Performance Testing and Comparison of A Turbine Ventilator, A Vent Column, and Their Combination Under Thermal Buoyancy and Wind Effects

Nguyen Q. Y *quocyn@gmail.com*
Department of Civil Engineering
HCMC University of Technology
HoChiMinh City, Vietnam

Nguyen T. Bay *nguyentbay@gmail.com*
Department of Civil Engineering
HCMC University of Technology
HoChiMinh City, Vietnam

Ha Phuong *haphuong852001@yahoo.com*
Department of Civil Engineering
HCMC University of Technology
HoChiMinh City, Vietnam

Abstract

Ventilation performance of a curved-blade turbine ventilator, a straight column covered with a flat hat, and a device of their combination of the same material and throat diameter of 21cm were tested on a room model of 3.0m long, 1.5m wide, and 3.0m high under simulated external wind and/or internal heat source. The wind speed was from 0m/s to 3.6m/s. The heat flux was up to 3KW. Air speed through each device was measured and plotted as functions of both the wind speed and the heat flux. The results show that when buoyancy effects were dominant, i.e. internal heat source under low wind speed, the column performed best, followed by the combined device and lastly the turbine. When wind effects were dominant, the combined device worked best, followed by the turbine which was close to the column. Performance of the column was seen to suffer from the external wind while that of the turbine and the combined device benefited from it. Performance of the combined device was found to be better than that of the turbine due to stack effects gained by an increased throat height compared to the turbine's. This observation suggests a simple modification to boost performance of current commercial low-throat turbine ventilators.

Keywords: Turbine Ventilator, Vent Column, Wind Effects, Buoyancy Effects, Ventilation Performance.

1. INTRODUCTION

Saving energy and utilizing natural, green energy resources are one of the key concerns of the world presently. In buildings, energy can be saved by employing natural methods for ventilation to replace electric fans or air conditioners. Natural ventilation strategies or devices are based on two main effects (Khan et al 2008a, Linden 1999, Awbi 2003): pressure induced by external wind and stack effects induced by temperature difference.

Among natural ventilation devices, wind-driven turbine ventilator is the most common one. The device works both as a turbine driven by the external wind and as a fan withdrawing air from buildings' interior (Khan 2008a, Khan 2008b, Lai 2003). Though this device has been used for long time, it still attracts research interests, particularly to compare its performance to other devices' in enhancing ventilation (Lai 2003, Revel & Huynh 2004, Khan 2008b). Lai (2003) tested turbines with different sizes, and ventilation performance of a turbine with blades fixed or removed (thus forming a simple hole) under external wind. He found that the stationary turbine with fixed blades worked identically to when the blades were removed, but poorly compared to when it was free to rotate. Revel & Huynh (2004) and Khan et al (2008b) compared flow rate through turbines and simple straight columns covered with plates of flat or conical shapes under wind effects. They reported the column with the flat cover gave the ventilation flow rate almost equivalent to that of the curved blade turbine of the same throat size.

To enhance performance of turbine ventilators, Lai (2006) tested a prototype of a turbine using combined wind and photovoltaic energy by installing a fan inside the turbine. His results showed that the fan helped to increase ventilation rate under low wind speed.

In this study, ventilation performance of a turbine ventilator is tested and compared with a simple vent column and another device, which is made from combination of the turbine and the column, under both wind and buoyancy effects.

Our work is motivated from two facts. Firstly, as reported by Revel & Huynh (2004) and Khan et al (2008), a simpler, hence cheaper, straight column can match performance of a more complicated, hence costlier, turbine ventilator under wind effects. Secondly, in Vietnam, it is advertised as well as believed by the majority of people that turbine ventilators can help withdraw hot air from inside of buildings or factories even without external wind. A question was then raised to us about actual performance of the turbine, particularly when it is compared to the simple straight vent column under effects of external wind and large temperature difference between inside and outside buildings. To our knowledge, such tests have not yet been reported in the literature.

In addition, it is also interesting to combine the turbine and the column to benefit from the strength of each device: rotating effects of the turbine blade under external wind and stack effects of the column under large outside-inside temperature difference. Therefore, the third device was formed by adding the column to the turbine.

2. EXPERIMENT

Experimental setup is described in Figure 1.

The experiments were to simulate practical situations where the turbine was placed on top of a building or a room for ventilation. External wind flowed only over the turbine rather than over the whole building. With heat sources inside the building, e.g. cookers, computers in dwellings or working machines in factories, there was large temperature difference between inside the buildings and ambient air.

To simulate a ventilated room, a room model was built with the size of (length x width x height) 3.0m x 1.5m x 3.0m, which was similar (in height and length) to those of a small real room. The model was made of wood for good heat insulation properties. Air entered the model through an inlet of 0.8m x 0.6m and exited through the tested devices on the top of the model.

External wind was simulated using a 50W electrical fan with the diameter of 40cm. Elevation of the fan, positioned on top of the room to make flow covering the tested devices but not the whole room, was adjusted to match that of each tested device. Metal screens were placed between the fan and the tested devices to reduce the rotating velocity component of the wind created by the fan and to increase its uniformity. Wind speed was adjusted by two means: adding electrical resistances connected serially to the fan and/or putting more screens.

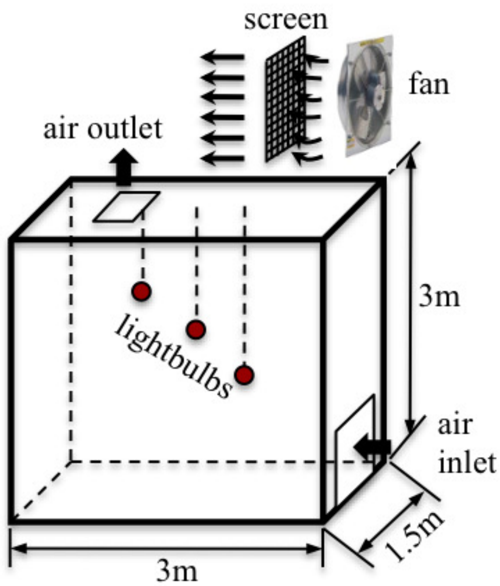

FIGURE 1: Sketch of the experimental setup.

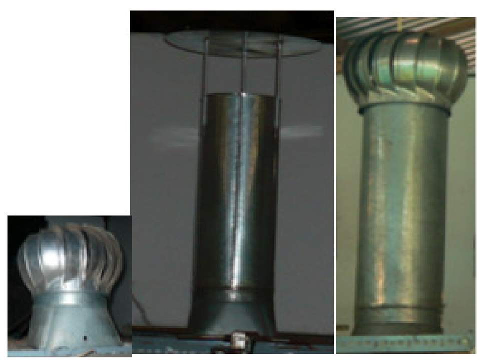

FIGURE 2: Three devices under test: (from left to right) turbine ventilator, straight column, and the combined turbine-column device.

For simulating internal heat sources, electric light bulbs of 200W each and distributed in the center plane of the room model were used. The heat flux was controlled by the number of lightbulbs turned on in each experiment.

With these apparatuses, the setup was capable of producing maximum wind speed of 3.6m/s, which was about the average wind speed in Hochiminh City, and maximum heat flux of 3kW, which yielded maximum inside-outside temperature difference of about 15^{o}C. Higher wind speed would require faster and bigger fans; hence more complicated systems to remove the wind's rotational velocity as well as to maintain its uniformity (for example, using a honeycomb). Higher heat flux would reduce the heat insulation ability of the model walls when the walls became hot quickly and large portion of heat was transferred to ambient environment.

Tested devices consisted of a turbine ventilator, a vent column, and a device of their combination, as shown in Figure 2. All of the three devices were made of the same metal material. The turbine had 16 curved blades with the throat diameter of 21cm and the height from the base to the throat of 18cm. The vent column was made by removing the blades of the turbine and connecting a circular tube to the throat to form the total height of 68cm. This height was over the minimum required value of 0.5m to prevent back draught (Awbi, 2003). The column was covered with a plane cap with the diameter of 42cm, or two times of the column's, and the distance from the top of the column is 15cm, or three quarters of the column diameter. The dimensions of the cap were selected after Khan (2008b). The combined device was made by replacing the cap of the column by the turbine blades. Consequently, all three devices had the same throat diameter of 21cm.

Speed and temperature of the air ventilated from the room model and through each device were measured under three conditions: external wind alone, internal heat source alone, and external wind coupled with internal heat source. Location of the measurement point was the same for three devices, namely at center of the throat of them. The external-wind speed was measured at a distance of 20cm in front of the devices. The speed of the air ventilated from the room model, the speed of the external-wind, and the temperature of the air were measured by a Kanomax A041 hotwire anemometer with the speed resolution of 1cm/s and the temperature resolution of 0.1^{o}C. Ambient air temperature was also read on an alcohol thermometer with a resolution of 0.25^{o}C. Testing range of the external wind speed was from 0m/s to 3.6m/s, and of the internal heat flux was 1KW, 2KW, and 3KW (equivalent to 5, 10 and 15 light bulbs turned on). Ambient temperature varied from 26^{o}C to 34^{o}C while internal temperature was from 26^{o}C to 50^{o}C.

3. RESULTS AND DISCUSSIONS

Figure 3 shows the air speed through the turbine's throat V_t for five test sets: external wind alone and the turbine was fixed intentionally (0KW-fixed); external wind alone and the turbine was free to rotate (0KW); wind coupled with 1KW, 2KW, and 3KW internal heat flux (1KW, 2KW, 3KW, respectively). V_t is seen to increase proportionally with both the wind speed and heat flux. In the test case 0KW, the free turbine did not rotate when the wind speed is 0m/s and 0.5m/s, and was identical to the fixed one. When the wind speed increased, the air speed through the free turbine was approximately twice of that of the fixed one. Therefore, hindered turbine ventilators, which are very common for the ones serving long time without maintenance, has very poor ventilation performance. This observation was also reported by Lai (2003). His results showed that a turbine with blades kept stationary could only produced ventilation flowrate of about one third of that when the blades were free to rotate.

It is noted that in the case of no wind and no heat (0m/s, 0KW) there still exists air speed through the turbine. This is believed to be due to the temperature difference caused by solar heat absorbed by the metal roof of the laboratory. Since all tests were done in nearly the same ambient conditions, this natural temperature difference affected all three tested devices similarly and thus should have negligible influence on the comparison of their performance.

With heat added (1KW, 2KW, and 3KW), but without external wind (0m/s), the turbine was still able to rotate with the air flow through it induced by the internal heat source. If the turbine was held stationary deliberately in these cases, the air speed through its throat decreased, as indicated by data point named "fixed" in Figure 3. From this observation, it can be interpreted that the freely rotating turbine, though received energy from the air flow to rotate, consumed less energy than the energy lost through the fixed turbine.

Khan (2008b) reported that turbines obey the fan law: the flow rate is proportional to the rotation speed. In our tests, as the wind speed increased and more heat was added, the turbine spun faster. Accordingly, the air speed should increase with both the wind speed and the heat flux, as seen in Figure 3.

In the case of combined wind-buoyancy effects, the empirical formula proposed by Walker and Wilson (Awbi 2003) allowed estimating the combined air speed:

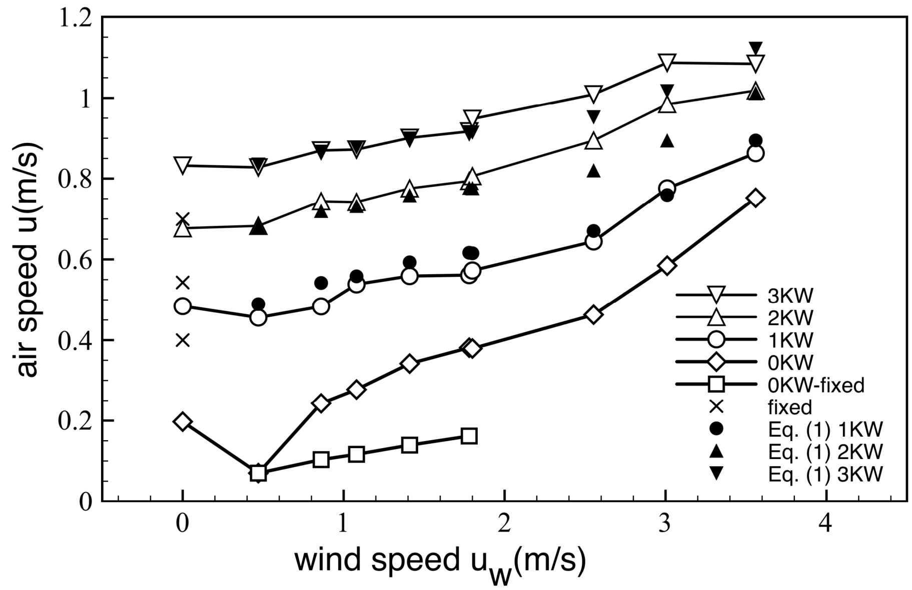

FIGURE 3: Air speed through the turbine ventilator.

$$u = \sqrt{u_w^2 + u_b^2} \tag{1}$$

where u_w, u_b, and u are the wind induced air speed, buoyancy-induced air speed, and the air speed under combined effects, respectively.

Eq. (1) was applied to estimate the air speed u for test cases of 1KW, 2KW, and 3KW from non-zero wind speed using u_w at 0KW and u_b at 1KW, 2KW, and 3KW but zero-wind speed, respectively. The results are also plotted in Figure 3, and show that Eq. (1) matches the measured data quite well, with maximum discrepancy about 10%.

To check reliability of the data, two test sets were conducted at wind speed of 1.8m/s which was obtained by two different combinations of the electrical resistances connected serially to the fan and the number of metal screens. Two separate data points of each test case (0KW, 1KW, 2KW and 3KW) at the wind speed of 1.8m/s in Figure 3 represent the results from this two test sets. Good reproductivity can be seen.

Figure 4 shows the air speed V_c through the column under combinations of the external wind and the internal heat source. As the heat flux increased, similar to the turbine, air speed increased accordingly. However, as the external wind speed increased, with and without the heat source, V_c seemed to vary in two regions. When wind speed was below about 1.3m/s, V_c was nearly constant. When the wind speed increased above 1.3m/s, in the test case of 0KW, V_c increased proportionally; in the test case of 1KW, V_c was nearly constant; but in the test case of 2KW and 3KW, V_c decreased.

From these observations, it can be seen that the external wind with speed below 1.3m/s had negligible effects on the air flow. Above this speed, with the wind alone, the airflow seems to benefit from negative pressure induced by the external wind on the top of column, hence V_c increased accordingly. With strong internal heat sources (test cases 2KW and 3KW), the air flow may be obstructed by the external wind with possible flow separation on the top of the column, hence effective area of the air flow was reduced and V_c decreased accordingly. With weak internal heat source (test case 1KW), air speed due to the heat alone was weak. Therefore, with an external wind, the air flow through the device was proportionally less obstructed by the wind flow separation, since the energy loss of the air flow was proportional to the square of its speed. In addition, in this test case, the nearly constant V_c at upper range of the wind speed can be explained from the balance between the reduction of the airflow area mentioned above and the negative pressure induced by the external wind.

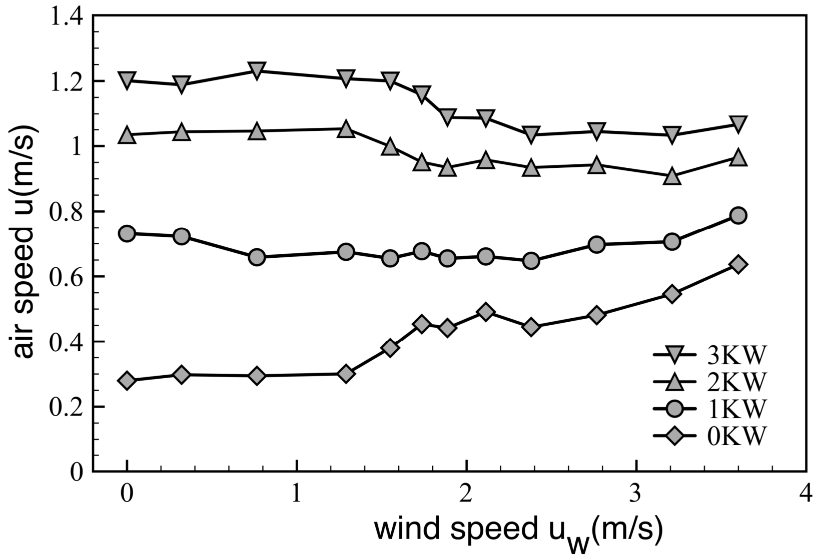

FIGURE 4: Air speed through the vent column.

As seen, for the column, wind effects did not assist buoyancy to enhance the air flow through the device. This is in contrast to Eq. (1). Consequently, Eq. (1) is not applicable to predict the combined wind-buoyancy effects on air flow through the column.

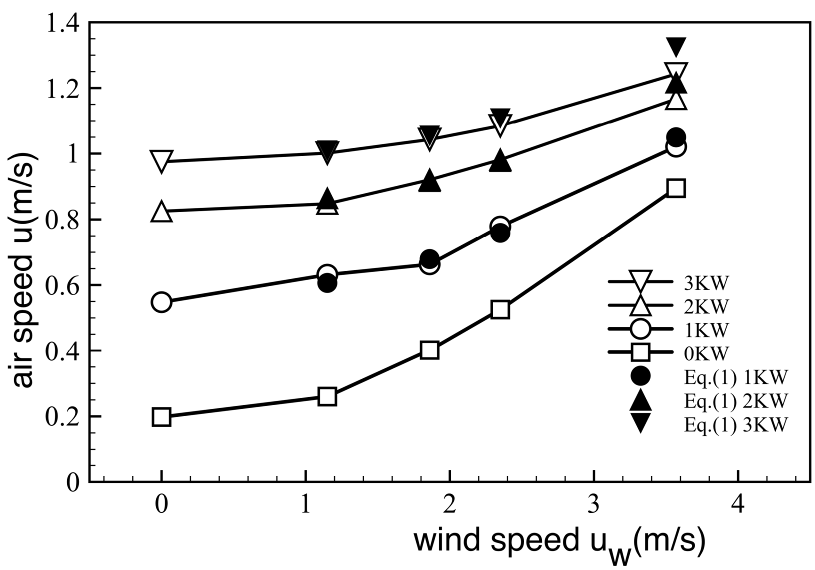

FIGURE 5: Air speed through the combined device.

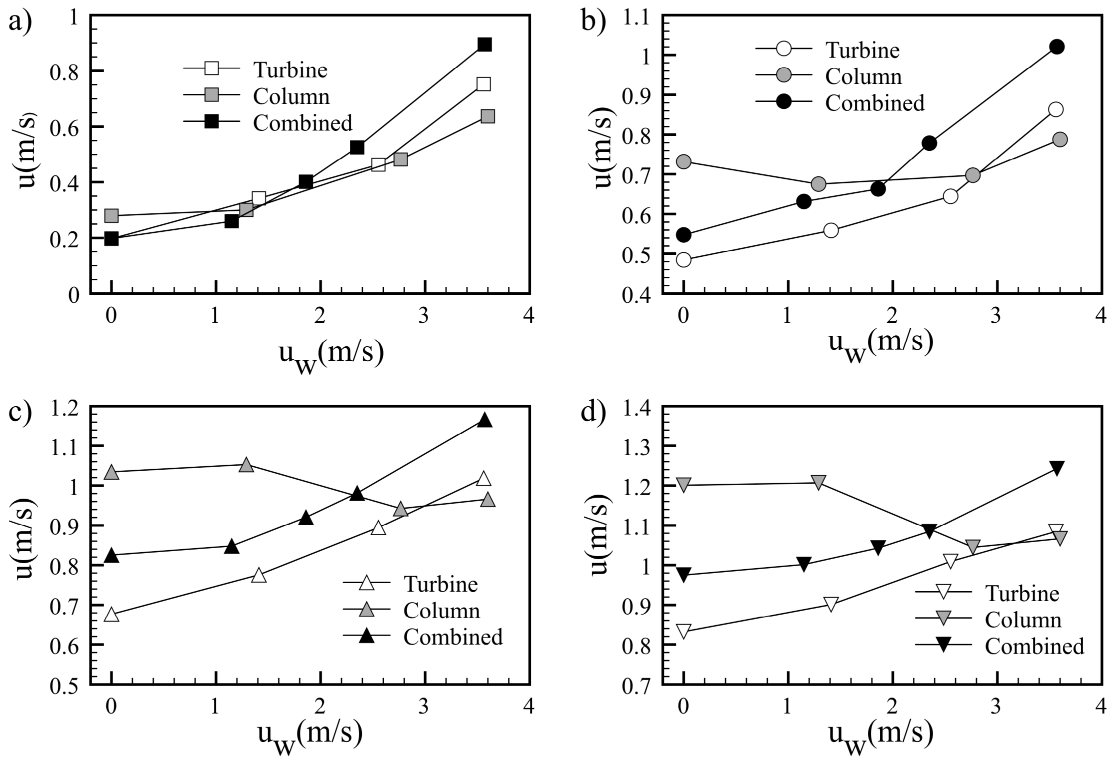

FIGURE 6: Air speed through three devices under different wind speed and heat flux: a) 0KW, b) 1KW, c) 2KW, d) 3KW

Figure 5 shows variation of the air speed V_{tc} through the turbine-column combined device. The variation is seen to be quite identical to that of the turbine; namely the air speed V_{tc} increased as both the wind speed and the heat flux increased. Eq. (1) was also applicable; the predicted data are also plotted in Figure 5. Agreement between the measured and the predicted data is seen to be even better than the case of the turbine.

To compare the performance of the three devices, their results are plotted together in Figure 6. With the wind alone (Figure 6a), performance of the turbine and the column are seen identical, except that at wind speed u_w=3.6m/s, the turbine gave a little more air speed. The combined device, however, outperformed the other two at the upper range of the wind speed, about from 2m/s and up.

Comparisons of the turbine and the column found in this test case are similar to the results by Khan (2008b). That author reported that a 250mm column with a flat cover, which was the design used in this study, “did manage to almost keep up” with a 250mm turbine up to a wind speed of 4.1m/s.

With the combined wind-heat (1KW, 2KW, and 3KW), performance of the turbine catches up to the column’s when wind speed was over about 3m/s. The combined device always performed better than the turbine at any heat flux and wind speed, and could only match the column at the wind speed of about 2.2m/s, and then demonstrated better performance afterward.

The combined device should benefit from stack effects that the column possessed but the turbine did not, and fan effects that the turbine had but the column did not. Meanwhile, it also suffered from the energy loss caused by the turbine. Consequently, performance of the combined device should be enhanced by the stack effects. On the other hand, since the stack effects mainly depend on the internal heat flux, performance line of the combined device at a specific heat flux is expected to run parallel to that of the turbine, as seen in Figure 6a, 6b, and 6c.

With the external wind alone, there is no stack effect. Accordingly, the performance of the combined device and of the turbine should be the same under the same fan effects. However, Figure 6a shows that at wind speed above 2m/s, the combined device drew more air. Reasons of this are not clear to the authors.

To seek a universal description of the results with the combined wind-heat effects, nondimensional parameters $u^*=u/(u_w+u_b)$ and $1/Ar$ (Etheridge 2002) are used and plotted in Figure 7, where:

- u_w: external wind speed (m/s).

- $u_b = \sqrt{\Delta T g h / T}$: buoyancy speed (m/s), in which T is the ambient temperature (^oK) and ΔT is the temperature difference between the ambient temperature (inlet temperature) and the air temperature at the outlet (^oK).

- $1/Ar = \rho u_w / \Delta \rho g h$: reciprocal of the Archimedes number, in which ρ is the ambient air density (kg/m^3) and $\Delta\rho$ is the air density difference between the inlet and the outlet (kg/m^3). ρ and $\Delta\rho$ are determined from the air temperature at the inlet and the outlet.

Wind effects are negligible for very small value of $1/Ar$ and buoyancy effects are negligible for very large value of $1/Ar$. Following Etheridge (2002), the test cases of wind alone are assigned to $1/Ar = 100$ and the test cases of heat alone are assigned to $1/Ar = 0.01$. At $1/Ar = 0.01$, values of $u^*=u/u_b$ (as u_w=0), are averaged ones from data of three tests of 1KW, 2KW and 3KW for each device, and at $1/Ar = 100$, values of $u^*=u/u_w$ (as u_b=0), are those corresponding to tests with maximum wind speed but without heat source, i.e. (u_w=3.6m/s, 0KW) for each device.

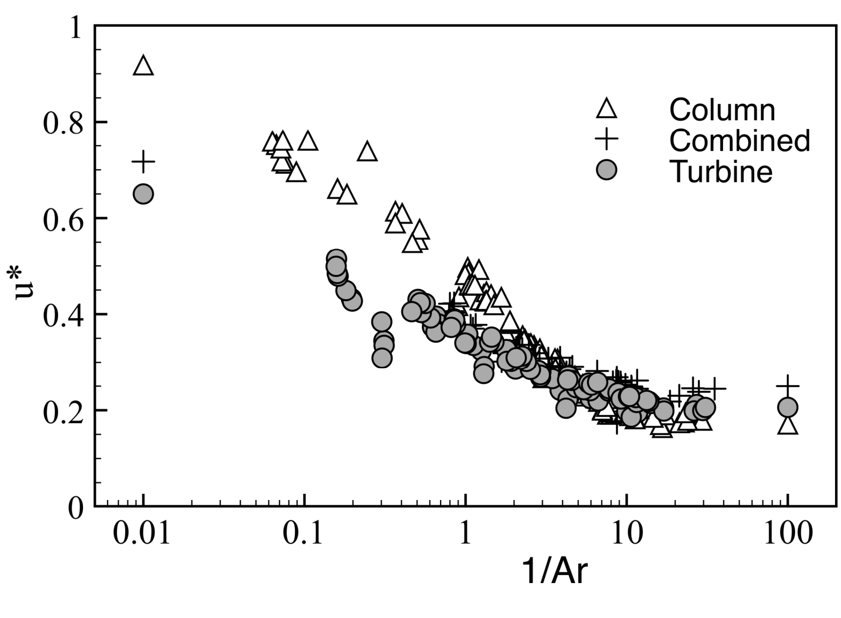

FIGURE 7: Nondimensional air speed through three devices against 1/Ar.

Figure 7 reconfirms that when the buoyancy effects are dominant, the column performs best, followed by the combined device and then the turbine. When wind effects are dominant, the combined device performs best, followed by the turbine and then the column. In addition, from the trend of the data curves in Figure 7, it seems that ratios between the air speed and the external wind speed approach to about 17%, 20%, and 25% for the column, the turbine, and the combined device respectively as the wind effects become strong.

From the above observations, with the purposes of maximum ventilation rate, for cases with strong buoyancy effects (high temperature difference and low wind speed), the column is recommended. For cases with strong wind effects (high wind speed and low temperature difference), the combined device is recommended. For general cases where both effects exist, the combined device should be the best solution.

Since the combined device is actually the turbine with higher throat, enhancing the throat height of an ordinary short-throat turbine should boost its ventilation performance under combined wind-buoyancy effects. This point may be useful for upgrading available short-throat turbines, since replacing their throat is simple, and should be considered for manufacturing new turbine ventilators.

4. SUMMARY

Ventilation performances of three devices, namely a turbine ventilator, a vent column, and a device made by their combination, all with the same throat area, were tested and compared under the effects of wind alone, buoyancy alone and coupled wind-buoyancy experimentally. Compared values were the air speed through the devices. When buoyancy effects were dominant, the column, though the simplest device, was the best. When wind effects were dominant, the combined device performed best. Under coupled wind-buoyancy effects, the combined device was seen to benefit from stack effects of the column to offer higher ventilation air speed than the turbine but still could not match the performance of the column.

From the experiments, two conclusions can be seen. Firstly, the turbine does not help to withdraw hot air from inside buildings as much as the column does, particularly when there is no or little external wind, though the former is much more expensive and advertised to do so effectively. Secondly, with the height of its throat increased, the turbine was seen to perform better. Therefore, ventilation performance of current commercial low-throat turbine ventilators can be boosted by simple modifications of increasing their throat height.

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REFERENCES

[1] H. Awbi. Ventilation of buildings. London and New York: Spon Press, 2003

[2] D.W. Etheridge. “Nondimensional methods for natural ventilation design”. Building and environment, vol. 37, pp. 1057-1072, 2002.

[3] N. Khan, Y. Su, S. B. Riffat. “A review on wind driven ventilation techniques”, Energy and Buildings, vol. 40, pp. 1586-1604, 2008 (a).

[4] N. Khan, S. Su, S.B. Riffat, C. Biggs. “Performance testing and comparison of turbine ventilators”. Renewable Energy, vol. 33, pp. 2441-2447, 2008 (b).

[5] C.M. Lai. “Experiments on the ventilation efficiency of turbine ventilators used for building and factory ventilation”. Energy and Buildings, vol. 35, pp. 927-932, 2003.

[6] C.M. Lai. "Prototype development of rooftop turbine ventilator powered by hybrid wind and photovoltaic energy". Energy and Buildings, vol. 38, pp. 174-180, 2006.

[7] P. F. Linden. "The fluid mechanics of natural ventilation". Annual review of fluid mechanics, vol. 31, pp. 201-238, 1999.

[8] A. Revel, B.P. Huynh. "Characterizing roof ventilators". Presented at 15th Australasian Fluid Mechanics Conference, The University of Sydney, Sydney, Australia, 2004.