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Analysis of Single-Side Ventilation for Effective Air Flow Rate and Cooling in Building

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ABSTRACT

Natural ventilation in buildings is intended to cool the body directly by convection across the skin and body, and absorption of perspiration. The air flow must be directed towards the "living" or occupied zones of a building. Window types in a building can be manipulated to increase or decrease the speed of the air movement. The opening windows can provide fresh air, which is natural ventilation. It is an important environmental factor that can affect occupants' satisfaction and also have great potential for energy saving. Good indoor air quality is important to achieve indoor comfort and health. Opening a window is the simplest way to improve indoor air quality. Data logger was used to record the environmental condition. LUGE L9 data logger (L92-1+): recording radiant temperature from -40C^0 to +70C^0 and relative humidity from 0% to 100%. The AIRFLOW thermal anemometer (TA-2-2): the working velocity range is between 0- 2m/s, with accuracy of ±3%FSD at 20C^0 and 1013mbar. While the solar radiation was calculated from ECOTECT software, the glazing area was divided into 30%, 40%, 50%, 60% and 70% facade areas. The results shows that when the opening size reach 30% of the total glazing area, then the effective air flow rate for cooling were achieved in these five cases. The two openings at different heights could reach a much higher volume flow rate than the single opening but under only the thermal buoyancy driven condition. Therefore, at no wind condition, the office with two openings had a more efficient performance than the single opening to remove the indoor heat. Recommendations were made that increasing temperature difference was more efficient for increasing volume flow rate in a single-side ventilated office.

Keywords: *Air flow, Glazing, Indoor cooling, Opening size, Single-side ventilation.*

1. Introduction

Different indoor ventilation strategies will affect the indoor ventilation efficiency and air flow pattern. Three types of ventilation configuration were indicated by Baker and Steemers (2000): single-sided ventilation, cross ventilation and stack ventilation.

Single-sided ventilation is applied in a typical single room. The air enters and leaves at the same side of the room. The room can be efficiently ventilated if the depth of it is about twice than the floor height. The wind is the main driving force in summer and the thermal stack effect in winter to achieve minimum fresh air. Double opening is another form of single-sided ventilation. Due to the height difference of openings, the thermal buoyancy and wind pressure would cause the pressure difference between the two openings, and then encourage the stack effect. The double opening type will give ventilation depth for three times floor to ceiling height (Baker and Steemers, 2000; Chime, 2022). This opening type is more efficient than the single opening. Compared with two other configurations, single-sided ventilation is the simplest and the most inexpensive but is low in efficiency.

2. Literature Review

Single sided ventilation relies on opening(s) on only one side of the ventilated enclosure. Fresh air enters the room through the same side as used air is exhausted. A typical example is the rooms of a cellular building with operable windows on one side and closed internal doors on the other side. With a single ventilation opening in the room, the main driving force is wind turbulence. In cases where ventilation openings are provided at different heights within the facade, the ventilation rate can be enhanced by the buoyancy effect (NBC, 2006; Gao and Lee 2010; Anunobi et al., 2015; Allard, 2022; Chime & Aki, 2023).

The contribution from thermal buoyancy depends on the temperature difference between the inside and the outside, the vertical distance between the openings, and the area of the openings. The greater vertical distance between the openings, and the greater temperature difference between the inside and the outside, the stronger is the effect of the buoyancy. Compared with other strategies, lower ventilation rates are generated, and the ventilation air does not penetrate so far into the space Figure 1.

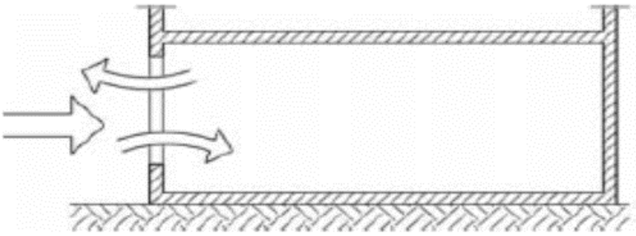


Figure 1: Sketch of single sided ventilation. As a rule of thumb, single-sided ventilation is effective to a depth of about 2 – 2.5 times the floor to ceiling height (Tine, 2006).

For natural ventilation to be effective, the depth and layout of the floor space must be considered along with the natural ventilation scheme used to ventilate the space. In cellular-type room plans, single sided ventilation is prevalent due to the configuration of offices. With this configuration, air enters and leaves the space on the same façade of the building. If the window opening is only at one height, then the NPL falls in the mid-point of the window; air enters in the lower half and exits out of the upper half of the window. This design would tend to create a concentration of warmer air at the ceiling and cooler air at the floor. An alternate configuration could use windows at two heights; the lower window then becomes the air inlet opening, while the upper window removes the exhaust air, thus having the capacity to remove more heat and lower the space temperature better than the single window design. The depth of natural ventilation effectiveness in the single sided case is usually said to be limited to approximately 2.5 times the height of the space (Givoni, 1994; Eftekhari, 1995; Awbi, 2003; NBC, 2006; Anunobi et al., 2015, Etheridge & Sandberg, 1996).

The empirical expressions for buoyancy driven, wind driven and buoyancy and wind combined condition are presented, and also the equation for calculating the effective air flow rate of cooling. The result of effective air flow rate of cooling on eight directions with different glazing areas and temperature difference is demonstrated.

- **Thermal buoyancy driven**

When air flow is driven by thermal buoyancy only through an opening window, it can be assumed that warm indoor air flows out on the top of the window and cold external air flows into the room through the bottom of the window. The common equation of air flow rates can be presented as:

$$Q = C_d \cdot A \cdot \sqrt{\frac{(T_i + 273)}{\Delta T g h}}$$

Equation 1: Air flow rate for thermal buoyancy driven in single-side ventilated room.

Where Q (m^3/s) is the air flow rate, Cd is the discharge coefficient, A (m^2) is the opening area of each aperture, Ti (°C) is the internal temperature, ΔT (K) is the internal and external air temperature difference, g (m/s^2) is the gravitational acceleration, and h (m) is the height between each opening if there are two openings in the room with a height difference or it is the height of the window for a single-opening office. The typical value of Cd is 0.25 for an opening window and 0.6 for two height different opening windows (CIBSE AM10, 2005, p46). Based on this equation, the different air flow rates between a single opening and two openings are due to different discharging coefficients. The rate in the two openings at different heights is about 2.4 times more than for a single opening.

- **Wind driven**

For the wind driven only single-side ventilation, the air flow rate in the office can be found from the equation:

$$Q = C \cdot A \cdot U$$

Equation 2: Air flow rate for wind driven only mode in single-side ventilated room.

Where A (m^2) is the area of each opening, U (m/s) is the wind speed, the values of C vary from 0.01 to 0.05, which depends on the shape of the opening, the place where the reference wind speed has been measured and the wind condition around the building. The average value at 0.025 is used for calculation in the CIBSE Guide A (2006, 4-17).

- **Thermal buoyancy and wind driven combined**

The thermal buoyancy and wind driven combined model is based on the empirical equation:

$$Q = Cd \cdot A \cdot \sqrt{\frac{2 \cdot |\Delta P|}{\rho}}$$

Equation 3: Air flow rate for thermal buoyancy and wind driven combined model in single-side ventilated room.

Where Q is the air flow rate (m^3/s), Cd is the discharge coefficient, A (m^2) is the opening area, ΔP (Pa) is the pressure difference between two sides of the opening, and ρ is the density of the air (kg/m^3) (CIBSE AM10). Larsen and Heiselberg (2008) divided ΔP into three parts, wind pressure difference, thermal buoyancy pressure difference, and fluctuation pressure difference. They also used a wind tunnel to measure the air flow rate in the single-side ventilation model under different environmental conditions. They concluded a new equation for the single-side natural ventilation calculation, as below:

$$Q = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot |C_p| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot H + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}}$$

Equation 4: Improved equation for calculate air flow rate at thermal buoyancy and wind driven combined model.

Where f(β) is a value depending on the wind direction, Cp is the wind pressure coefficient, U (m/s) is the wind speed, ΔT (°C) is the difference of internal and external air temperature, H (m) is the height of the opening, ΔCp, opening (Pa) is the pressure difference in the opening caused by flow turbulence, C1, C2, C3 are constant numbers according to wind tunnel measurement, and the discharge coefficient (Cd) is included in these constant numbers.

The empirical equation is used to find the impact of wind speed, temperature difference and wind directions on air flow rate in a single-side natural ventilation. The wind direction was divided into eight directions. When the wind was directly towards the opening side it was set as 0° and each direction was at intervals of 45°. Also the wind pressure coefficient was correlated (Liddament, 1996).

3. Research Methodology

The study area is Delta State in southern part of Nigeria within the warm-humid climate zone. The monitored building is shown in Figure 2, and Figure 3. The readings of the indoor air temperature was recorded when the building was running naturally and windows were open & air-condition were off. Data logger was used to record the environmental condition as shown in Figure 4 and Figure 5. LUGE L9 data logger (L92-1+): recording radiant temperature from -40C^0 to +70C^0 and relative humidity from 0% to 100%. The accuracy of temperature reading is ±0.2C^0 and the accuracy for relative humidity is ±2%RH. The reading resolution for temperature and relative humidity are 0.1C^0 and 0.1%. The AIRFLOW thermal anemometer (TA-2-2): the working velocity range is between 0- 2m/s, with accuracy of ±3%FSD at 20C^0 and 1013mbar.

- **Effective air flow rates for cooling**

The air flow rate for cooling can be calculated from the equation:

$$Q = \frac{H}{\rho \cdot C_p \cdot \Delta T}$$

Equation 5: Effective air flow rate for cooling. Where Q (m^3/s) is the effective flow rates, H (w/m^2) is the total internal heat gain, ρ (kg/m^3) is the air density, Cp (J/kg·K) is the air specific heat capacity, and ΔT (°C) is the indoor and outdoor temperature difference. According to Equation 2.5, H was the total internal heat gains including solar radiation and internal heat. Where the solar radiation was calculated from ECOTECT software, the glazing area was divided into 30%, 40%, 50%, 60% and 70% facade areas, and the solar radiation in different orientations was calculated clockwise from south to south-west in eight directions.

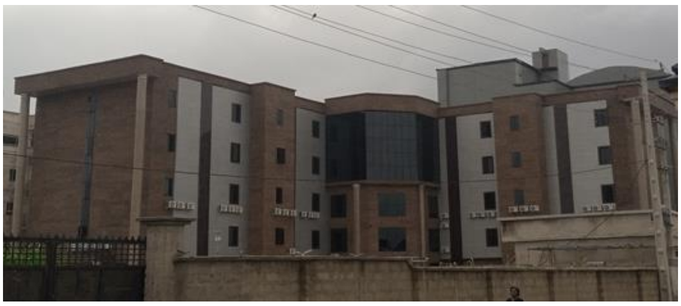


Figure 2: Shewing the case study building in Nigeria

Building dimension of single-side ventilated office: The building with a length and width ratio of 2:1, had a double bank, and the cellular office room size in it was 4.8m×3.6m×3m. This is based on the general building module in Nigeria.

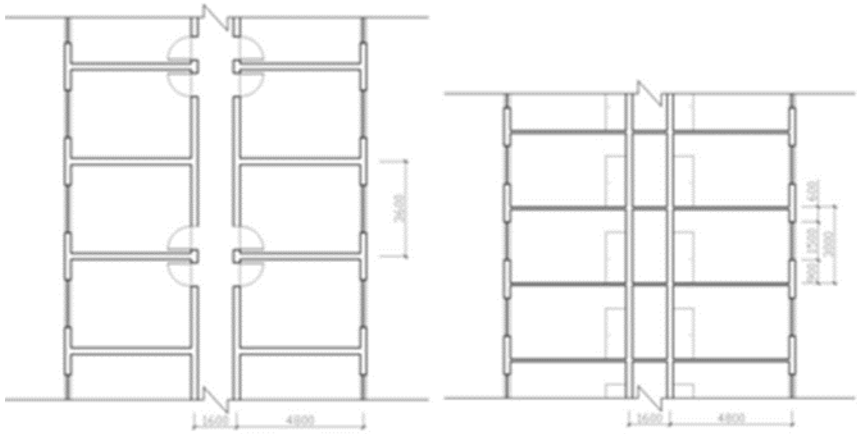


Figure 3: Plan and section of single-side ventilation office.

Figure 4: LUGE L9 data logger (L92-1+):

Figure 5: AIRFLOW thermal anemometer (TA-2-2):

3.1. Data Presentation:

In order to provide more detailed results, hourly data during the natural ventilated period were used. The dry bulb indoor air temperature was used to analyse the temperature percentages within the building. When the temperature outside was lower than inside, natural ventilation was an effective way to reduce the indoor temperature.

- **Air flow rates in a single-side ventilated office**

In the initial study, the basic equation was used to calculate the effective air flow rate for cooling and to find the relationship between air flow rates temperature difference, wind speed difference and wind direction in a generic office building.

- **Wind driven only and thermal buoyancy combined with wind driven condition**

The results show the air flow driven by thermal buoyancy in a single opening room. It was clear that the bigger opening size and high temperature difference resulted in a higher air flow rate. In a 30% glazing area office, when the air temperature difference was 3°C, the opening needed to be 75% of the glazing area in order to achieve a cooling purpose, and 50% of the glazing area when the temperature difference was 10°C. In a 40% glazing area office, 75% of the glazing area needed to be open when the temperature difference was 3°C, and 50% when the temperature difference was 5°C. For 50%, 60% and 70% of glazing area offices, if 50% of the glazing area was open and the temperature difference was 3°C, then the effective air flow rate for cooling could be achieved. The room had two openings and the air flow rate of it was higher than the single-opening room. If the opening size could reach 30% of the total glazing area, then the effective air flow rate for cooling could be achieved in these five cases. The two openings at different heights could reach a much higher volume flow rate than the single opening but under only the thermal buoyancy driven condition. Therefore, at no wind condition, the room with two openings had a more efficient performance than the single opening to remove the indoor heat.

The measured data at different points on different opening were unified as shown in Figure 6, Figure 7, Figure 8, Figure 9, and Figure 10.

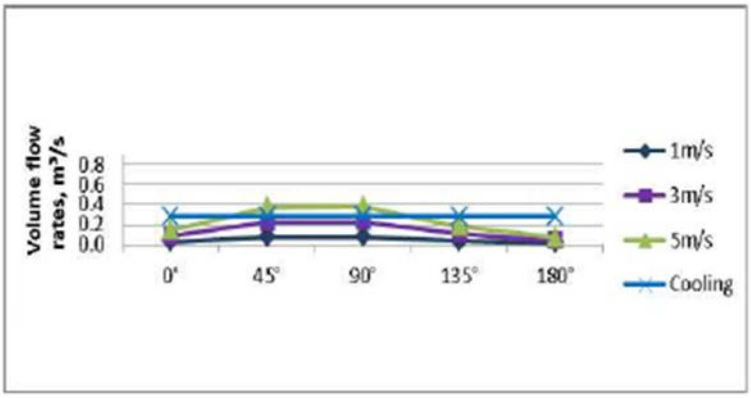


Figure 6: The effect single-side window on air flow rate at 30% opening (Field work, 2024).

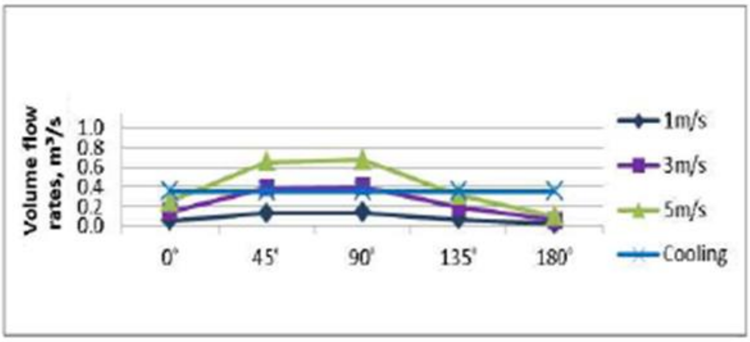


Figure 7: The effect single-side window on air flow rate at 40% opening (Field work, 2024).

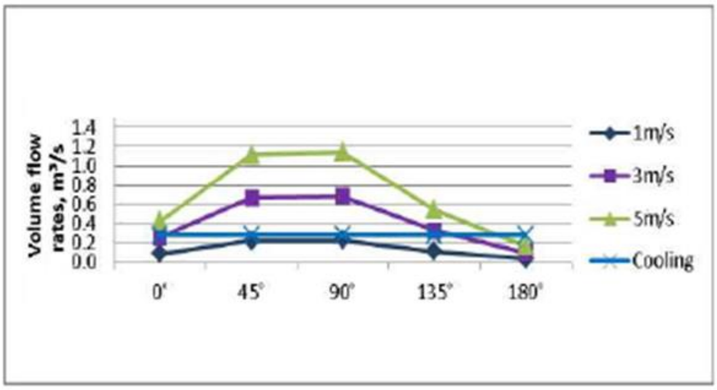
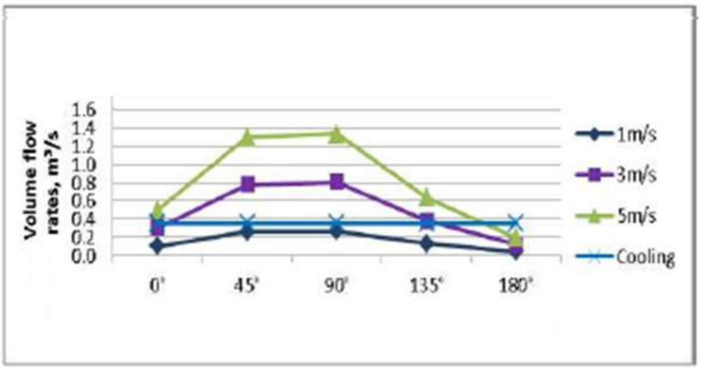


Figure 8: The effect single-side window on air flow rate at 50% opening (Field work, 2024).



Casement window at 50% opening

Figure 9: The effect single-side window on air flow rate at 60% opening (Field work, 2024).

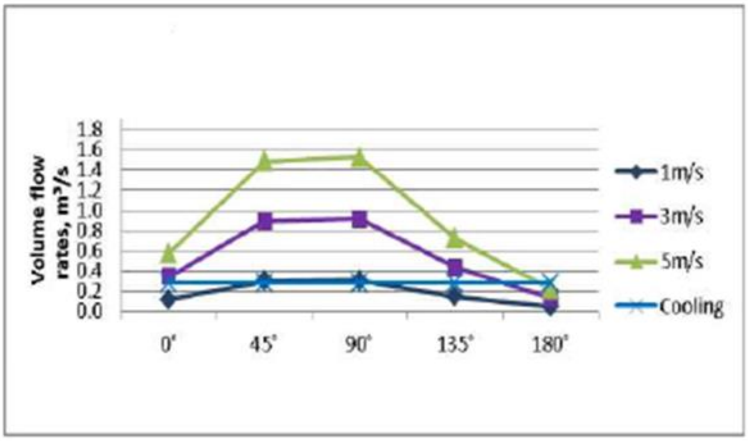


Figure 10: The effect single-side window on air flow rate at 70% opening (Field work, 2024).

When the air temperature difference between indoor and outdoor was 0°C, it could be considered as wind driven only. The two opening was not considered under these two conditions. Because, based on the empirical equation, at the wind driven only condition, two openings and a single opening are similar. And the thermal buoyancy and wind driven combined condition with two opening at different heights was considered. The result showed the air flow rate as a function of increasing wind speed and temperature difference. When indoor and outdoor temperature difference was 0°C, the wind became the main driving force. The volume flow rate was the lowest when the opening window faced the leeward side (180°). Increasing external air flow speed and free opening size would have significant effect on the volume flow rate, which would increase with the increase of wind speed and free opening size. Therefore, the opening window facing leeward under the wind driven only condition was not good for natural ventilation in room. Under the same external air flow speed, the volume flow rates were close to each other when the wind directions were 0° and 135°, 45° and 90°. But the volume flow rate at wind directions of 0° and 135° was lower than that at 45° and 90°. When the wind directions were at 45° and 90°, the volume flow rate reached the highest in the room, and it would obviously rise up along with increasing wind speed and free opening size. When the wind speed was 3m/s, and the opening size was 50% of the glazing area, it could achieve cooling demand in all cases in these two directions. Besides, when the wind speed was 1m/s, it was difficult to achieve the cooling purpose in most cases unless the room had a 70% glazing area which was fully opened. Thus, for the wind driven only condition, the wind direction at 45° and 90° could cause the highest volume flow rate in the room, while 180° is the worst direction for natural ventilation. Even by rising wind speed, it would not have significant impact on volume flow rate on 180° and the effect is limited with lower external air flow speed (1m/s).

4. Discussion of Results

The field studies carried out in office-buildings in the southern part of Nigeria during both the dry and the rainy seasons. The reduced opening area would drop the air exchange rate in the office. In the wind and thermal buoyancy driven combined case, when the free opening size was still, increasing the temperature difference between indoor and outdoor or raising the wind speed would not cause significant increase in volume flow rate. The impact was little by changing these factors, especially with a small free opening size. However, when the temperature difference between indoor and outdoor was increased, the volume flow rate for cooling could be achieved more easily, and extending the free opening area was more effective on increasing the volume flow rate. Changing wind speed had a different impact on each direction, but at the same wind speed the pattern of volume flow rate on each direction with different temperature differences was similar. When the wind speed was 1m/s, the volume flow rates at 0°, 45° and 90° were very close and the lowest was at 90°. The highest volume flow rate occurs on 135°, and on 180° the volume flow rate was slightly lower than 135°. When wind speed was 3m/s, the lowest volume flow rate was on 90°, and the volume flow rate at 0° and 180° was higher than 90° and close to each other. The highest rate occurs on 45° or 135° with temperature different changes. When the wind speed rises to 5m/s, the pattern of volume flow rate on each direction is similar to when the wind speed was 3m/s. But the volume flow rates on 0° and 180° are close and lower than other directions. The highest rate was on 45°C, then on 135° and 90°. Therefore, when the temperature difference rises, the volume flow rate on 90°, 135° and 180°, in which the three opening was on the leeward side, would drop, especially with the air flow speed at 3m/s and 5m/s. At these three directions, when temperature difference was 10°C, the volume flow rate with 3m/s and 5m/s was lower than 1m/s, so it seems the thermal buoyancy force dominates the volume flow rate.

5. Conclusions

According to measured results in offices, the indoor air temperatures varied in the comfort range in most of working hours. It can be concluded that in the wind driven only case, increasing wind speed and free opening area would result in the rise of volume flow rate, especially when the wind directions were 45° and 90° with significant impact. When natural ventilation was driven by the buoyancy and wind combined case, at low wind speed and parallel or leeward direction, thermal buoyancy had a bigger influence than wind forces. Therefore, at these conditions, increasing temperature difference was more efficient for increasing volume flow rate in a single-side ventilated office. When the wind direction was 45°, increasing temperature would not have an important impact on volume flow rate, while the wind is the main driven force.

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