SOLAR CHIMNEY FOR ENHANCED NATURAL VENTILATION BASED ON CFD-SIMULATION FOR A HOUSING PROTOTYPE IN ALEXANDRIA, EGYPT

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Abstract— Natural ventilation is being increasingly proposed as an alternative passive technique for mechanical air conditioning ventilation, which could minimize the operation hours of active cooling solutions in Residential Buildings in hot regions like Egypt. This study investigates the effect of the solar chimney on the indoor thermal performance by CFD simulation for a room in a residential prototype in Alexandria, Egypt. The influence on the ventilation velocity and indoor operative air temperature affected by air gap widths is investigated based on a number of CFD Simulation results using DesignBuilder software. Results show that the thermal performance of the operative air temperature has been reduced by 0.81 C° and air velocity of the room has been improved after introducing Solar Chimney by 50% at the hottest hour. This has shown that the solar chimney is useful and functions as a stack ventilation tool.

Index Terms— CFD Simulation, Residential, Solar Chimney, Stack Ventilation, Thermal Performance.

I. INTRODUCTION

Operation hours of air conditioners is rapidly increasing in the residential buildings sector through summer season [1], that is consequently responsible for a higher demand for heating and cooling, which already accounts for 50% of energy consumption in Egypt [2].

Natural ventilation can lead to indoor thermal comfort without the use of mechanical cooling. The very common way of natural ventilation in residential buildings is the passive stack ventilation that could be a promising energy-efficient strategy and an alternative for cross-ventilation, under the limitations and constrains [3].

A. Solar Chimney

Solar chimney has proven as one of the effective passive solar-induced ventilation tools inherited from vernacular architecture. It can be designed as a vertical element utilizing solar energy to enhance the natural stack ventilation through a building [4].

Enhanced Stack effect occurs due to the increase in buoyancy-driven flow by heating up the upper cavity and resulting into a greater temperature difference near the outlet area in order to induce the air velocity and reduces the air temperature of the room.

Enhancements have been conducted on contemporary chimneys to be similar to conventional ones except that the south-oriented wall is covered by a glazing, and coated by a black-painted absorber material [1] to trap solar radiation at the top of the chimney as shown in Figure (1). This trapping of heat enhances the stack effect inside the chimneys, pulling warm air from the space below.

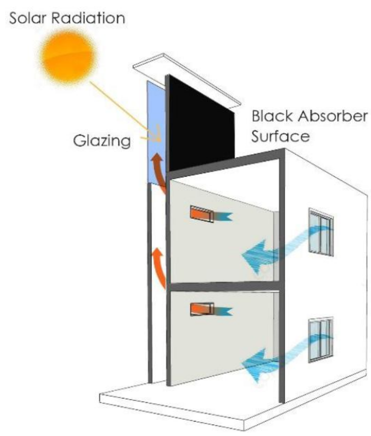

Figure 1: Operation of Solar Chimney illustration.

One of the advantages of the system is its ability to self-balance. The hotter the day, the hotter the solar air heat collector and faster the air movement [5].

B. Computational Fluid Dynamic (CFD)

In recent years, Computational Fluid Dynamic (CFD) has been identified as the most sophisticated airflow modeling techniques that generate the prediction analysis of airflow, and heat transfer around and inside the buildings [6].
Incorporation of CFD in the architectural process enabled the designer to overview the thermal performance of the building that functions well in responds to the microclimatic factors [7].

II. SIMULATION-BASED APPROACH

A. Research Objective

The objective of this study is to evaluate the optimum performance of solar chimney construction design based on CFD simulation to assess the effect of air gap width on the indoor operative temperature and air velocity on a room in a residential prototype in Alexandria, Egypt. According to Givoni B. [8], high air velocity will accelerate the convective heat transfer and evaporative heat loss, which increase the thermal indoor comfort.

B. CFD Simulation Tool

Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs test BESTTEST/ASHARE STD 14 [9].

C. Methodology

In order to achieve the stipulated aim, the simulation study traces the following steps:

- Natural ventilation studies were performed through CFD simulation of indoor airflow for the housing prototype case-study using the weather files of Alexandria, Egypt (Climate Region 4A) for accurate results.
- Based on Predicted Percentage Dissatisfied (PPD) simulation results. The room of the most percentage of thermally dissatisfied people is selected to study the effect of introducing a solar chimney to enhance the stack natural ventilation.
- A sensitivity analysis is conducted to study the effect of air gap width at different values of 0.2, 0.4, 0.6, and 0.8m to test the thermal performance and comfort levels within the selected room.

III. CASE-STUDY SIMULATION

A. Alexandria's Climate Condition

Alexandria has a hot desert climate (Köppen climate classification: BWh), The city's climate is influenced by the Mediterranean Sea, moderating its temperatures, causing variable rainy winters and moderately hot summers that, at times, can be very humid.

According to the weather data reports exported from the software (Climate Consultant 5) using Alexandria, EGY weather data valid from the Department of Energy (DOE 2011d). The warm season lasts from June 6 to October 10 with an average daily high temperature above 28°C. The hottest day of the year is August 5, with an average high of 30°C and low of 24°C. While, the cold season lasts from December 10 to March 21 with an average daily high temperature below 20°C. The coldest day of the year is February 2, with an average low of 9°C and high of 18°C.

The highest average wind speed of 5 m/s occurs around July 14, at which time the average daily maximum wind speed is 7 m/s. While, the lowest average wind speed of 3 m/s occurs around November 22, at which time the average daily maximum wind speed is 6 m/s.

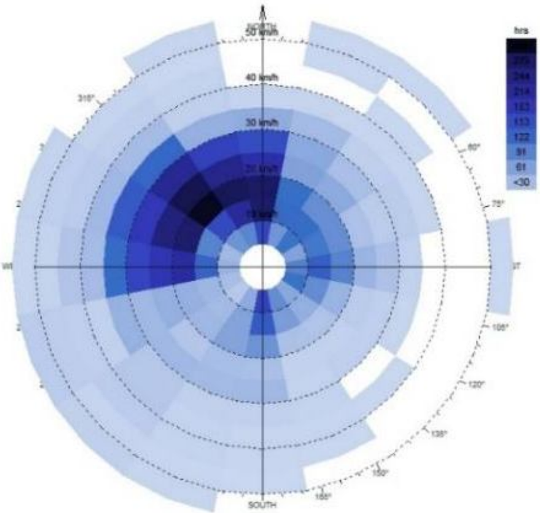

Figure 2: Prevailing Winds – Wind Frequency, Alexandria, Egypt 31.2°, 30.0° - exported from Weather Manager.

As illustrated in Figure (2), the wind is most often out of the North West (28% of the time) and North (23% of the time). The wind is least often out of the South East (4% of the time) and South West (4% of the time).

B. Prototype Description

A single family two-storey housing prototype with built up area of 135 m² is selected as the case study. As shown in Figure (3), the plan has a rectangular form of an aspect ratio of 1:3 oriented along east/west axis which can perform well in hot climates [10]. The ground floor is comprised of living, dining space and kitchen. The first floor has three units of bedroom and family sitting area. For accurate results, the proposed plan was classified in DesignBuilder into zones according to the activity of each space.

Figure 3: Floor plans for the single-family two-storey housing prototype.

C. CFD Simulation

In order to carry out natural ventilation simulation in DesignBuider, "Calculated" module is preferred over "Scheduled" module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.

In order to perform a CFD, a thermal simulation has to be operated first. Hourly thermal simulation was performed within the typical summer week period which can be used in defining the whole summer behavior starting 1 August to 7 August through Alexandria_EGY weather data file.

Based on the results of thermal simulation, 4th of August at 12:00 was selected since it has the highest indoor air temperature (29.45 C^o) among other days. Simulations were carried out for the prototype where CFD Boundary condition was brought over from the thermal simulation results. DesignBuilder CFD generated automatically a uniform rectilinear Cartesian grid with a spacing of 0.3m and merging tolerance of 0.03m and the CFD grid system with total amount of 28 X-cells, 56 Y-cells, and 24 Z-cells were applied.

Predicted Percentage of Dissatisfied (PPD); a method of describing thermal comfort developed by Ole Fanger [11] that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale is being selected.

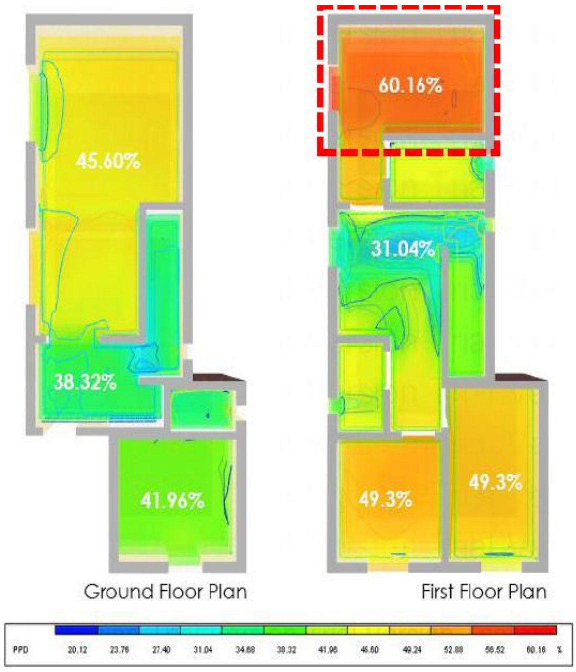

Figure 4: Predicted Percentage of Dissatisfied CFD Simulation.

As observed from the simulation results in Figure (4), the master bedroom, with an area of 3.10m x 4.60m (14.26 m²) and height of 3.00m is selected to be the space under study since it has the highest percentage of thermally dissatisfied people.

CFD Simulations were carried out showing a section of the reference case (Master Bedroom) that has a single-directional air flow ventilation technique resulting in an indoor air temperature of 29.45 C^o on the lower part and 30.27 C^o on the upper part of the room. The opening area positioned in the northern façade of the space is (1m x 1.2m) 1.2m² with a single clear glazing of 3mm.

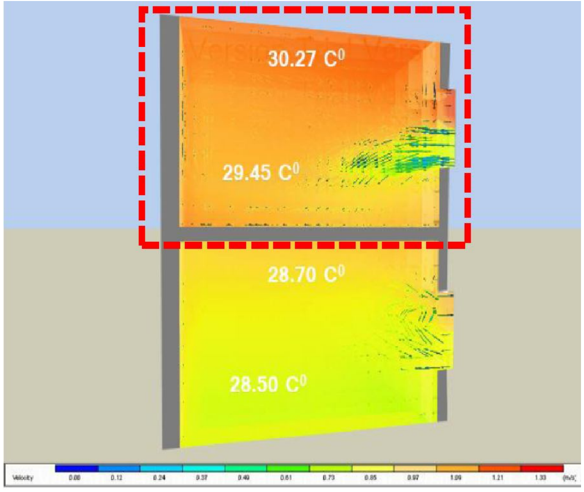

Figure 5: CFD slice showing the operative temperature and air flow direction for the master bedroom on the first floor and living space on the ground floor.

As concluded from Figure (5), in the master bedroom 3.10m x 4.60m (14.26 m²), the buoyancy effect makes the cold air enters at the lower part and the hot air exits at the upper part of the opening, so the single-sided ventilation is not an effective solution for cooling. While the living and dining space 8.5m x 4.6m (39.1 m²) on the ground floor has two openings of (2m x 1m) which has a better ventilation rate, so it will not be included in the simulation since the openings are too large in comparison to the chimney outlet, so it's unlikely to present a significant air-flow within the space.

IV. SOLAR CHIMNEY CFD SIMULATION

Simulation target is enhancing the flow rates and comfort conditions in the master bedroom by applying a solar chimney system on the southern façade which may affect positively natural ventilation rate and thermal comfort conditions within the space of the room. The vertical length of the chimney is equal to the first-floor height plus an additional 2m above the roof.

A south-facing (2m x 1.5m) glass is modeled at the top area of the chimney with a painted black concrete behind the air-gap. The solar radiation will transmit through the clear glass and then absorbed by the black concrete that will radiate back towards the glass, heating up that air in the gap which then rises up by the stack effect, which promote the indoor natural ventilation.

Warm air within the building will tend to move up and flow out of the modeled exhaust openings (0.8m x 0.4m) while cooler outdoor air will tend to flow in through main window inlet (1.2m x1m) to replace it.

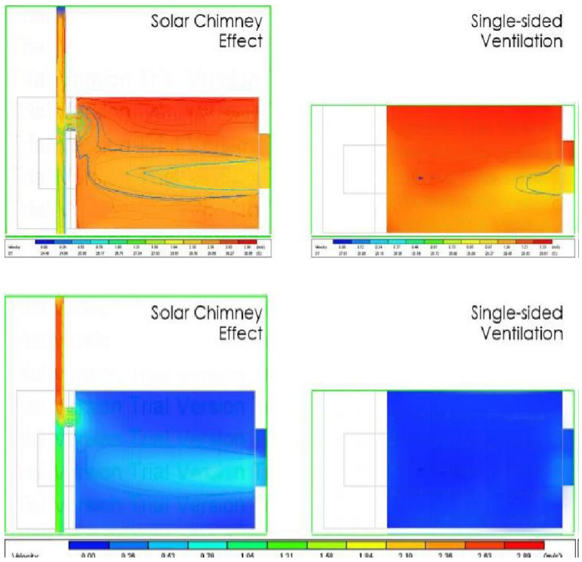

Figure 6: CFD slices showing the operative temperature and air velocity difference between the single-sided ventilation room and on introducing a solar chimney.

According to the results in Figure (6), Solar Chimney of 0.2m x 1.5m gap can provide an effective source of cooling, spreading at low levels toward the outlet of the chimney. The Operative Temperature of the indoor with solar chimney marked as 28.51 C^{o}, shows a positive results which is 0.94 C^{o} lower than the case study without the solar chimney. While, the air velocity is induced by the solar chimney and an increase of 32% of air velocity is observed.

There are many parameters that can affect the exit velocity of a solar chimney, such as solar intensity, air gap width, type of glazing, type of absorber, inlet area, chimney height, and inclination of solar chimney. In this research we discuss the exit velocity affected by air gap width. It has been mentioned by Bouchier, 1994 [12] that an optimum chimney length/gap width ratio for the optimum air velocity is necessary. Reverse circulation and turbulence would happen if the solar chimney gap was too big since there will be a downward flow of air through the center of the duct.

In this research the length of the chimney is fixed to 1.5 m, and varies of width gaps at different values of (0.2m, 0.4m, 0.6m, and 0.8m) were studied with a fixed total height from the ground floor of 8 m.

Indoor air velocity and operative temperature were recorded for each air gap value as shown. The operative temperature combines the air and mean radiant temperatures into one numerical quantity. It is a measure of the body's response to the convection and radiation energy exchange [13].

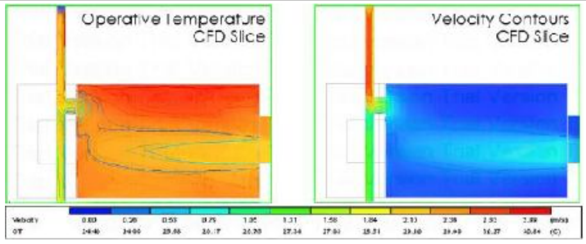

Figure 7: CFD slices showing the operative temperature and the air velocity pattern of the room on using airgap width 0.2m x 1.5 length with fixed height of 2 meters above the room roof.

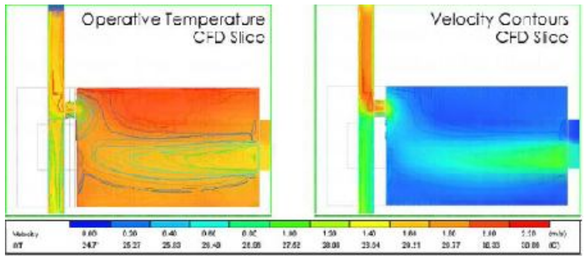

Figure 8: CFD slices showing the operative temperature and the air velocity pattern of the room on using airgap width 0.4m x 1.5 length with fixed height of 2 meters above the room roof.

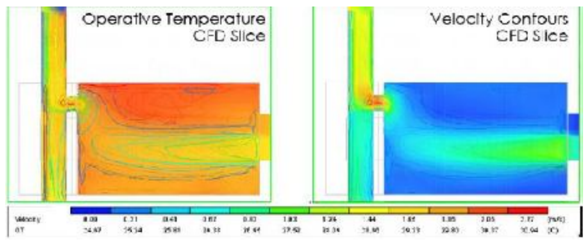

Figure 9: CFD slices showing the operative temperature and the air velocity pattern of the room on using airgap width 0.6m x 1.5 length with fixed height of 2 meters above the room roof.

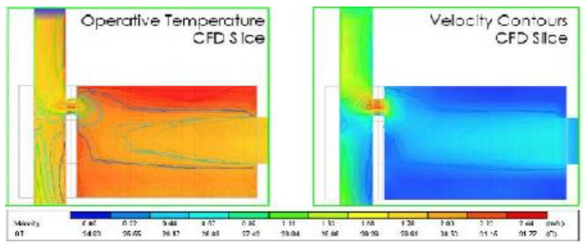

Figure 10: CFD slices showing the operative temperature and the air velocity pattern of the room on using airgap width 0.8m x 1.5 length with fixed height of 2 meters above the room roof.

The air flow velocities and the operative temperature for the CFD slices were taken from the monitoring points (A and B) 1.5m above the first floor level while the points (C and D) 2.5m, and the point (E) 4m as shown in figure (11).

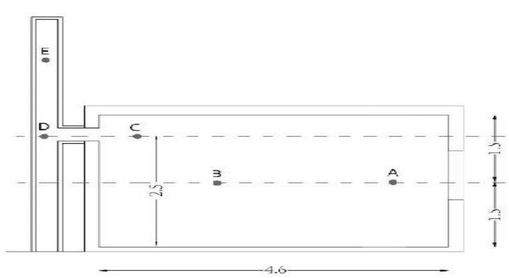

Figure 11: The position of monitoring points in the case study room.

V. RESULTS AND FINDINGS

The results of CFD show that the effective width gap for a 14.26 m² room ranged from 0.2m to 0.8m when the length is 1.5m, whereby the induced air speed ranged from 0.04 m/s to 0.223 m/s.

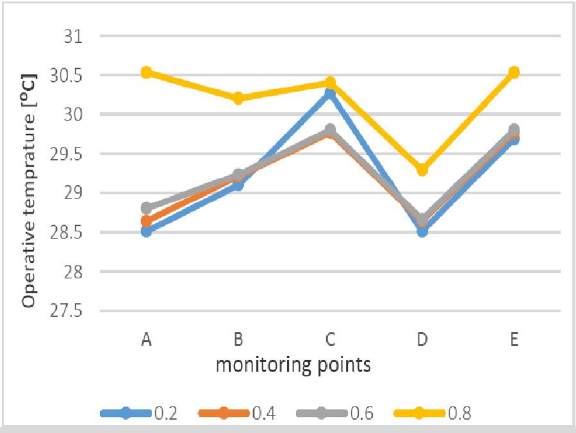

Figure 12: Operative Temperature chart according to the monitoring points for the air gap widths 0.2, 0.4, 0.6, and 0.8m

As shown in Figure (12), from the four variable air gap widths, models 0.4x1.5m and 0.6x1.5m show better results since the average operative temperature in the bedroom have lower temperature, which is 28.64 C° and 28.66 C° respectively. The high operative temperature in the 0.8x1.5m model happened due to the reverse circulation and downward flow of air through the chimney.

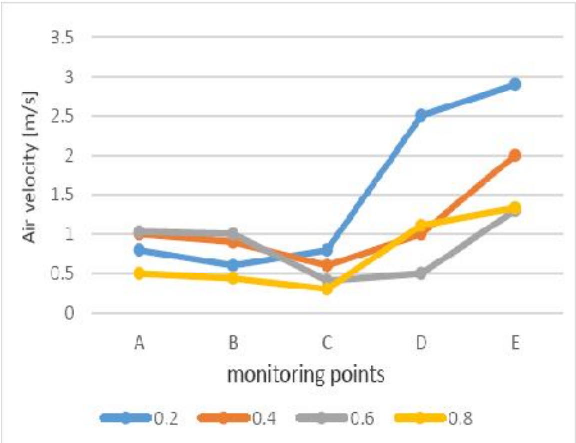

Figure 13: Air Velocity chart according to the monitoring points for the air gap widths 0.2, 0.4, 0.6, and 0.8m

As shown in Figure (13), the distribution of air speed in the chimney is not uniform, air speed near the wall of heat storage is much greater than the middle. From the four variable air gap widths, model 0.4x1.5 and 0.6x1.5 show better air velocity results in point A & B where the average air velocity is increased by 50%. The reason for the highest air velocity at point (D & E) In the case of model 0.2m gap width, is that decreasing the air gap makes the bulk air more affected by the absorbing wall and thus having a higher temperature than the air close to the glass cover which leads to an increase in the air velocity.

CONCLUSION

CFD simulations have the potential to be a useful tool in order to investigate the indoor climate in buildings. The aim of the study is to shows that the case study prototype thermal performance can be enhanced via the application of solar chimney, where the air temperature at the hottest point could be reduce and shows that the natural ventilation can be improved.

The findings show that the installation of solar chimney can decrease average daily operative temperature from 29.45 C° to 28.64 C° and increase the air velocity by 50% on using a solar chimney of cross section 0.4x1.5m or 0.6x1.5m with fixed height of an additional 2m above the roof of the room; a total height of 8m.

In summary, although the air flow and air temperature do not achieve the standard thermal comfort condition, however, the significant improvement could enhance the thermal performance comparable to outdoor temperature.

Further experiments are required to determine the optimum configurations of solar chimney geometry to enhance the natural ventilation of the prototype. There are many parameters that can affect the exit velocity of a solar chimney, such as solar intensity, air gap width, type of glazing, type of absorber, inlet area, chimney height, and inclination of solar chimney.

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