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Thermal Performance of Windcatchers: Evaluation in Buildings Under Tropical Climate

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Abstract*– Windcatchers are structures that have been developed primarily in the Middle East, particularly in the country of Iran, throughout history. In recent decades they have spread to countries in Europe and are effective in tropical climates as well. These structures utilize the aerodynamic principles of natural ventilation which results in a practical method to improve occupants' health by positively influencing air quality and reducing electrical consumption for air conditioning in buildings. Thus, the objective of this study is to evaluate the thermal performance of wind traps, in terms of air renewal rate, operating temperature, and indoor relative humidity, in a climate like that of Panama City using dynamic energy simulation of seven case studies varying their geometry, for a single-family residential building, during days with more and less wind. For a single-family house, case B1 presents the best performance by handling acceptable air exchange rates with relative humidity within comfort parameters. On the other hand, for larger buildings, case B2 presents the best air exchange rates, but with very high relative humidities outside the comfort limit, so another option would be case A2 or C2 which handle air exchange rates a little lower than B2, but with relative humidities within the comfort range.

***Keywords*—Air exchange rate, natural ventilation, thermal comfort, tropical climate, windcatcher.**

I. Introduction

Since antiquity, windcatchers have been part of Middle Eastern architecture, having been in evolution throughout 1300 years and reaching heights of up to 33.0 m, with ducts of different shapes [1], [2]. Most of the windcatchers are found in Iran, owing to its climatic conditions, history, and the utilization of various kinds of wind towers [1]. However, the use of these structures is not only limited to the Middle East geographic zone; in the last decade, they have begun to be implemented in countries such as the United Kingdom, Algeria, and Egypt, among others [3], [4], to provide natural ventilation, cooling, and generating thermal comfort in buildings in countries with arid and/or humid climates [2], [4], [5]. Research conducted in European countries such as the United Kingdom, Sweden, Netherlands, as well as in the USA and Australia, demonstrates the implementation of this system utilizing Modern Windcatchers. These systems incorporate sensors and dampers and even introduce a new system called Mono Draught Windcatcher, which are automatic structures capable of adjusting depending on the needs of the place [6]. In Latin America, a study conducted in Monterrey, Nuevo León, México, implemented a two-sided windcatcher under outdoor temperature conditions of 28.1 °C, with an airspeed of 1.27 m/s, in a semi-arid climate, and using a model categorized as an idealized room. This research utilized the method of RANS equations, steady-state, and turbulent regime. The results obtained indicate that 50% of the main room achieve a state of comfort, utilizing local velocity variables and temperature [7].

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Currently, the primary drivers of high energy consumption in buildings are heating, ventilation, and air conditioning systems [8], [9], [10], [11]. While the issues associated with heating can be reduced through the application of better thermal insulation, cooling, and ventilation systems play a greater role in the energy demand of buildings [12], and reducing it requires the implementation of more complex solutions to study as windcatchers.

To understand the operation of a windcatcher, it is important to distinguish between two different concepts. The first one is known as single-side ventilation, and the second one as cross ventilation. Single-side ventilation is a condition where openings are on the same façade. On the other hand, cross ventilation is characterized by having openings on opposite sides of a room, and even on more than two opposite facades [13]. In that way, a windcatcher operates with a cross-natural ventilation system.

Cross-natural ventilation is a practical method that is used to reduce energy consumption and improve human health by directly influencing internal air quality (*IAQ*) [5].

A windcatcher works by having an air inlet located at the top of a tower and an outlet on the facade opposite where the wind tower is situated. With openings on both facades of the enclosure, an overpressure is created on the windward wall and a low pressure on the opposite side (*leeward*), generating an airflow inside the room [1], [2], [5], [14]. This pressure difference serves as the driving force for internal airflow in the presence of openings such as windows and doors [2].

Two methods are used to find the generated pressure difference. The first examines the external wind flow, and the second evaluates the temperature gradient between the external and internal air. In this way, by making a small modification in the design of the building roof, back pressure can be generated, which helps circulation for natural ventilation [2], [5]. Another way to study it is through thermal gradients in the vertical direction, as it creates a pressure differential that results in a displacement of internal air, where the recirculation flow pushes the hot air toward the outlet opening [15].

However, for the appropriate design of a windcatcher, aerodynamic parameters such as wind speed, wind flow direction, turbulence zones, pressure zones, and dilution zones [16], [17], and physical parameters such as geometry and location of openings are of great importance [14], [15]. This suggests that it (the windcatcher) should be designed differently for each geographical zone.

The flux at the internal side of a windcatcher is complicated due to being influenced directly by the flow separation, recirculation, and the secondary flow or vortex. This phenomenon occurs when air enters the 90° bend of the windcatcher, it undergoes a sudden change in direction, resulting in a centrifugal force that displaces the flow towards the outer wall of the bend generating a radial pressure gradient in the direction of the inner wall (minimum pressure) and the outer wall (maximum pressure) [18].

The geometries found in the literature encompass a variety of shapes, including circular, triangular, square, and U-shaped structures with a single opening [2], as well as windcatchers with two, three, and four sides, hexahedral and octahedral designs [19], and even windcatchers with extensions [18].

Many studies have concluded that natural ventilation is more effective in tropical climates than in other types, due to the small temperature difference between the inner and outer spaces of a building [5].

Parameters that benefit from natural ventilation include thermal comfort, electrical consumption, indoor air quality, CO_2 reduction, air exchange rate, and the speed and temperature of occupied areas [5], [20]. That is why modern architecture now considers windcatchers as an effective bioclimatic technique [2].

This study seeks to analyze the performance of six different windcatcher geometries under tropical climate characteristics, using dynamic simulation, in terms of the air exchange rate (ac/h), operating temperature, and relative humidity of the indoor environment. A single-story residence was chosen for the case study. The results of this research answer the question: What is the performance and effect of windcatchers in buildings in a tropical climate such as Panama?

II. METHODOLOGY

A. *Literature review*

To find information related to this topic, Google Scholar is used, employing a wide range of keywords along with logical operators such as "AND" and "OR", in both English and Spanish, for articles with an age of five years or less. The keywords chosen are windcatcher, tropical climate, thermal comfort, air exchange rate, cross ventilation, and natural ventilation.

B. *Case Study Description*

Studies have demonstrated that the building's geometry, as well as the position and size of its air inlet and outlet openings, significantly influence the behavior of natural ventilation and the pressure differences between both points [5]. This pressure difference (ΔP) through each opening or located at any point on the building's surface is an essential aerodynamic parameter that can be expressed in terms of the pressure coefficient (Cp) [5]:

$$C_P = \frac{\Delta P}{\frac{1}{2}\rho {U_\infty}^2} \tag{1}$$

Where P represents pressure, ρ refers to the fluid density (in this case, air density), and U_∞ is the abbreviation for free-stream fluid velocity.

To investigate the flow field and the temperature distribution in a windcatcher under steady-state conditions, turbulent and incompressible flow, it is advisable to refer to (2), (3), and (4), which govern these behaviors [15]:

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0 \tag{2}$$

$$\rho\frac{\partial(u_i u_j)}{\partial x_j} = \frac{\partial(P_i)}{\partial x_i} + u\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{3}$$

$$\frac{\partial}{\partial x_j}\left[u_j(\rho E + P)\right] = \frac{\partial}{\partial x_j}\left[(k_f + k_t)\frac{\partial T}{\partial x_j}\right] \tag{4}$$

Where u is the velocity component in the x coordinate, δ is Kronecker delta, E is the energy, and k is the thermal conductivity [15].

Now that these equations are known, the next step is to use DesignBuilder v7.0.1.6 software, with its EnergyPlus engine, to formulate the reference case study and simulate these behaviors.

The software DesignBuilder utilizes the Airflow Network method to estimate indoor airflow. This work is as follows: Each zone of the model represents a node. With several interior zones, there are several nodes. For the exterior, it is considered as a single node. Between each zone, there exists an interconnection of airflow represented through doors, windows, and external openings. This method connects the interior nodes through these interconnections, while also linking these internal nodes with the external node through doors, windows, and external openings. The method then utilizes the Bernoulli equation, expressing airflow movements in terms of velocities related to indoor-indoor and indoor-outdoor pressure differences caused by temperature differences or wind effect. This method also includes a discharge coefficient depending on the type of opening. Finally, the Airflow Network method represents an approximation of mass and force conservation equations, while implementing assumptions made by the Bernoulli equation, such as steady state and uniform flow.

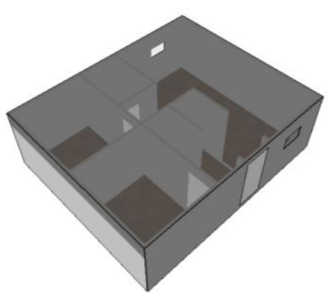
On the other hand, DesignBuilder uses the Energy conservation equation to conduct heat balances in each zone. The heat transfer associated with airflow is treated as another term within the heat balance, which is performed in a transient state. It considers convective interactions between the interior air and the internal surfaces, using convective heat transfer coefficients based on conventional correlations.

To assess the thermal performance, this study utilizes the integrated comfort modules within the software to calculate building environmental parameters. These include the operating temperature (considered a superior measure of comfort in naturally ventilated spaces, representing a balance between convective and radiative indoor exchanges, with a comfort range between 23.5 and 28.5 °C for Panama), relative humidity (with a range of 60 – 70% for Panama), and the air exchange rate (indicating how many air volume changes occur per hour).

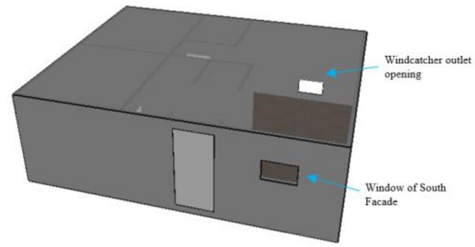
The reference case study encompasses a one-floor house, with two bedrooms, a kitchen, and a bathroom. The only two openings of the house are in the kitchen. The first one is on the north façade, and the second one is on the south façade as shown in Fig. 1a. The wall material is from fibro cement, and the roof is made of zinc. The building's geographic position is situated at Marcos A. Gelabert I., Panama City, Panama; an area characterized by a tropical climate and North-South wind direction, which intersects the windcatcher's inlet opening at a 90° angle [21].

The building is configured with external and internal windows, and the internal door in the fully open position at all times, while the external door is configured as fully closed 24/7. It is simulated for February 26 and 27, which represent the dates with the highest airflow, and September 16 and 17, which are the days with the lowest airflow recorded during the year 2022 for Panama City [22]. For the inclusion of the windcatcher, the house was adapted, mainly by including free openings in the interior partitions.

For the addition of a windcatcher, three different geometries, with two different lengths, are chosen from the literature. The windcatcher will have a height of 9.0 m, with an upper air inlet and a lower fluid outlet through which air flows into the building. The wall opposite the windcatcher outlet opening, a window is placed opposite the windcatcher opening, but at half the height of the wall [15], as shown in the following figure:



a)



b)

Fig. 1 a) Reference Case Study Configuration; b) Position of the windcatcher outlet opening and location of south façade window.

The windcatcher geometries to be studied are short traditional rectangular [2], long traditional rectangular [4], short semicircular because it is found that this geometry increases the air velocity by 28% compared to the traditional rectangular [2], long semicircular, short rectangular with extension in the entrance opening which will allow the area where the flow enters the windcatcher to be less affected by the presence of the building avoiding the negative impact of the skewed entrance, improving the efficiency of the windcatcher [4], and finally the long rectangular case with extension in the entrance opening. In these cases, the facade with the windcatcher is oriented to the incident direction of the wind to increase its utilization, as detailed below, and shown in Fig. 2:

- *Case A1. Short rectangular windcatcher:* For this case the base of the wind trap is square, measuring 1.0x1.0 m, with a rectangular inlet at the top of its north facade measuring 0.8x1.0 m. In addition, it has an air outlet at the bottom of its south façade measuring 0.8x0.5 m that connects to the interior of the house.
- *Case A2. Long rectangular windcatcher:* In this case the base of the windcatcher is rectangular, measuring 7.8x1.0 m along the back wall of the house, with a rectangular hole in the upper part of its north façade measuring 7.6x1.0 m. It has two air outlets in the lower part of its south facade measuring 3.32x0.5 m, one connecting to the interior of the kitchen and the other connecting to the interior of bedroom 1 measuring 2.6x1.0 m.
- *Case B1. Short semicircular windcatcher:* For this case, the base of the windcatcher is semicircular with a diameter of 1.0 m and a depth of 0.25 m, it has an opening in the upper part of its north facade that measures 2.36x1.0 m. In addition, it has an air outlet in the lower part of its south facade of the same size as in case A1.
- *Case B2. Long semicircular windcatcher:* In this distribution, the base of the windcatcher is semicircular with a diameter of 7.8 m and a depth of 0.5 m along the wall of the house, with an opening in the upper part of its north facade measuring 13.04x1.0 m. It also has two air outlets at the bottom, the same as in case A2.
- *Case C1. Rectangular windcatcher with short extension:* In this case, the base of the windcatcher is 1.0x1.0 m square, with an extension at the top of its north facade measuring 0.5 m. It has a rectangular opening measuring

1.0x1.0 m. In addition, it has an air outlet at the bottom of its south façade with the same dimensions as A1.

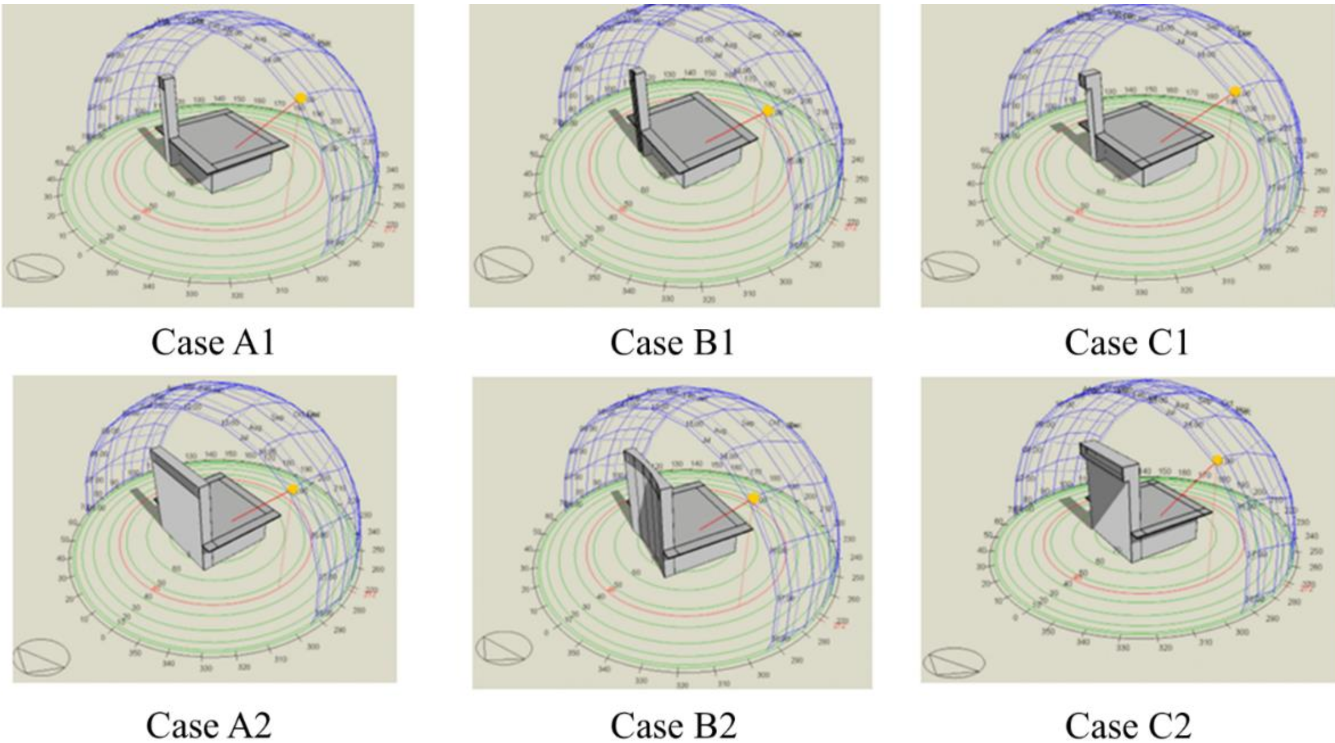


Fig. 2 3D models for case studies simulated in DesignBuilder v7.0.1.6

• *Case C2. Rectangular windcatcher with long extension:* For this configuration, the base of the windcatcher is rectangular 7.8x1.0 m along the wall of the house, with an extension at the top of its north façade measuring 0.5 m. It has a rectangular opening measuring 7.6x1.0 m. In addition, it has two air outlets in the lower part of the south facade of the same dimensions as in cases A2 and B2.

This study is limited to examining the wind effect and its impact on global variables such as the air exchange rate, operative temperature, and relative humidity inside the building. If a CFD study were to be conducted, it could analyze both the exterior and interior of the model using local variables. It would involve comparing the pressure coefficient (Cp) at different positions.

III. Results and Discussion

The case studies are simulated for two different dates. The first one refers to February 26th and 27th, exemplifying the days with the highest wind speed during 2022, and the second one is set for September 16th and 17th, which simulate the days with the lowest wind speeds in the year 2022.

A. *Analysis for the days with the highest wind speeds in the year (February 26th and 27th)*

To study the performance of each type of windcatcher, it is necessary to compare them with each other and with previous studies to ensure the efficiency or not of their inclusion in a building. Characteristics such as air exchange rate, operating temperature, and relative humidity should be compared to identify which windcatcher is more effective depending on the place that needs to be ventilated.

For the short windcatcher, as can be seen in Fig. 3, the B1 case has an air exchange rate 75% higher than the reference case, and increases by 62% compared to the A1 case, as it could be foreseen to happen by referencing it in [2], in which the circular shape (B1), increases the wind speed by 28%, compared to the square or traditional shape (A1), so the air renewal rate would increase respectively. However, this mentioned study was done in the region of Bechar, southwestern Algeria, which has a sub-tropical desert climate with mild winters where nights are usually cold, and sunny and hot summers. If compared with the climate of Panama, at least in this parameter, the theory that natural ventilation is more effective in tropical climates than in other types of climates, as mentioned in the introduction, can be affirmed. For this reason, case B2 has a higher air exchange rate than the other case studies (700% higher than the reference case) since it has a circular shape but with an air inlet 6.6 m wider than case B1. On the other hand, case C1 showed only a 4.17% increase in the air exchange rate concerning the reference case, being even 4.16% lower than case A1. The reference [18], shows that C1 increased about 19% in airflow by having an extension of 0.5 m at the windcatcher inlet (extension used for this study), which would imply that the air exchange rate should also increase. However, our study revealed a lower air exchange rate for this case (C1) compared to case A1, which suggests the hypothesis that the geographical position and the period of the year in which the research was done may have affected the outcome of the study.

Taking into account the results of the parameters studied, the geometric characteristics of the building and its geographical location, Case B1 is the best solution since its air renewal rate is 75% higher than the reference case, the operating temperature is 24°C to 35 °C and the relative humidity is 43 to 69 RH, these values are close to the comfort range of Panama, which highlights that this study simulates the days with the highest air flow of the year, coinciding with the summer season in the country. If we compare this with the results in [4], where if the air velocity outside the windcatcher increases, the relative humidity decreases and the temperature inside increases, then the same thing happens in our study because as the day progresses after some time, due to convection, the wind velocity increases, while at night the wind velocity decreases. It can be seen in Figures 4 and 5 that the operating temperature increases as the day progresses, while at night it decreases. Humidity increases at night but decreases as the day progresses.

Regarding operating temperature, all cases have a similar range, with the best cases for operating temperature parameters being B1 and B2 (24.0°C to 35.0°C and 23.0°C to 35.0°C, respectively). Case C2, on the other hand, shows the lowest temperature in the early morning (22.5°C) among all the cases studied, but at the same time also presents the highest temperature recorded in the afternoon (37.5°C).

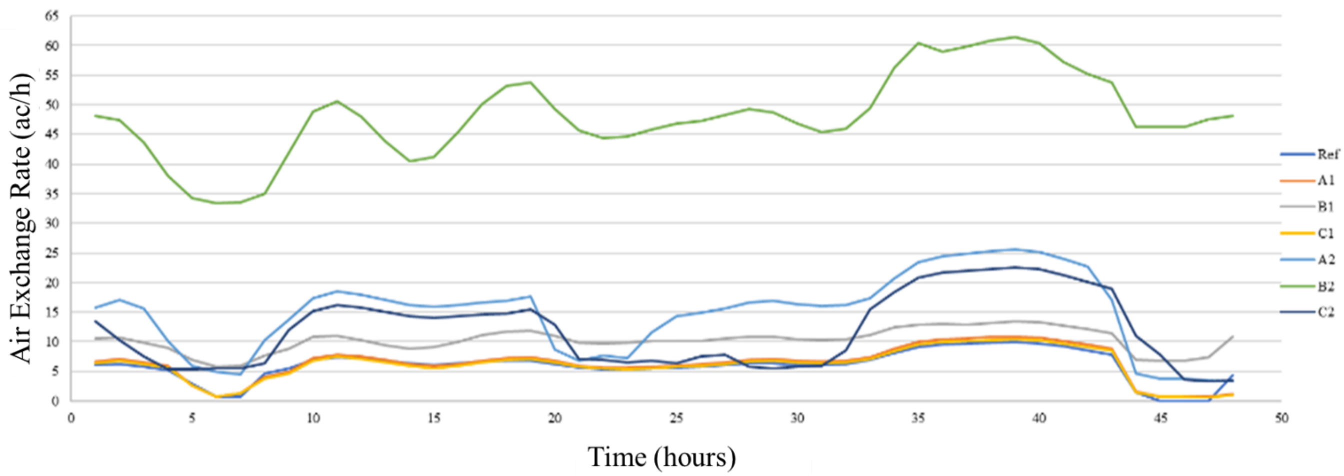


Fig. 3 Air Exchange Rate for February 26th and 27th

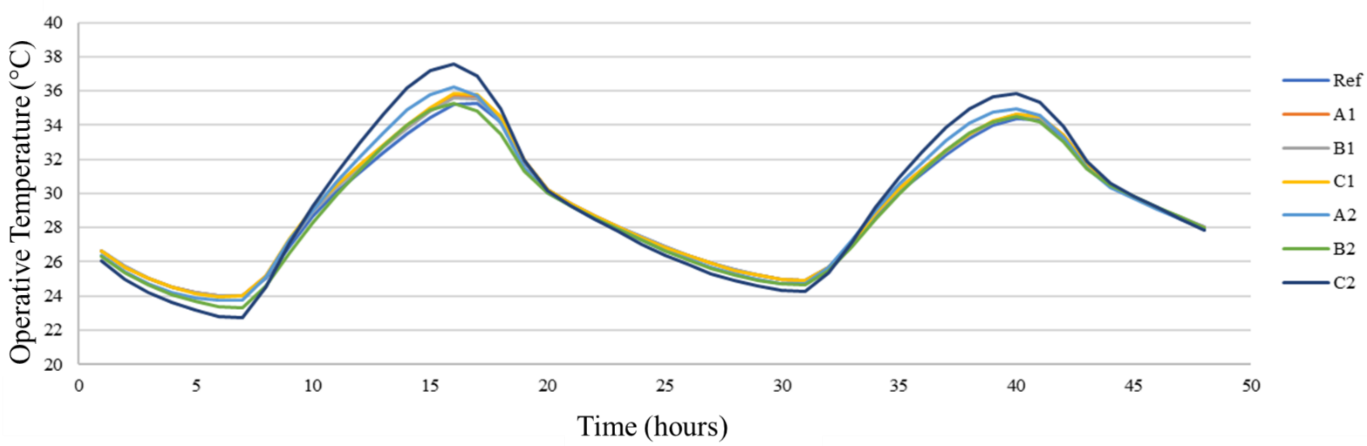


Fig. 4 Operative Temperature for February 26th and 27th

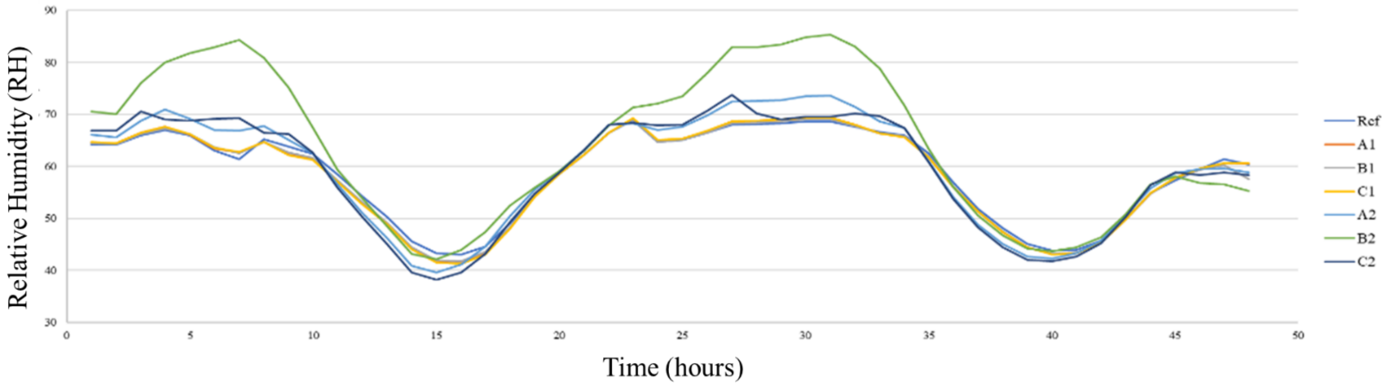


Fig. 5 Relative Humidity for February 26th and 27th

Taking into account the results of the parameters studied, the geometric characteristics of the building and its geographical location, Case B1 is the best solution since its air renewal rate is 75% higher than the reference case, the operating temperature is 24°C to 35 °C and the relative humidity is 43 to 69 RH, these values are close to the comfort range of Panama, which highlights that this study simulates the days with the highest air flow of the year, coinciding with the summer season in the country.

B. Analysis for the days with the lowest wind speeds in the year (September 16th and 17th)

According to simulation results for the days with the lowest wind speeds in the year, which are related to the rainy season, it is observed in Fig. 6, that there is a decrease in the values of the air exchange rate and operative temperature, along with an increase in relative humidity compared to the days with the highest wind speeds of the year. However, there is still an observed increase of 160% in the air exchange rate for case B2, compared to the reference case, which represents the scenario with the highest air exchange rate among all options, like the findings in the study conducted on the days with the highest wind speeds of the year.

For the shorter windcatchers, it has been observed in Fig. 6 that case B1 exhibits a 35% increase in air exchange rate compared to the reference case, as predicted by the findings in [2], as explained in the previous section. Conversely, cases A1 and C1 present at least a 10% increase in air exchange rate compared to the reference case. This parameter is still similar between case A1 and C1, unlike the days with the highest wind speeds, where case C1 shows a decrease in this parameter compared to A1.

On the other hand, cases A1, B1, and C1 exhibited minimal variation in relative humidity throughout the day, ranging from 63 to 78 RH, where the minimum value falls within the comfort parameters for Panama, while the maximum value is eight points above the threshold. In contrast, case B2 represents the largest difference in relative humidity, from 74 to 99 RH, with both values exceeding the allowed comfort limits for occupants living in Panama throughout the day. However, cases A2 and C2 demonstrated similar relative humidity patterns, but they remained outside the comfort limits for most of the day. The reference case only exceeds these limits for about three hours per day (from 12:00 pm to 3:00 pm).

For these days of the year, as depicted in Fig. 7 and 8, the behavior of the operative temperature and relative humidity parameters is similar to that revealed in [4], referenced in the preceding section.

Regarding the operative temperature, all studies exhibit a similar behavior where the optimal case is reflected in B2, showcasing a range from 22.5°C to 29.0°C. On the other hand, cases A1, B1, and C1 exhibit temperature variations spanning from 23.0°C to 31.0°C. Additionally, the reference case registers an increase in temperature reaching 32.0°C, and case C2 shows the lowest temperatures among all cases studied (21.5°C) during the early morning; however, it also presents a maximum temperature similar to the reference case (31.5°C) during the afternoon.

Considering the findings of the studied parameters, the geometric characteristics of the building, and its geographical location, cases A1, B1, and C1, by presenting similar values in all three studied parameters, stand as the ideal geometries to be employed during this period of the year in Panama.

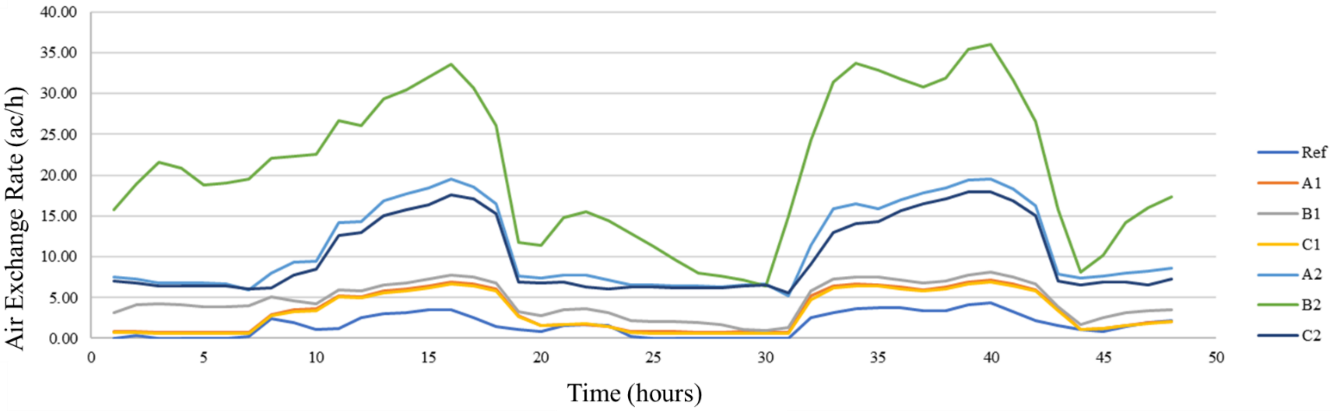


Fig. 6 Air Exchange Rate for September 16th and 17th

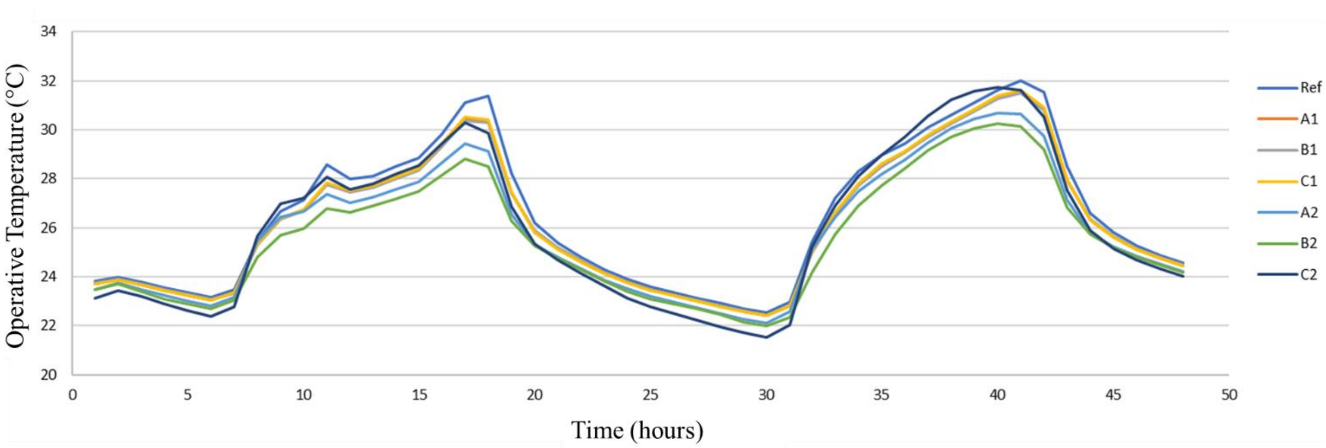


Fig. 7 Operative Temperature for September 16th and 17th

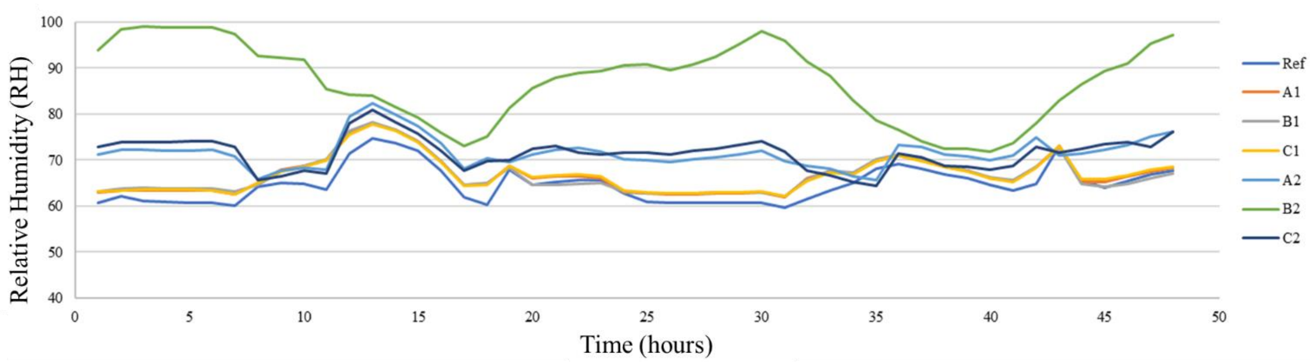


Fig. 8 Relative Humidity for September 16th and 17th

IV. CONCLUSIONS

This study has revealed that the adoption of such technology can represent a beneficial solution for ventilating a space efficiently and passively using renewable wind resources. However, to fully exploit the benefits of a windcatcher, it is necessary to understand the wind behavior throughout the year, as well as to consider the geometry, dimensions, and openings of both the windcatcher and the building itself. This will allow for determining which specific design may be most effective in each case. Furthermore, the type of space being ventilated must be considered, as its characteristics and ventilation requirements may vary depending on its intended use. Therefore, it is essential to adapt the design and length of the windcatcher employed, based on these specific considerations to achieve optimal results in terms of ventilation and indoor comfort.

It can be concluded that for a single-family house, the best-performing windcatcher will be case B1, as it can manage acceptable air exchange rates during the seasons with higher wind flow, with relative humidity partially within comfort parameters (dry season), as well as the season with lower wind currents (monsoon), during which more favorable conditions are provided to the occupants both in terms of operating parameters and temperature. However, if it is desired to be used in buildings with larger occupied spaces, the behavior of Case B2 will be optimal; however, it should be evaluated to handle a very high relative humidity that is beyond the comfort range of the occupants and therefore can be targeted to other types of applications or user research. Other viable options are Case A1 or C1, handling the three parameters studied at similar values to Case B1 during the season of the year when wind speeds are lower, however, consideration could be given to adding another method that would help increase wind power in both cases. The aerial updates below are not as good as Case B1 and are not significantly different from the reference case.

In comparison with the study performed in Monterrey, Nuevo León, México [7], it can be established that the studies are comparable from a certain point of view, since in addition to being developed in similar climates, both use temperature and velocity variables. However, this study develops local variables, while ours develops global variables. Although this study developed in Panama does not specifically evaluate comfort, it does show promising results for maintaining comfortable indoor conditions, in terms of operating temperature, relative humidity, and air exchange rate, similar to those presented in the study in Mexico.

To continue with the study of the implementation of windcatchers in buildings in countries with tropical climates, the study of these cases using computational fluid dynamics (CFD), which has an integrated module in the DesignBuilder v7.0.1.6 software, will be used to understand the behavior of airflow in three dimensions, both outside and inside the building and to find from the aerodynamic perspective parameters that give more information about the different windcatcher options shown in this study, and consequently, to present an optimization of the geometries.

Additionally, it is planned to simulate these cases over extended periods, including months and potentially the entire year, which would allow verifying the effectiveness of this type of structure in tropical climates. Furthermore, if its implementation proves effective in isolated buildings, the possibility of simulating the implementation of these structures in buildings surrounded by other constructions is contemplated. This would provide insight into how nearby buildings or structures affect the efficiency of the windcatcher when the wind experiences disturbances before reaching its upper inlet.

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