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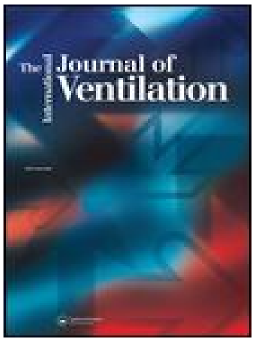

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The development of hybrid longitudinal windcatcher for basement ventilation in warm humid climate

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ABSTRACT

This paper reports the development of a longitudinal hybrid windcatcher (LHWC) to provide thermal comfort and healthy ventilation for basement in warm humid climate. Two full-scaled computer models and a one-tenth physical model were constructed. The computer simulation found that outdoor wind speed of 1–5 m/s generated air velocities of 0.19–1.01 m/s at the occupants' zone when the inlet's height was 1 m above the surrounding roofs. Raising the inlet 3 m higher did not produce significant difference air velocity at the occupants' zone. The physical model experiment outdoor found that 3 m/s wind induced 0.3 m/s air velocity inside it. Meanwhile, with the absence of outdoor wind, the four small exhaust fans could induce 0.05 m/s air velocity inside it. From the computer simulation and physical model, it can be concluded that outdoor wind air could induce physiological cooling and ventilation at the basement. The array of exhaust fans could only induce very low air velocity but it was considered able to ventilate the used air for the basement.

KEYWORDS

CFD; basement; hybrid; windcatcher; ventilation; warm humid climate

1. Introduction

Applications of passive ventilations on modern building design have become more popular since the last decades and are expected to be more popular in the future. Global warming and urban heat island effect have raised air temperature to its upper limit of thermal comfort. The easiest way to remedy it is by installing air conditioners (ACs). However, energy price increase and environment quality deterioration have made developing passive ventilation crucial. Air conditioning consumes around 35% of building electricity. Even though newer technologies make ACs more energy efficient, adopting zero energy (passive) ventilation, when it is possible, is still a better choice.

In terms of passive ventilation, warm humid climate is difficult to handle. The air temperature is neither extreme high nor low (Figure 1.) In low-land cities of Indonesia, for example, air temperatures are between 25 °C and 32 °C. (Recently, air temperature of 34 °C becomes more common in cities like Jakarta and Surabaya. In October 2014, Jakarta experienced 39 °C air temperature.) The daily amplitude of maximum and minimum air temperature is rarely beyond 6 °C. Relative humidity is mostly high, between 70% and 96%, which prevents easy sweat evaporation. Thus, a combination of warm air and high humidity creates thermally uncomfortable atmosphere. To induce physiological cooling, sufficient air velocity is needed. Unfortunately, in warm humid climate, wind speed is mostly

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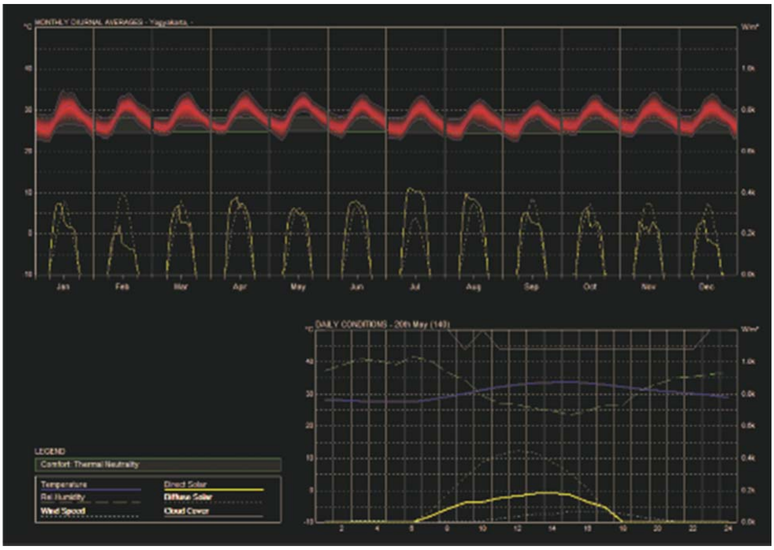

Figure 1. Weather profile of Yogyakarta showing almost similar monthly pattern throughout the year. Daily air temperature swing is small and rarely exceeds 6 °C. There is no extreme hot or cold.

low and calm days are more frequent (more than 80% of the time). Psychrometric chart of Yogyakarta shows the chance to obtain thermal comfort with passive ventilation (Figure 2).

There is a gap between ventilation method in Indonesian traditional and modern architectures. Indonesian traditional architectures respond to the warm humid climate differently though they share some similarities. Plan is commonly simple to minimise indoor air obstruction and maximise cross-ventilation. Windows are not, surprisingly, always wide. Continuous ventilation is obtained by using porous building envelopes such as woven bamboo (for walls) and handmade clay tiles (for roofs). Some traditional architectures adopt elevated floors with one of their purposes is to expose the buildings to higher wind speed. Indonesian modern (or contemporary) architectures mostly

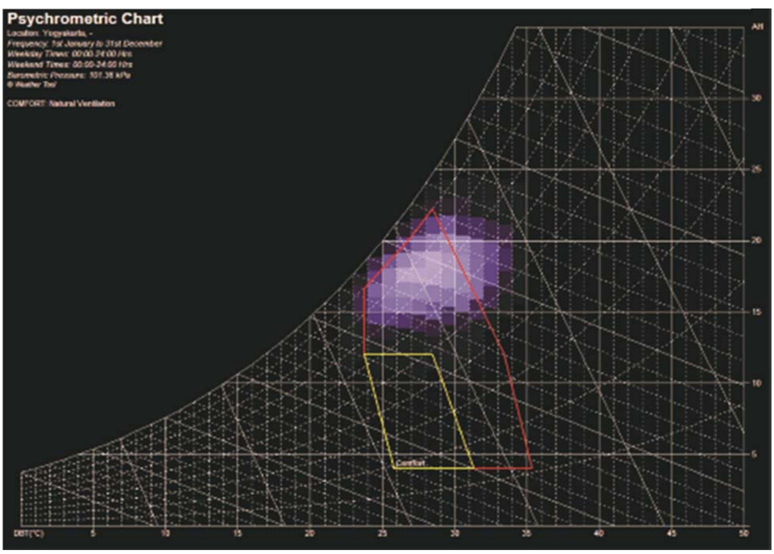

Figure 2. Atmospheric condition of Yogyakarta (bluish squares) which is out of thermal comfort zone (bordered by yellow line). Passive ventilation can generate physiological cooling to create comfort (bordered by red line).

adopt windows with various styles. When those windows cannot provide comfortable indoor air, ACs are installed. Windows are the most common means of passive ventilation in Indonesian architectures. Roof ventilators, solar chimneys, double skin facades and windcatchers are not popular yet.

Basement is not a typical building part of Indonesian architectures. It has no root in Indonesian architectures. Heavy rains that easily cause floods, high humidity, crawling creatures may have made basement unpopular. However, now it is common that contemporary Indonesian architectures, particularly multi-level buildings, have basements for structural stability, utility and parking spaces. Nowadays, basements are used for supermarkets, cinemas, cafes, malls, auditorium and other functions than merely for utility and parking spaces.

With the absence of windows, natural air can be conveyed to basements by windcatchers. Unfortunately, windcatcher has never been developed in Indonesia. Low wind speeds and low wind presences in warm humid climate have made windcatchers not promising passive ventilation means. A combination of longitudinal windcatcher and low wattage exhaust fans creates continual ventilation that avoids heat accumulation and provides evenly distributed comfortable indoor air velocity. This paper reports a research project that develops a longitudinal hybrid windcatcher for a basement.

2. Research question

The research project reported in this paper is based on a question how to develop a prototype of longitudinal hybrid windcatcher that can provide continuous thermal comfort and healthy ventilation for basement in warm humid climate where wind speed is low and relative humidity is high. It means, during the frequent calm wind, the windcatcher should have backup from exhaust fans to keep the ventilation going.

3. Research method

This research used three main methods. Literature study, the first method, was conducted to explore the state of the art of windcatcher. Computer simulation using a CFD program, the second method, was used to develop the prototype of the longitudinal hybrid windcatcher. The computer simulation involved preliminary experiments using trial-and-error method to find the most promising prototype to develop. This optimum design was then studied further. Physical model measurement, the third method, was used to see the performance of the optimum design found at the computer simulation in a real model.

Literature study listed findings from previous research on windcatcher so that the model development can be more efficient. Computer simulation was used since there was no reliable wind tunnel to test building models available in Indonesia. Computer simulation has some advantages over physical experiment in that it is easy to adjust the model, less labour, less expensive, no need to scale down the building, gives considerable and various results that are ready to post-process. Physical model is important to get the real world sense. The physical model experiment is not to validate computer simulation findings as they have different scales.

For the computer simulation, the research used CFD-ACE+ ver.4.0. For the physical model measurement, this research built a one-tenth scaled model and used two anemometers. Smoke for air tracing was generated by burning dry Sukun trees's flowers (eng. Breadfruit tree's flower, lt. Artocarpus altilis), locally named *onthel*. Four small fans were used to replicate four exhaust fans.

4. Objectives

The development of the hybrid longitudinal wind catcher (HLWC) is based on the following objectives:

(1) HLWC uses low-wattage exhaust fans as backups to keep the ventilation going in no-wind days thus avoids heat accumulation;

(2) HLWC provides evenly distributed comfort air flow in the occupants' zone. The longitudinal-shaped windcatcher at the basement, though only applied on the two opposite walls, follows a common recommendation in warm humid on ground architectures where wide openings or porous walls are important to induce cross-ventilation;
(3) HLWC makes basements useable for activities other than utilities and parking spaces;
(4) HLWC makes use of the narrow thermal comfort margin in warm humid climate. The 29 °C air temperature can be comfortably warm provided there is sufficient air velocity. HLWC generates around 0.5 m/s indoor air velocity that induces physiological cooling without necessarily causes disturbance for sedentary activities (such as reading and writing);
(5) HLWC uses low-wattage exhaust fans (around 25 watts) that do not consume too much electricity energy (thus keep the electricity bill and carbon emission low), do not create high ambient noise as their noise class is around 55dB and have low technology and low maintenance cost (that are suitable for low profile institutions such as public schools);
(6) HLWC uses light double walls that are actually the wall of the above room. Thick wall up to 30cm are common in Indonesia, in the colonial era, when the Dutch built bearing walls made of bricks. HLWC is used as the light thick walls (since it is made of metal claddings) of the room above the basement.

5. Windcatchers

Windcatchers (Persian: badger, badgeer) were originated from Iran, around eight century Hijri (around thirteenth century AD), and are claimed as the symbol of Persian civilization. The main purpose of wind catchers is to cool the interior and structure through convection and evaporation (Pirhayati, Ainechi, Torkjazi, &Ashrafi, 2013). Even though Iran is the original land of wind catchers, countries across the Middle East from Pakistan to North Africa (Iran, Afghanistan, Pakistan, Egypt, Iraq, United Arab Emirates) seem to have their variants of wind catchers (Bahramzadeh, Sadeghi, & Rou, 2013). Hassan Fathy, a prominent Egyptian architect, assigned the emergence of wind catchers in Egypt.

Khalaf (2012) stated that windcatcher has a strong existence in Arabic countries, which share almost similar climate. He claimed that windcatcher is an identity of Arabian cities. Another researcher, Ferrante (2012), states that wind catcher has zero-energy building potential for Mediterranean climate in the future. For passive cooling in this climate, vertical air extraction and windcatcher are two most effective techniques.

The airflow mechanism of wind catcher has been studied in depth by Hughes and Cheuk-Ming (2011) based on external wind and buoyancy. He utilised CFD program as his tool. He found that external driving wind force providing 76% more internal ventilation than buoyancy. Buoyancy effect is insignificant without an external airflow passage other than windcatcher itself. Additional air passage increased ventilation by 47%.

Designs of windcatchers have been evaluated by independent researchers such as Elmualim (2006b). He found that incorporation of dampers and egg crate grille at ceiling level reduces and regulates the airflow rate with an average pressure loss coefficient of 0.001. Saadatin, Haw, Sopian and Sulaiman (2012) conducted thorough review involving windcatcher attributes, configurations and technologies. He grouped windcatchers into three groups, i.e. Vernacular, modern and super modern. He found that octagonal shape windcatcher is weaker than square and rectangular ones. Dampers and egg crate can reduce up to 71% of wind speed. He studied from two openings to twelve openings. His experiment found that 0° incident angle of wind induces only 0.029 m^3/s, which was confirmed by CFD for 0.031 m^3/s.

Montazeri and Azizian (2009) studied windcatchers using empirical and mathematical (CFD) method. Two one-sided wind catchers were placed back to back to form two-sided windcatcher. Maximum efficiency was found when air incident angle was 90^0 that is 20% more than 0°. From 0° to 50° there is no significant difference between two-sided and one-sided. Two-sided windcatcher did not tend to have zero. Distance-to-adjacent buildings affect performance of windcatchers. Close buildings created wake flow that produced suction effect. Farther building induced airflow.

Many researchers have studied wind catchers with different tools. Zarandi (2009) analysed 53 wind catchers of Iran using field measurement and computational fluid dynamic software (CFD). He studied three positions of wind catchers with various forms, i.e. circle (very rare), octagon, polygon, square and oblong. He found that + (plus) shape wind catchers give the best performance among others. High air temperature of 40 °C can be reduced to 29.3 °C and the low relative humidity of 17% can be risen to 36%. Various shapes have also been studied by Maleki (2011).

Elmualim (2006a) used wind tunnel and CFX program to study wind catchers. He found that the performance of wind catchers depends greatly on the direction and speed of the wind in relation to the wind catcher quadrants. Ventilation rate increases with wind speed and decreases with the increase of the angle of the wind, particularly at low wind speed. In terms of research tool, he found that wind tunnel and CFX test correlate relatively well, especially for 0°–15°.

Windcatchers are mostly used in dominated hot and dry regions. Even though those regions sometimes experience hot humid season as well, their humidity may not as high as in warm humid tropical regions such as in Indonesia. Traditional architectures of Indonesia do not have wind catchers that might tell that wind catchers are not suitable for warm humid tropical climate. Priya, Sundarraja and Radhakrishnan (2012) studied one-sided wind catchers in coastal region of Nagapattinam (India) during summer and winter. The building has heavy thermal mass. With outdoor wind speed of 1–8 m/s, indoor airflow can be of 0–1.5 m/s.

Modern windcatchers were developed and innovated. Chen and Zhong (2008), for example, innovated wind catchers with PV boards, integrated techniques, combining structure technology with new material technology and aerothermodynamics theory to solve thermal protection and insulation in buildings. There is improvement of overall efficiency. Phan (2010) studied innovative wall integrated passive evaporative cooling system in the context of Seville (Spain). He states that evaporative desert cooler risk of microbiological contamination and conventional desert coolers 25% less energy but unsightly. Elmualim (2006c) studied hybrid natural ventilation windcatchers and air-conditioning system (Bluewater Shopping Mall in Kent) and assessed the contribution of windcatchers to indoor air environments and energy savings. The rotating wind catchers are automatically controlled in conjunction with mechanical ventilation system.

Elmualim and Awbi (2003) conducted post occupancy evaluation at the seminar room at the University of Reading, UK that applied wind catchers combined with light pipe to form Sun-Catcher. They found that 75% of the occupants were satisfied. Indoor air quality parameters were found to be within acceptable levels when windcatcher was in operation. Air change rate was 1.5 ac/h–6.8 ac/h. This proved that wind catchers are welcome in UK buildings. In terms of CFD program use, steady state condition could not accurately establish the performance of natural ventilation.

Windcatchers in western world, different climate with Iran, are the product of innovation. They integrated the principles of windcatchers with modern technology and modern devices. Combining traditional knowledge and advanced technology is necessary. Research is necessary to develop practical guidelines for the design of wind catchers for all types of building. Leading architects' works will attract wider public. Windcatchers are promising for the twenty-first century architecture (Shorbagy, 2010). There is demanding for truly understand windcatcher for future development. High towers of the region grew too large during a period of economic boom and soaring social hubris. These structure may survive less well than if they had been more modest in their design (Aryan, Ehsan, Amin, & Masoud, 2010).

Windcatchers are applied to various rooms. Their applications to induce airflow in basement have been found in Iran and Iraq and mostly with inclined top with 2-m high and 2.5 m x 2.5 m section area (Bahramzadeh et al., 2013).

Based on the above citations and discussions, the prototype of HLWC for basement ventilation in warm humid climate was developed. It was not a straightforward process. Instead, it was an iterative,

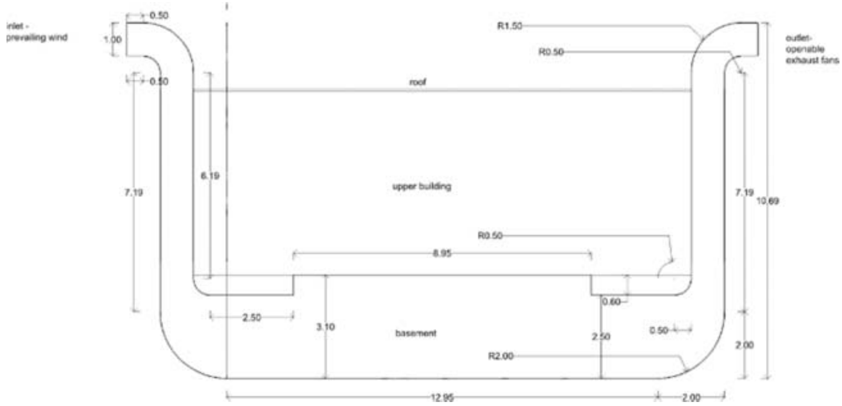

Figure 3. A rough sketch of 1 m high HLWC prototype (full-scaled, in meter). 1-m high is measured between the inlet's lower edge and the average surrounding roofs' height.

trial and error, process before an optimum model was found. The HLWC's sketch is shown in Figure 3. The prototype features are as follows:

(1) It is a longitudinal windcatcher with rectangular section to provide evenly distributed airflow. Thus, instead of adopting centric windcatcher form, which will not provide evenly distributed airflow, the prototype uses the whole length of the basement as reference.
(2) The longitudinal walls of the basement are incorporated with the windcatcher to form longitudinal inlet and outlet.
(3) The chimneys of the longitudinal windcatcher are formed in such a way to provide openings for the upper building.
(4) No grills are applied at the inlet and outlet to avoid too much wind speed reduction.
(5) Fans are installed at the outlet to draw the warm and humid indoor air out when there is no wind flow outside. Thus, these fans assure continual ventilation. This feature elaborates the original windcatcher design. The array of fans is held by an adjustable plane that fit to the outlet. During the calm condition, this plane is put down and the fans are turn on. When there is wind, this plane is lifted up to let the cross-ventilation exists. Consequently, the inlet should be oriented to the prevailing wind direction.
(6) A CFD program is used to digitally simulate the performance of the full-scaled prototype.
(7) A one-tenth scaled physical model is constructed based on the computer model.

6. Modelling

The object of this research is a basement of the Public Vocational Senior High School number 2 (Sekolah Menengah Kejuruan Negeri 2), which is located in Wonosari, Gunung Kidul Regency. This 8.40 m long x 6.82 m wide x 3.11 m high basement is used for drawing workshop and operated from 07.00 to 15.00, from Monday to Saturday. It can host 16 students and 2 teachers. Drawing tables are used. Therefore, internal heat gains are from lamps and occupants. Currently, its ventilation is served by two industrial exhaust fans (6.7 m/s), which produce noise (up to 70 dB) and can maintain the basement's air temperatures around 28 °C (ranges from 27.2 °C to 28.6 °C) with Relative Humidity around 76%.

Based on the literature study and preliminary trial-and-error experiments two computer models of a longitudinal windcatcher was made (see Figures 4 and 5). Since CFD program does not require the model to be scaled down, the models were made in their full-scale. They were the interior envelope of the basement with longitudinal windcatcher. These models were placed within a virtual wind

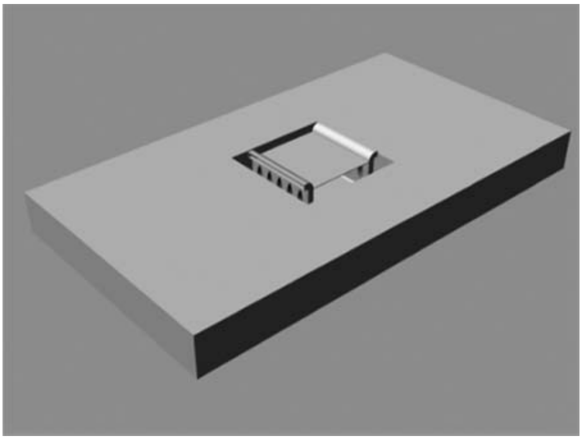

Figure 4. The 1-m high windcatcher computer model. The inlet's and outlet's lower edge of the windcatcher are 1-m higher than the surrounding roofs. To simplify the modeling of the surrounding roofs, their heights were averaged and then constructed as flat surroundings. Otherwise, the CFD program would be exhausted and crashed.

tunnel. These two models were different in their inlet height, 1 and 4 m above the averaged surrounding roofs. Measurements were conducted at point 1 (at the middle of the inlet), point 2 (1.2 m above floor at the middle of the room) and occupants' zone (averaged air velocities at the section area 1.2 m above floor).

A one-tenth scaled physical model was constructed at the Architectural Technology Planning and Design Laboratory, Fakultas Teknik, Universitas Atma Jaya Yogyakarta (Figure 6). This physical model was built based on the optimum ventilating performance of windcatcher design found in the computer simulation. Due to budget limitation, only one physical model was constructed, i.e. the 1-m high windcatcher. It was made of multiplex wood and transparent material (mica) to observe the wind pattern inside it. Four detachable 3 watt-12 volt fans were installed on one of the opening to suck the air out. One anemometer was inserted at the bottom of the model. Smoke was generated by burning a *sukun flower* (lt. Artocarpus altilis) and inserting it in a hole below the inlet. The smoke showed the airflow pattern.

The experiment consisted of two experiments, i.e. computer simulations and physical model experiment. For the computer simulation, the two types of windcatchers were simulated under five

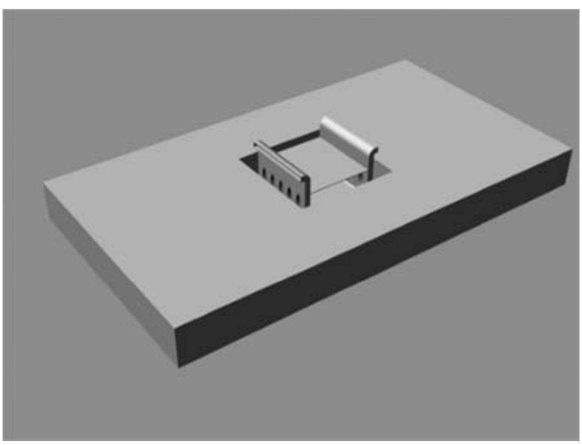

Figure 5. The 4-m high windcatcher computer model.

Figure 6. The one-tenth scaled model of the hybrid longitudinal windcatcher (HLWC).

different wind speed (1 to 5 m/s) representing wind speed at 10 m above ground. These speeds were input at the inlet of the virtual wind tunnel, one at a time. An atmospheric boundary layer profile was applied for the incoming wind profile (Figure 7). For the one-tenth physical model simulation, two experiments were conducted, with natural wind speed and with exhaust fans installed at its outlet (representing a condition when the wind speed is zero so that exhaust fans are used to maintain the cross-ventilation).

7. Experiment 1: computer simulation

The computer simulation used an optimum model found in the preliminary trial-and-error experiments. The trial-and-error experiments have evolved the optimum windcatcher model from 27

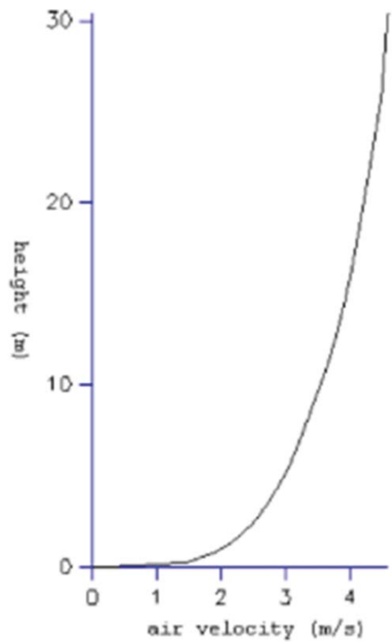

Figure 7. Atmospheric boundary layer applied at the inlet of the virtual wind tunnel.

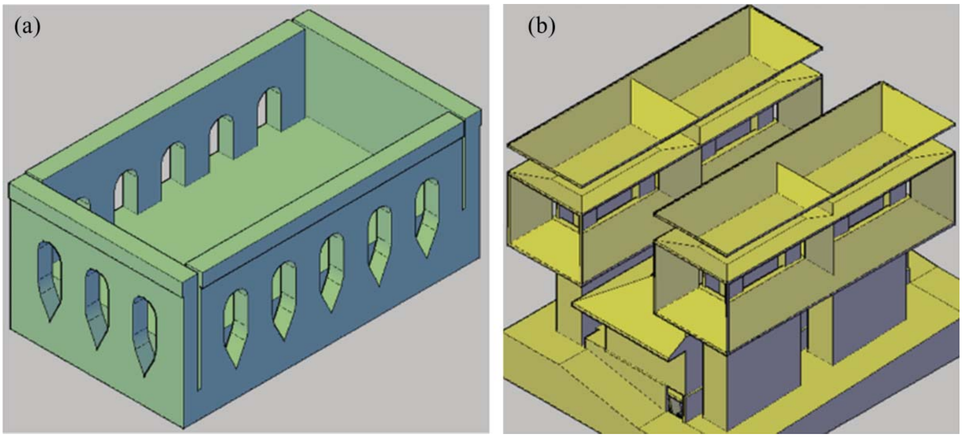

Figure 8. (a). A model of windcatcher with inlet/outlet in its four sides. Openings on the chimneys provide wind path for building above the basement. (b). A model of windcatcher with special shape of inlet and outlet to create Venturi effect.

previous models. Those models were developed based on ideas emerging during the literature study. Figure 8(a) and 8(b) shows two of the previous models with various heights, orientations of the inlet and outlet, the forms of the chimney (with openings and without openings for the upper building), continuous and separated chimneys, and the form of the inlets (to create Venturi effect).

Table 1 shows the simulation result of the 1-m high windcatcher. Outdoor wind speeds decrease at the inlet with linear correlation. Outdoor wind speed of 1 m/s decreases to 0.47 m/s when it is about to enter the inlet (point 1). It flows down along the inlet cavity to the basement and produces 0.17 m/s at a point 2. Averagely, 1 m/s outdoor wind generates 0.19 m/s at the occupant zone, which is too low to generate physiological cooling. However, this low air velocity is still able to ventilate the used air at the basement and avoid heat accumulation from the activities. 5 m/s wind speed generates averagely 1.01 m/s at the occupant zone, which is good for physiological cooling (but it will disrupt clerical works).

Local data state that average wind speed is around 3 m/s. This speed generates an average indoor air at the occupant zone 0.55 m/s, which is considered comfortable.

Table 2 shows the simulation result of the 4-m high windcatcher. Outdoor wind speeds of 1 m/s and 5 m/s generate average indoor air velocity of, respectively, 0.06 m/s and 1.05 m/s at the occupant zone.

Table 1. The 1-m high windcatcher.

Outdoor air velocity (m/s)	Air velocity at inlet (m/s)	Air velocity at a point in the middle of the room, 1.2 m above floor (m/s)	Average air velocity in the occupants' zone 1.2 m above floor (m/s)
1	0.47	0.17	0.19
2	0.69	0.25	0.26
3	1.38	0.54	0.55
4	1.96	0.77	0.79
5	2.51	0.98	1.01

Table 2. The 4-m high windcatcher.

Outdoor air velocity (m/s)	Air velocity at inlet (m/s)	Air velocity at a point in the middle of the room, 1.2 m high from floor (m/s)	Average air velocity in the occupants' zone 1.2 m above floor (m/s)
1	0.20	0.07	0.06
2	0.66	0.22	0.21
3	1.53	0.45	0.50
4	2.90	0.76	0.81
5	3.09	0.98	1.05

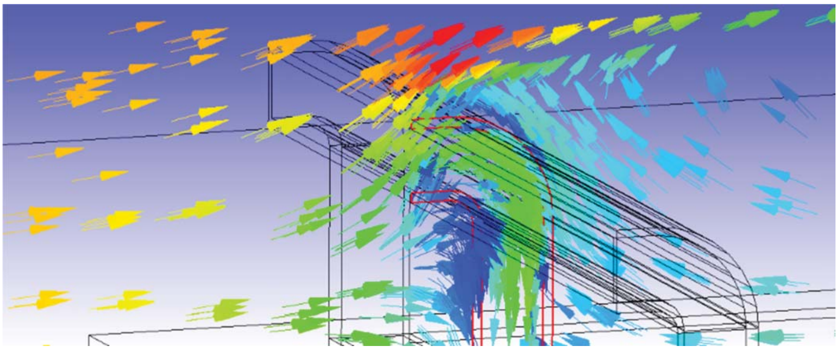

Figure 9. Wind pattern around the inlet.

Comparing Table 1 with Table 2 shows no significant difference. Raising the inlet of the windcatcher 3-m high does not give significant difference of the indoor air velocity. A zoomed view of the 4-m high inlet shows the air pattern around the inlet (Figure 9). The wind flows upward that might slow down the speed of wind air entering the inlet.

The wind speed linearly influences the indoor air velocity. In both models, the 1- and 4-m high windcatchers, the change in wind speed directly affects the indoor air velocity. The mathematical expressions of the relation between outdoor wind speed and indoor air velocity in the 1- and 4-m high windcatchers are, respectively, $y = 0.217x - 0.091$ and $y = 0.258x - 0.248$ with R^2 of 0.9761 and 0.9892. Those R^2s show a strong relation between outdoor and indoor air velocity.

Figure 10 shows the distribution of indoor air velocity in the 4-m high windcatcher. It shows that the air velocity was evenly distributed at the occupants' zone. Openings on the chimneys do not seem to affect the distribution of the air velocity at the occupants' zone. This is good as those openings are important for the building above the basement.

Particle tracing shows almost laminar airflow inside the 1-m high windcatcher (Figure 11). A minor turbulent flow existed at the lower part of the inlet chimney. This can be understandable since the air velocity is relatively low. More turbulent flows are expected in higher air velocities.

The results of the computer simulation can be further discussed as follows:

(1) Increasing the height of the chimney 3-m high gives insignificant indoor air velocity increase even though it increases the air velocity at the inlet (Figures 12 and 13). This is because the area of the inlet is much smaller than the area of the longitudinal section (perpendicular to the airflow) of the room. Thus, even though the volume of air passing through both sections

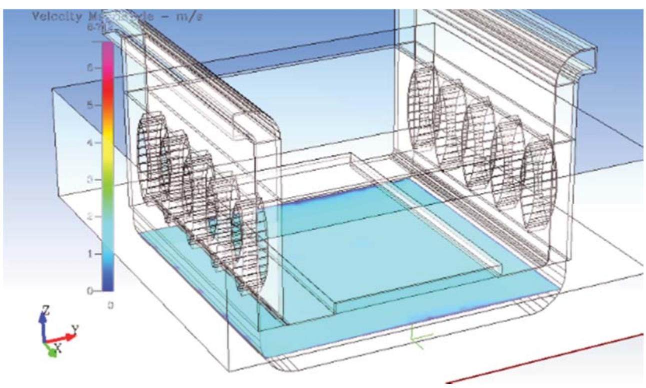

Figure 10. The air velocity distribution at the occupants' zone showing even distribution.

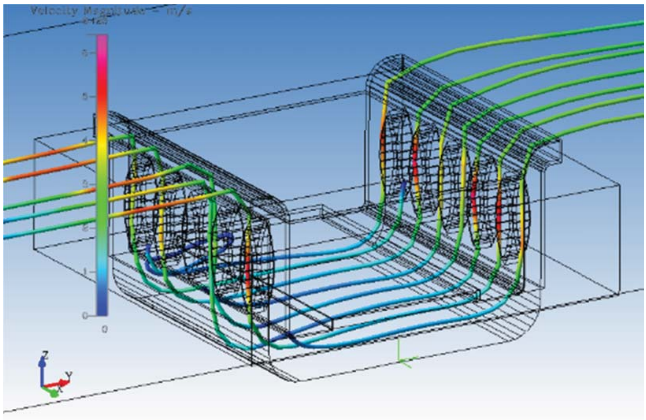

Figure 11. Particle tracing at the 1-m high windcatcher showing laminar flow.

are the same, the air velocity at the longitudinal section of the room is much lower than air velocity at the inlet.

(2) Shaping the chimney's upper and lower elbows curved (curved heels and curved throats) minimises the presence of vortexes. Otherwise, square elbows will reduce the smoothness of the airflow and, eventually, reduces the indoor air velocity. HLWC applies smooth radii, which ensures uniformity of airflow.
(3) Shaping the chimney wall's openings curved (with sharp ends) helps smoothing the airflow pattern after passing through the narrow passages and then forms evenly distributed air velocity toward the room.

8. Experiment 2: physical model simulation

Experiment with the physical model showed that the exhaust fans array could generate evenly distributed airflow. As it has been mentioned previously, four small fans were used to imitate the exhaust fans (Figure 14). Air velocity of 3 m/s was detected at 30 cm in front of one of these fans when they were turned on. It can be seen from Figure 15 that the smoke flowed evenly inside the model. There was no obvious presence of turbulence. The air velocity inside the model was very low so that it could not be detected by the anemometer. Unfortunately, there was no Kata thermometer available to measure this low air velocity. Using visual method, the time of the smoke passing in front

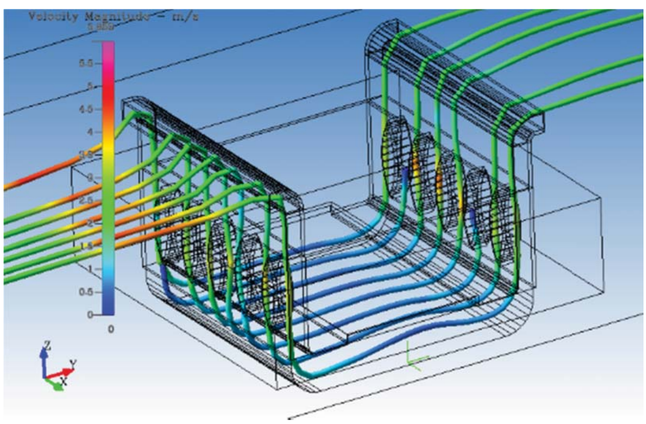

Figure 12. Particle tracing at the 4-m high windcatcher.

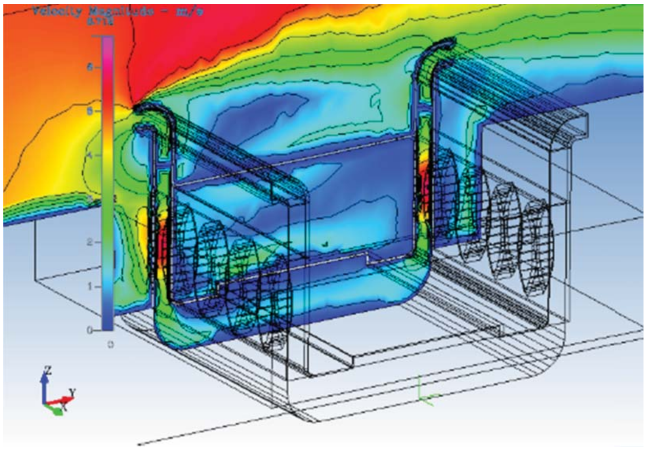

Figure 13. Vertical section through the chimney of the 4-m high HLWC shows air velocity distribution. Occupants' zone in the basement is swept by airflow that is good for physiological cooling and avoids heat and pollutant accumulation.

of the 10 cm grid paper could be estimated. It was estimated that the fans array could generate around 0.05 m/s air velocity.

Experiments with the physical model outdoor found that wind could generate indoor airflow. The experiment was conducted in the afternoon when wind flow was likely. Two anemometers were used, one was placed at the middle of the inlet and the other was placed inside the model, right at the middle of the room. It was found that air velocity in the model was approximately one-tenth of the air velocity at the inlet. Air velocity of 3 m/s at the opening generated 0.3 m/s air velocity inside the model. The smoke showed mostly laminar airflow with temporary turbulent. (Figure 16) During the experiment, the air temperature was 31.8 °C and the Relative Humidity was 52.1%.

The result of the physical model simulation can be further discussed as follows:

(1) Indoor airflow shows a dominant laminar flow with minor turbulent even though the outdoor wind fluctuates. Entering the larger space (from the chimney to the room) reduces the wind speed while the air in the room acts as a damper which reduces the speed fluctuation.
(2) The curved elbows smooth the airflow and minimise vortexes (which can result in uneven airflow distribution in the room).

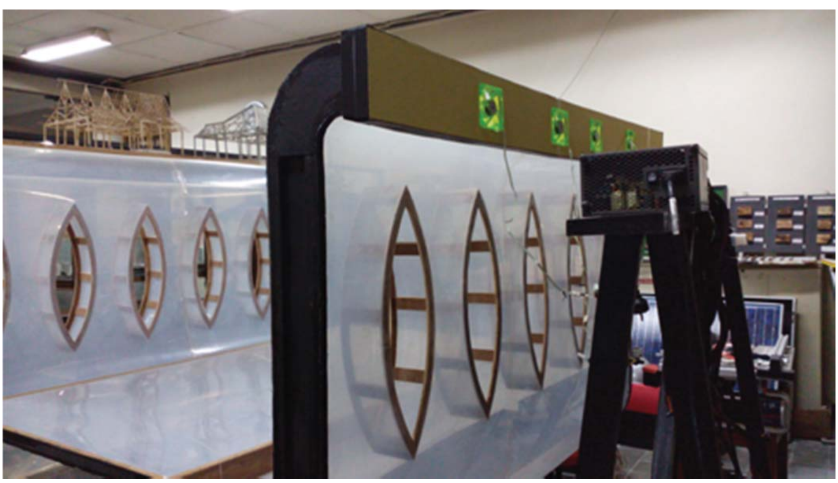

Figure 14. An array of four fans induces airflow inside the model to imitate the calm days.

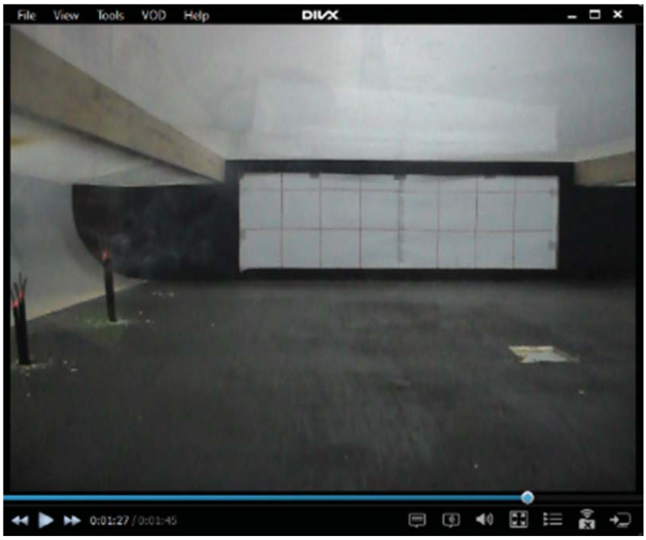

Figure 15. A snapshot to the video shows the smoke flowing when the exhaust fans turned on. This imitates the calm day situation.

Computer and physical model simulations can be compared as follows:

(1) With the same wind velocity of 3 m/s at the inlet, the full-scaled computer model and the one-tenth scaled physical model induce, respectively, 1 m/s and 0.3 m/s indoor air velocity. Airflow near the walls is subject to wall resistance. The farther the airflow from the walls the less the resistance effect is. In the full-scaled model, the air flows more freely than in the one-tenth scaled model. The size of the model is scalable, but the property of the air (in this case its density) is not scalable. Thus, scaling the model's size is not linearly scaling the indoor air velocity.
(2) The computer and physical simulations show a dominantly laminar airflow though the latter tended to have a bit more of light turbulent flow at some locations. This difference might be a matter of grid resolution setting of the CFD software. A higher grid resolution (requiring more powerful computer) might reveal those light turbulent flows.

Sensitivity analysis of HLWC can be conducted so that it can perform as expected:

(1) Both computer and physical model simulations were conducted with wind flowed perpendicular to the inlet, which induced optimum indoor air velocity. Thus, orienting the inlet to the

Figure 16. A snapshot to the video showing the smoke flowing when the model was placed outdoor while there was wind.

prevailing wind is necessary. However, it is not always practical. Placing adjustable fins in front of the inlet to direct oblique wind flow perpendicular toward the inlet might improve the wind speed.

(2) HLWC works with providing a pressure difference between its inlet and outlet to induce indoor airflow. A higher chimney will generate stronger stack effect from its bigger air temperature difference (or bigger air density difference) between the lower and upper air to generate a stronger vertical airflow. This effect is useful if there are openings at the room. Since there are no windows at the basement (which directly connect to the outdoor) the stack effect is not useful and might affect the efficiency of HLWC. Thus, keeping the height of the inlet just above the averaged neighbouring roofs are preferable.

(3) Since increasing the height of the chimney for a few meters does not give a significant increase in indoor air velocity, keeping the chimney low is preferable as it will help minimizing wind pressure on the chimney walls as well as the construction cost.

(4) Curved elbows, with smooth radius, smooth the airflow and minimise turbulent. Even though constructing them is not as simple as constructing square elbows, it is worth it to keep the curved forms.

(5) The simulations were done with the inlet free from any wind obstruction. In warm humid climate, torrential rains and insects may need the installation of overhangs and insect screens, which will significantly reduce the efficiency of HLWC.

(6) All simulations were conducted without any indoor wind obstructions, which helped indoor air flowing freely. To maintain this performance, wind obstructing partitions and furniture should be avoided.

(7) To maximise the physiological cooling effect of the generated indoor air velocity, internal heat gain should be minimised. Using low heat emission LED lamps and laptop computers (instead of desk top computers) are recommended.

9. Conclusion

The hybrid longitudinal windcatcher has been able to provide good ventilation for the basement with the presence of wind and with the backup of exhaust fans during the calm days. Computer simulation using full-scaled model of windcatcher showed that prevailing outdoor wind speed of 3 m/s generates 0.50 m/s at occupant zone, which is comfortable for class activities. Raising the inlet of windcatcher 3-m high does not produce significant difference. Thanks to the longitudinal configuration, the indoor air movement at the occupant's zone is evenly distributed. Experiment with a one-tenth scaled physical model showed that 3 m/s outdoor wind induced 0.3 m/s air velocity inside the model with mostly laminar flow interrupted by a small turbulent flow. Installing an array of four exhaust fans, without outdoor wind presence, generated low air velocity of 0.05 m/s. This low air ventilation is still useful to provide ventilation and avoid heat accumulation inside the building. The hybrid longitudinal windcatcher is a promising mean to provide thermally comfortable and healthy ventilation for basement in warm humid tropical climate such as in Indonesia.

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References

Aryan, A., Ehsan, Z., Amin, S., & Masoud, K. (2010). Wind catchers: Remarkable example of Iranian sustainable architecture. *Journal of Sustainable Development, 3*, 89–97.

Bahramzadeh, M., Sadeghi, B., & Rou, S.S. (2013). A comparative study to compare the wind catcher types in the architecture of Islamic countries. *Journal of Basic and Applied Science Research, 3*, 312–316.

Chen, X., & Zhong, D. (2008). Economy-oriented strategy of appropriate technique. *Front Archit. Civil Engineering China*, *2*, 371–378.

Elmualim, A.A. (2006a). Dynamic modeling of a wind catcher/tower turret for natural ventilation. *Building Service Engineering Research Technology, 27*, 165–182.

Elmualim, A.A. (2006b). Effect of damper and heat source on wind catcher natural ventilation performance. *Energy and Buildings, 38*, 939–948.

Elmualim, A.A. (2006c). Failure of a control strategy for a hybrid air-conditioning and wind catchers/towers system at Bluewater shopping mall in Kent, UK. *Facilities, 24*, 399–411.

Elmualim, A.A., & Awbi, H.B. (2003). Post occupancy evaluation of a building employing windcatchers for summer ventilation. *Facilities, 21*, 323–332.

Ferrante, A. (2012). Zero-and low-energy housing for Mediterranean climate. *Advances in Building Energy Research, 6*, 81–118.

Hughes, B.R., & Cheuk-Ming, M. (2011). A study of wind and buoyancy driven flows through commercial wind towers. *Energy and Buildings, 43*, 1748–1791.

Khalaf, R.W. (2012). Traditional vs modern Arabian morphologies. *Journal of Cultural Heritage Management and Sustainable Development, 2*, 27–43.

Maleki, B.A. (2011). Wind catcher: Passive and low energy cooling system in Iranian vernacular architecture. *International Journal on Technical and Physical Problems of Engineering, 8*, 130–137.

Montazeri, H., & Azizian, R. (2009). Experimental study on natural ventilation performance of a two-sided wind catcher. *Proceeding ImechE, 233* (Part A: J. Power and Energy), 387–400.

Phan R.S. (2010). Environmental retrofit: Building integrated passive cooling in housing. *ARQ, 14*, 139–151.

Pirhayati, M., Ainechi, S., Torkjazi, M., & Ashrafi, E. (2013). Ancient Iran, the origin land of wind catcher in the world. *Research Journal of Environmental and Earth Science, 5*, 433–439.

Priya, R.S., Sundarraja, M.C., & Radhakrishnan, S. (2012). Experimental study on the thermal performance of a traditional house with one-sided wind catcher during summer and winter. *Energy Efficiency, 5*, 483–496.

Saadatin, O., Haw, L.C., Sopian, K., & Sulaiman, M.Y. (2012). Review of windcatcher technologies. *Renewable and Sustainable Energy Reviews, 16*, 1477–1495.

Shorbagy, A.E. (2010). Design with nature: Windcatcher as a paradigm of natural ventilation device in buildings. *International Journal of Civil & Environmental Engineering, 10*, 21–26.

Zarandi, M.M. (2009). Analysis on Iranian wind catcher and its effect on natural ventilation as a solution towards sustainable architecture (case study: Yazd). *World Academy of Science, Engineering and Technology, 54*, 574–579.