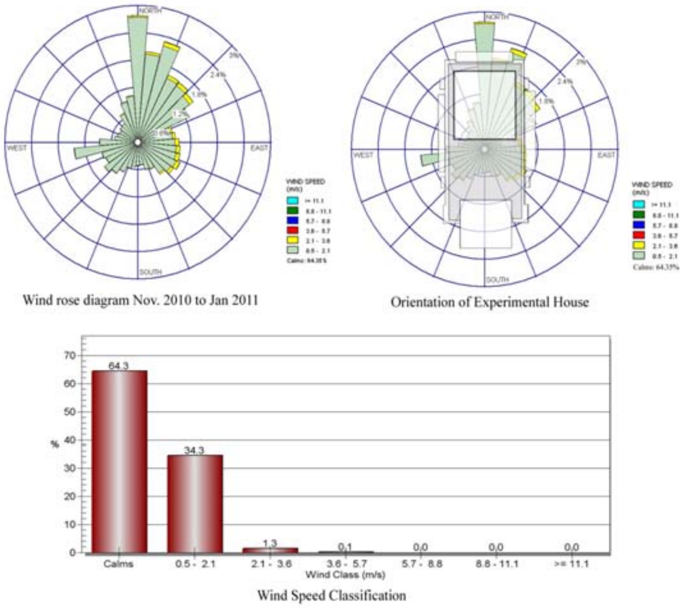


Fig. 5 Data acquisition and monitoring system & weather station

V. SITE WIND PROFILE ANALYSIS

Malaysia is located in the equatorial region. The wind is dependent on monsoons and its availability varies with specific location [8]. Based on the weather data collected from November to January 2011, the analysis of the wind rose diagram as shown in Fig. 6 revealed that, the prevailing wind is seen as blowing from the North direction. Fig. 6 also indicates the classification of wind speed with the total of 64.3% are classified as calm days and only 34.3% of the days have posses wind speed ranging from 0.5m/s to 2.1m/s.

The wind data analysis revealed that generally the site of which the experimental house was built had very low outdoor wind speed. The experimental house is orientated along the North-South axis orientation with the front facade facing south direction. The height of the anemometer at the weather station is 11.4m. The mean wind speed recorded by the anemometer at the height of 11.4m is 0.85m/s.



Wind rose diagram Nov. 2010 to Jan 2011

Orientation of Experimental House

Wind Speed Classification

Fig. 6 (a) Wind rose from Nov. 2010 to Jan. 2011; (b) orientation of experimental house; (c) classification of wind speed for the site

The wind data collected from the weather station is used for the generation of the site Wind Profile. The Log Law Model equation is used to compute the mean wind speed at 10m reference height (V_{ref}.). Subsequently, the mean wind speed (V_{10}) at 10m reference height is used to generate the Wind Profile for the site using Flovent Boundary Layer Generator software.

Table 1 Atmospheric Boundary Layer (ABL) characteristic for different terrain roughness. [9]

Class	**Terrain Description**	**Z_o(m)**	**α**	***I_u* (%)**	**Exp.**	**Z_g(m)**
1	Open sea, fetch at least 5km	0.0002	0.1	9.2	D	215
2	Mud flats, snow, no vegetation, no obstacles	0.005	0.13	13.2	D	215
3	Open flat terrain; grass, few isolated obstacles	0.03	0.15	17.2	C	275
4	Low crops; occasional large obstacles, x'/h>20	0.1	0.18	27.1	C	275
5	High crops; scattered obstacles, residential suburban, 15<x'/h<20	0.25	0.22	27.1	B	370
6	Parkland, bushes; numerous obstacles, x'/h~10	0.5	0.29	33.4	B	370
7	Regular large obstacles coverage (dense spacing of low buildings, forest)	1.0 – 2.0	0.33	43.4	A	460
8	City centre with high and low-rise buildings	≥2.0	0.40 ~ 0.67	-	A	460

(Note: x' is the distance between the obstacles and the subject while h is the height of the obstacles)

The Log Law Model equation that is used to determine the mean wind speed (V_z) is as follows:

$$V_Z = V_{ref} [\log(Z/Z_o) / \log(Z_{ref} / Z_o)] \quad (1)$$

Where,

V_z = mean wind speed at height Z (Gradient wind)
V_{ref} = 0.85 m/s (mean wind speed at reference height Z_{ref})
Z_{ref} = 11.4m (reference height of anemometer at site)
Z = 370m [height for which the wind speed V_z is computed (Gradient height)]
Z_o = 0.5 (roughness length of log layer Constant)

For the purpose of the computation, the Class type of the site needed to be identified, and these are listed in Table 1. Our site falls under Class 6 specifically: "Class 6: Terrain type of Parkland, bushes; numerous obstacles, x'/h ~10" is used for the computation.

Therefore,

$$V_{114} = 0.85 [\log(370/0.5) / \log(114/0.5)] \quad (2)$$

$$V_{114} = 0.85 [8.53/3.52] \quad (3)$$

$$V_{114} = 2.06 \text{ m/s} \quad (4)$$

In order to determine the mean wind speed at reference height (V_{ref}) of 10m from equation (1), V_{ref} can be calculated as follows:

$$V_{ref} = V_z / [\log(Z/Z_o) / \log(Z_{ref} / Z_o)] \quad (5)$$

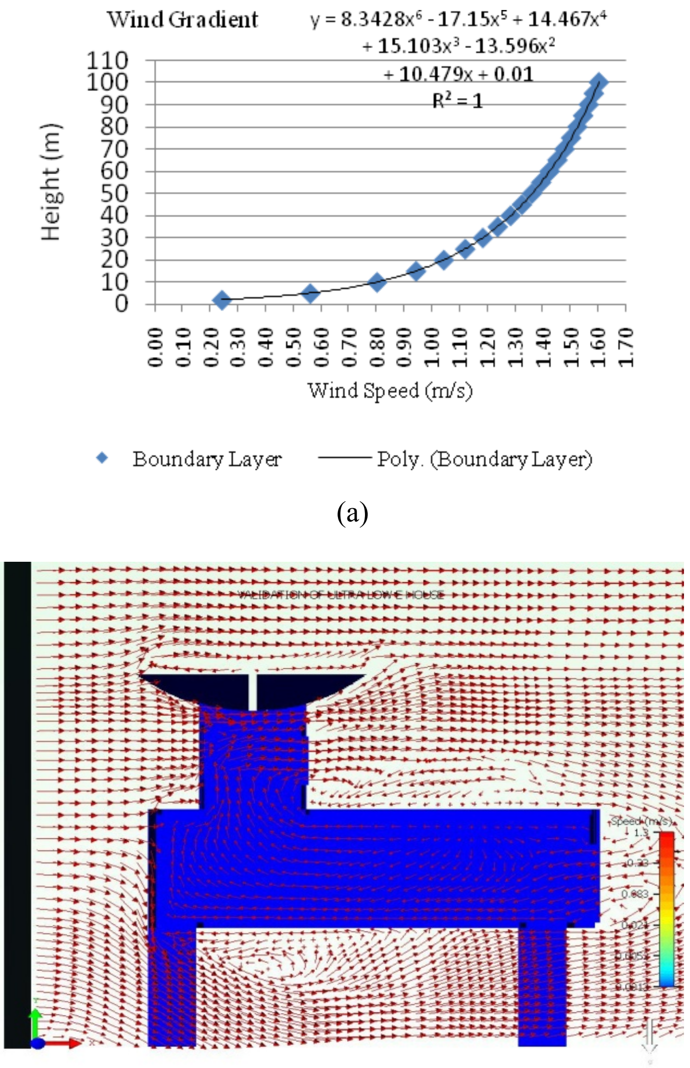
$$V_{10} = 2.06 / [\log(370/0.5) / \log(10 / 0.5)] \quad (6)$$

$$V_{10} = 2.06 / [8.53 / 3.32] \quad (7)$$

$$V_{10} = 0.80 \text{ m/s} \quad (8)$$

To generate the wind gradient for the site, the mean wind speed (V_{ref}) of 0.80 m/s at reference height of 10m is inserted into the Flovent Boundary Layer Generator software for generation of the Boundary Layer. Subsequently, the Boundary Layer in PDML format which is produced by Flovent Boundary Layer Generator is imported into Flovent CFD software for final simulation. Fig. 7(a), shows the wind gradient graph for the site of the experimental house which is vital information for designing a wind-induced ventilation tower.

The Wind Profile changes from urban to open country due to the terrain roughness. The wind profile at the "Urban Centre" is much steeper in comparison to the wind profile for "Rough wooded country" and "Open country or sea". In order to ascertain the air flow in the experimental house, Flovent CFD software is also used to model and simulate the internal and external air flow pattern and this is indicated in Fig. 7(b).



(a)

(b)

Fig. 7(a) Wind profile generated by FloVent Boundary Layer Generator software for the site of the experimental house; (b) CFD Simulation result of wind flow pattern using FloVent Software for the experimental house

VI. RESULTS AND DISCUSSION

Fig. 8 shows the indoor average air speed taken from field measurement fluctuating between 0.2 m/s to 1.38 m/s. As can be seen, indoor average air speed is lower between midnight and early morning and increases gradually after 10am and culminates between 3pm to 5pm with a maximum average air speed of 1.38 m/s. The high air speed during the afternoon period is caused by lower air density. This is due to high air temperature and low relative humidity. This allows the air to move much easier in the afternoon in comparison to the morning period due its lighter density.

The field measurement data obtained by Azni Z.A. *et al.*, (2005) as shown in Table 2 indicates the mean air speed for conventional Malaysian homes only ranges from 0.03m/s to 0.08m/s and this problem of low air movement can be enhanced with wind-induced natural ventilation tower[10]. The wind-induced natural ventilation tower method without any aid of the mechanical system has the potential to increase the mean indoor air speed to 0.2 m/s from 0.08 m/s.

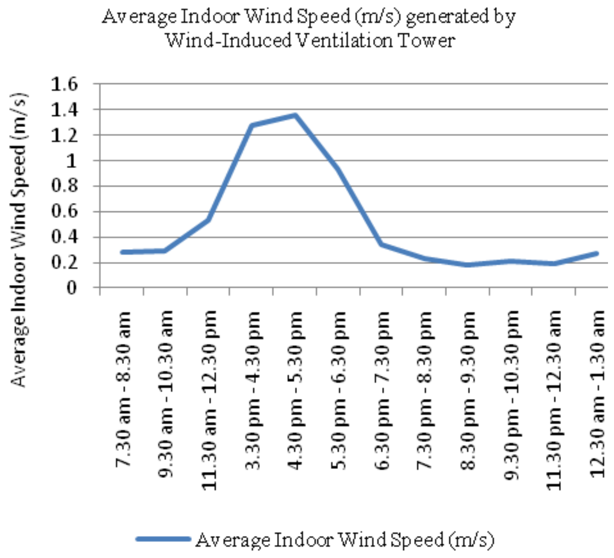
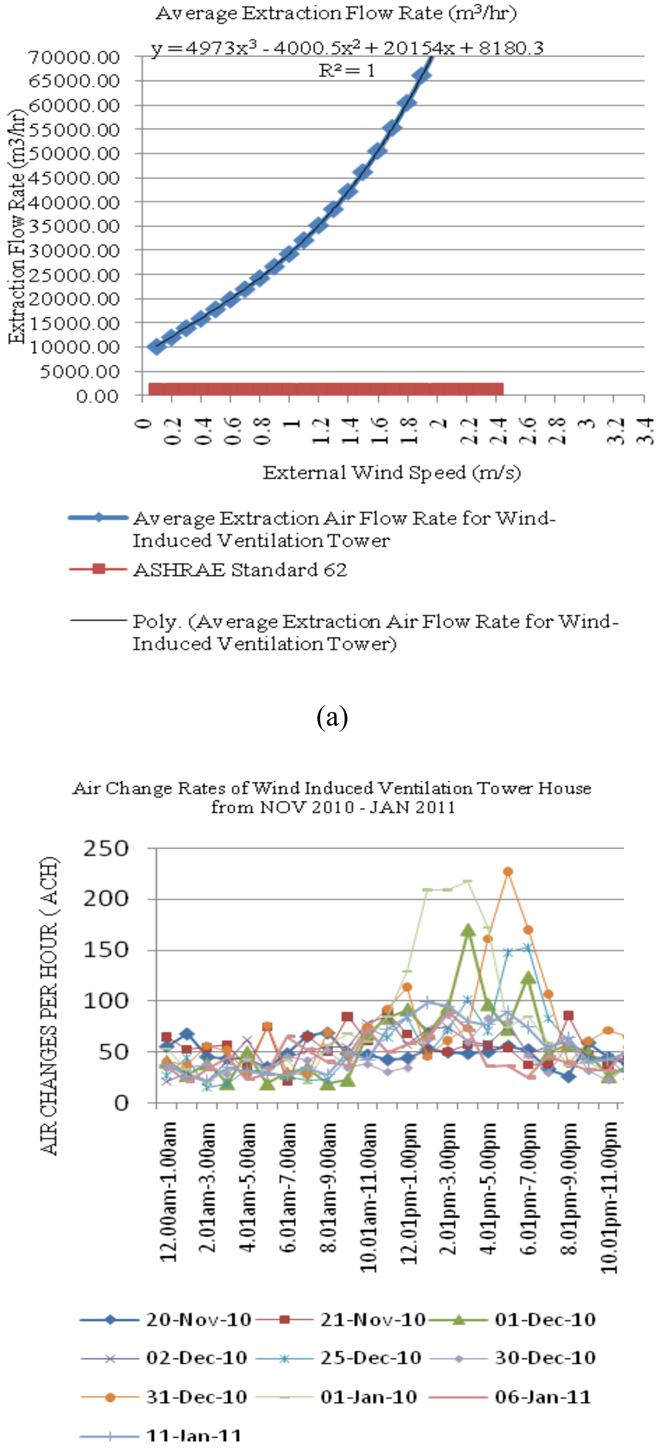


Fig. 8 Average indoor air speed from field measurement

Table 2 Mean Indoor Air Speed (m/s) for Typical Residential Types in Malaysia [10]

House Types	Mean Indoor Air Speed (m/s)
Semi-Detached	0.08
Bungalow	0.03
Terrace	0.08



(a)

(b)

Fig. 9(a) Average extraction air flow rate of wind-induced natural ventilation tower based on external wind speed; (b) Air Changes per hour (ACH) of wind-induced natural ventilation tower house

Fig. 9(a) revealed that there is a correlation between the external wind speed and the extraction air flow rate. The higher the external wind speed, the higher will be the extraction air flow rate.

Based on the field experiment conducted by Chi-ming Lai, with an outdoor wind speed of 2 m/s, the Monodraught^{TM} windcatcher ABS 500 model with the 450mm diameter is able to achieve an extraction flow rate of 30 l/s or 108 m^3/h. [11]. Moreover, with the same external wind speed of 2 m/s, the inverted airfoil roof wind-induced natural ventilation tower is able to generate an average extraction flow rate of 47,634.6m^3/h as shown in Fig. 9(a).

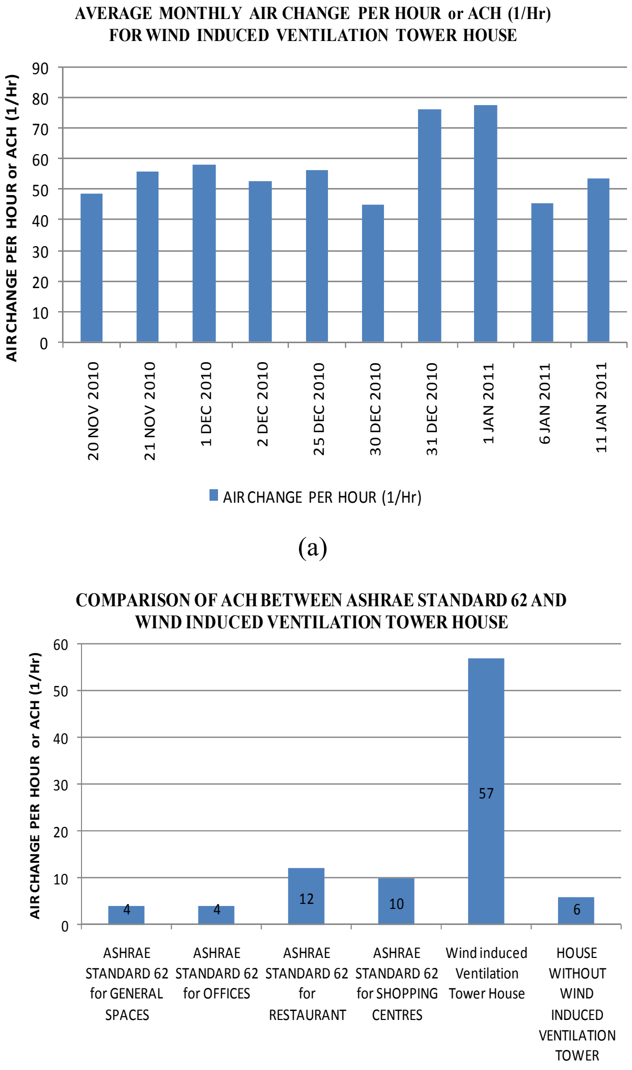
This extraction flow rate of inverted airfoil roof wind-induced natural ventilation tower is equivalent to 441 units of Monodraught^{TM} windcatcher ABS 500 model. In addition, with an external wind speed of 0.1 m/s, the inverted airfoil roof wind induced natural ventilation tower is able to generate a ventilation rate of 10,000m^3/h which surpasses the ASHAE Standard 62:2001 requirement for ventilation rate which is 1260 m^3/h.

The ventilation rate in buildings can be expressed in terms of air changes per hour (ACH). ACH is the number of times in an hour that a volume of air equal to the volume of a room or building is renewed with fresh outdoor air. There is a correlation between the air changes and carbon dioxide level [12]. Therefore, air changes per hour are important in order to achieve desirable indoor air quality for building occupants.

The graph at Fig. 9(b) reveals the ACH pattern from 12am until 12 midnight. The ACH starts to increase from average 50ACH to 70ACH between 1pm to 5pm and it slowly decreases in the evenings until early morning when it starts to increase again [see Fig. 9(b)].

It can be seen from Fig. 10(a) that the daily average ACH generated by the wind-induced natural ventilation tower for the experimental house fluctuates from 45ACH to maximum of 75ACH. The Fig. 10(a) & (b) also shows that average ACH for wind-induced natural ventilation tower is 57 ACH which is above the requirement set by ASHAE Standard 62 ventilation for general spaces, offices, restaurants and shopping centres. Other studies conducted by N.K. Bansal et al [13] and M.N. Bahadori [14] revealed that the conventional wind tower can provide 20 ACH at an ambient wind speed of 1m/s and it can reached to 60 ACH using the combination of solar chimney and wind tower.

This shows that the aerodynamic performance of inverted airfoil roof wind-induced natural ventilation tower in hot and humid climate is comparable to the conventional wind tower in hot arid of the Middle East regions.



(a)

(b)

Fig. 10(a) Average daily ACH & comparison of ACH between ASHAE standard 62 and wind-induced natural ventilation tower house

VII. CONCLUSION

Maintaining good indoor thermal environment and reduction of energy consumption are the key criteria in identifying low energy architecture [15]. The wind-induced natural ventilation is one of the most effective passive technologies in providing indoor comfort. The empirical data and analysis reveals that the inverted airfoil roof wind-induced natural ventilation tower has a great potential to generate sufficient air flow rate and ACH for good indoor air quality for naturally ventilated buildings in hot and humid climatic conditions. The study has shown that the aerodynamic performance of the inverted airfoil roof of the wind-induced natural ventilation tower can produce the negative pressure required to induced the air flow from the indoor spaces upwards to the tower and out from the building. At 0.1m/s of external wind speed, the inverted airfoil roof wind-induced ventilation tower able to generate the extraction air flow rate of 10,000m^3/h with an average of 57 ACH for common residential homes to provide greater indoor air quality to its occupants. Based on ASHAE Standard 62, the wind-induced natural ventilation tower can be used to elevate the indoor air speed to fulfil the standard requirement of 1260 m^3/h. In conclusion, this experimental research demonstrates the potential application of wind-induced natural ventilation tower under hot and humid climatic conditions to produce sufficient air changes and indoor air flow rate for its occupants [16] [17].

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Associate Prof Lim Chin Haw, Ar.
Solar Energy Research Institute, National University of Malaysia (UKM),

Ar. Lim Chin Haw is an associate professor in Architecture. He has graduated from the top university of Malaysia namely UTM and he further continued his Master at UM in Architecture. He is also a certified architect of Malaysia holding the title of Ar. He is serving Solar Energy Research Institute, National University of Malaysia (UKM) as a senior research fellow. His expertise is in Low Energy Architecture and Solar Energy, Building Integrated PV System, Solar Assisted Air Conditioning System, Building Rating Tools.

His contact details are:
http://www.ukm.my/SERI/senior.htm
chinhaw.lim@gmail.com

Omidreza Saadatian, PhD.
Solar Energy Research Institute, National University of Malaysia (UKM)

Omidreza Saadatian graduated from the Faculty of Design and Architecture University Putra Malaysia. He is a Civil Engineer and has a Master and PhD of Urban Planning and Design. His expertise is in sustainable development and renewable energy. Currently he serves the Solar Energy Research Institute (SERI) as a researcher.

His contact details are:
http://www.ukm.my/SERI/postdoctoral.htm
omid.saadatian@gmail.com

M. Yusof Sulaiman, PhD.
Solar Energy Research Institute, National University of Malaysia (UKM)

M. Yusof Sulaiman is a physicist and obtained his PhD from London. He currently serves as a principal research fellow in Solar Energy Research Institute. His expertise is in solar adsorption cooling, solar thermal and solar cells.

His contact details are:
http://www.ukm.my/SERI/principal.htm
sulaiman_yusof@yahoo.com

Sohif Bin Mat, PhD.
Solar Energy Research Institute, National University of Malaysia (UKM)

Sohif Bin Mat is a Malaysian Scholar who has obtained a PhD in Mechanical Engineering from University of Malaya in 1990. He is currently serves a research fellow as well as head of industrialization of Solar Energy Research Institute. His expertise is in sustainable development, wind energy, solar system and Indoor Environment Quality.

His contact details are:
http://www.ukm.my/SERI/fellow.htm
sohif@ukm.my

Dato' Kamaruzzaman Sopian, PhD.
Solar Energy Research Institute, National University of Malaysia (UKM)

Dato' Kamaruzzaman Sopian is a professor in Mechanical Engineering and Solar Energy. He has finished his studies in USA and currently serves as the director of Solar Energy Research Institute. His 700 publications and hiscontribution to the field of solar energy triggered the King of Malaysia to honour him the royal title of Dato ship in 2011. He was awarded in May 2012, the special of award of World Renewable Energy Network in Colorado, USA.

His contact details are:
ksopian@vlsi.eng.ukm.my