Computational Investigation for The Windcatcher Top Roof Length Effect on Indoor Air Quality – simulation study

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ABSTRACT:

The main aim of the current research is to calculate the optimum top roof length of windcatcher for enhancing indoor air quality (IAQ) parameters such as (AAV) average air velocity, (AFR) air flow rate, (ACR)air change rate, (MAA) mean age of air and (ACE) air change effectiveness. This work assesses the effect of the top roof length of windcatcher on indoor natural ventilation in a tropical climate or dense urban areas. The research method was conducted through Autodesk CFD 2019 software for simulation purposes. The reference tested model is composed of a rectangular cuboid with 8 m length, 6 m width and 3 m height which represents a small model room for applying the numerical simulation and the windcatcher was combined with the room roof. The tested windcatcher form is a rectangular cuboid of 1.4 m length, 1 m width and 1.5 m height, while the inlet and outlet openings of the wind catcher are 1 m by 1 m. The windcatcher simulation is aimed to determine the IAQ parameters for different 11 case studies with different top roof projection length ranges from 0 cm to 100 cm with an interval each 10 cm.

The main results of these CFD simulations are representing the effect of the projection length of top roof of windcatcher on the parameters of natural ventilation performance. Based on the simulation, it can be concluded that the increasing of the top roof of windcatcher to 100 cm leads to increase in the AAV with 10.5%, increase AFR with 190%, increase ACH with 11% at inlet. Also increase AVA with 14%, decrease MAA with 14% and increase ACE with 67% inside the tested model. Depending on the results, this paper suggests a regression equation that can predict the inlet and indoor average air velocity for different projection lengths for the tested model.

KEYWORD

Windcatcher –Natural Ventilation – Indoor Air Quality

1. Introduction

Natural ventilation during the building design process is considered one of the most important issues for a successful architectural design of different building types. The main functions of the natural ventilation are to remove odor particles, volatile organic compounds as well as humidity (due to human exhalation) [17]. It is also necessary to dilute the amount of CO2, which causes inactivity for space occupants, and to remove the accumulated hot air inside architectural spaces [34]. The innovative approaches for achieving effective natural ventilation inside buildings spaces attracted the attention from the architectural building designers, planners and the research community. Continues feedings of fresh air for indoor spaces is an enhancement strategy for thermal comfort conditions by harnessing the ventilative cooling potential of air in the ambient environment[27]. Wind catcher is a wind-driven natural ventilation building element, which is utilizing for achieving the natural ventilation of large or small building types,

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particularly throughout the summer periods [2]. Wind catchers are used in various countries in Middle East and North Africa in order to improve indoor air environment and to reduce reliance on cooling load [23]. Wind catchers can introduce several advantages, especially in compact urban areas and in regions where wind speed is rather low [20].

The traditional architecture systems for passive and low energy cooling systems that is found in the buildings in the hot countries are using the wind catcher. The wind catcher, a natural ventilation system, is similar to vertical chimney; it is served as a vertical building-integrated element mounted on the building roof, which induces the fresh air from outside the building into indoor building spaces due to the pressure difference over the building roof and across the wind catcher openings [17]. The utilization of wind catchers in the Middle East countries dates back to thousands of years [17],[17]. **Figure 1** shows the different types and forms of Middle East windcatchers. Modern wind catchers currently have a wide usage, especially in populous indoor spaces such as schools and other workplaces[17].

Figure 1 the different forms of Windcatcher in Middle East

Parts of a windcatcher (side walls and the top roof) play an important role to lead and control the outdoor air flow toward the internal building spaces by projecting portions of sides and the top from the windcatcher openings [33]. The wind pressure difference between the windcatcher windward and leeward surfaces is the cause of the flow of fresh air into and out of the space [10]: It is therefore suggested that the use of a projections elements of windcatcher may lead to improve the natural ventilation rates inside buildings. The main two driving forces cause the continued function of windcatcher; wind force due to the differences of air pressure and buoyancy force due to difference of temperature between inside and outside of the building [28].

Windcatchers are classified into different groups, according to; numbers of openings, number of stores, cross-section, and interior dividing. With regard to the number of openings, windcatchers are classified to One-sided windcatchers - Two-sided windcatchers - Four-sided windcatchers - Six-sided windcatchers - Eight-sided windcatchers [32].

Previous studies generally indicated that windcatchers are widely used in regions where the wind speed ranges from 3 to 5 m/s. In lower wind speed conditions, the implementation of windcatchers is quite limited and insignificant [13].

H. Montazeri, [11] investigated the different aspects of the used wind catchers in cross ventilation. Many researchers [19] studied the components that control airflow on the windcatchers while others focused on the role of windcatchers as a building element in improving the indoor and outdoor natural ventilation rates.[11], [36]

Effects of the integration between wind-catchers with other passive ventilation solutions such as solar chimneys, dome and evaporative cooling systems in building design were the research topic for others, [30]:[1]

In the study of Afshin et al [3], ventilation performance was investigated for the two-sided windcatcher underwent wind tunnel, experimenting with different wind slops ranging from 0 to 90, the study concluded that the transition angles of the building window and windward opening for all different wind velocities occur at the wind angles of 39° and 55°, respectively. Also, the wind-catcher is served as a chimney for the wind angle larger than the windward transition angle ($\alpha = 55°$) and the highest ventilation rate obtained with 90° wind slop.

Mak, C.M., [22] investigated that wing walls are especially operative on sites where outdoor wind velocity is low and wind directions are varied as the wing walls contribute to increase the difference in pressure through the openings which lead to improve air exchange. Thus, the current research proposes that the natural ventilation rate can increase under low wind speed conditions when the windcatcher is combined with the wing top roof.

At the Florida Solar Energy Center, the wing walls performance was studied by Chandra et al, [9] in a full-scale experimental building and different models. The main aim of the study was to evaluate the effect of two vertical walls placed on the both side of the window opening on natural ventilation inside building spaces. From this study, it was concluded that adding wing walls on the both side of the opening is an effective process capable of providing natural ventilation for the building spaces due to the generated zones of positive and negative pressure at the building openings when the angle at which wind blows to the walls is different from the normal condition.

Jamal khodakarami [18]studied the impact of openings number and outdoor flow direction on the indoor vertical flow velocity in windcatchers. During the study; different models of wind catchers with different numbers of upper openings, also different slop angles of wind (including 0°, 45°, 90°, 135° and 180) were tested by CFD simulation. The study concluded that the multi-pressure traditional wind catchers give more stable and more predictable indoor air flow, and hence better efficiency more than the single pressure traditional types of wind catchers.

From the foregoing, it can be concluded that none of the mentioned studies investigated the effect of one side windcatcher integration with top roof parameters. The current work investigates the impact of wing top roof parameters (wind slop and length of top projection) on basic flow characteristics of cross-ventilation using windcatcher integrated into a single-zone isolated building in a neutral atmospheric boundary layer.

The simulations of cross-ventilation are performed on 24 cases for different building slops and projection lengths of the opening top roof. The evaluation criteria for the mentioned cases are based on the induced airflow rate, age of air, and air change efficiency. Thus, current study represents an opportunity to investigate this research gap.

2. Materials and Methods

The simulations of current study are performed for a single-zone isolated building with an integrated one-sided windcatcher. The reference model, Figure 2 is composed of a rectangular cuboid with 8 m length, 6 m width and 3 m height which represents a small model room for applying the numerical simulation and the windcatcher was combined with the room roof. The windcatcher is a rectangular cuboid of 1.4 m length, 1 m width and 1.5 m height, while the inlet and outlet are of windcatcher openings are 1 m by 1 m.

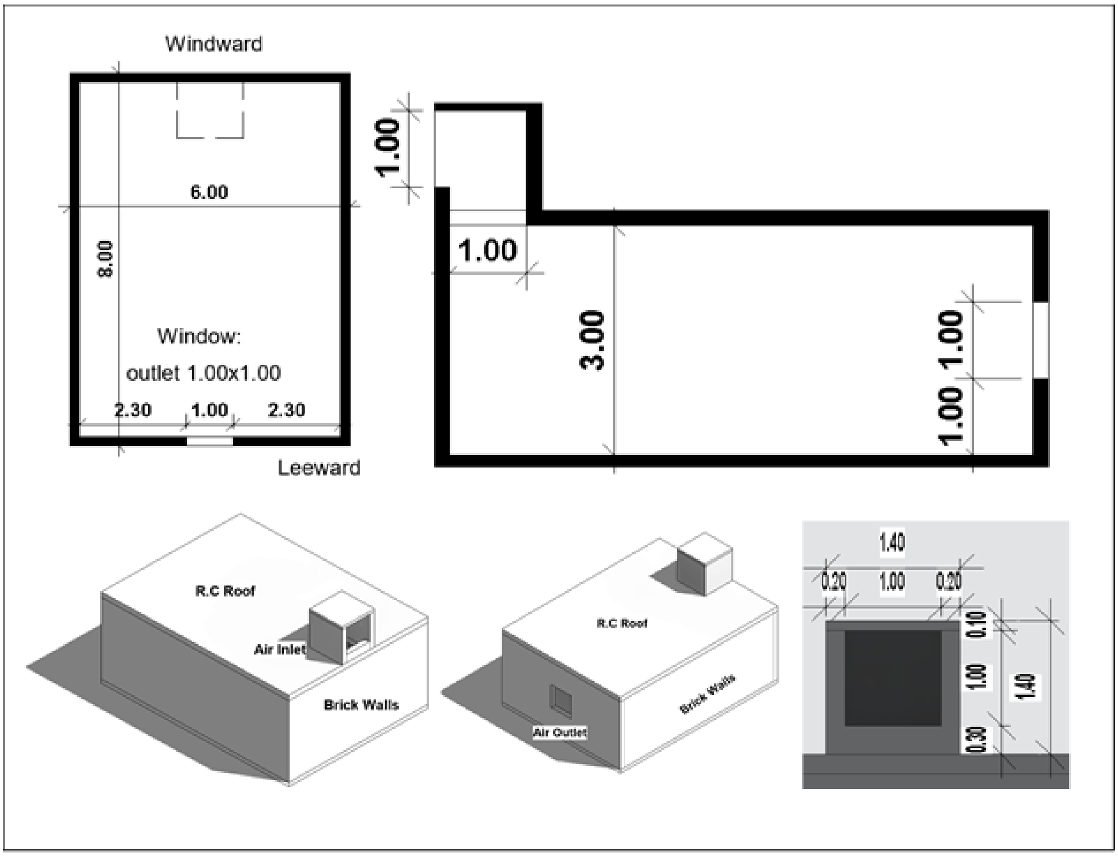


Figure 2 the reference model and Windcatcher dimensions (Plan, section, Isometric and detail)

The building models are divided according to the top roof projection length. The tested model has a single window opening with a surface area equal to 1m by 1m. The window is placed in the middle of the leeward elevation to improve the efficiency of the natural ventilation system. The projection length ranges from 0 cm to 100 cm with an interval each 10 cm. For CFD simulation, the tested model has put in an external volume to present the air flow inside and around the model. **Figure 3** shows the dimensions of the external volume which is depending on the model dimensions [11]. **Figure 4** shows the different cases for CFD simulation.

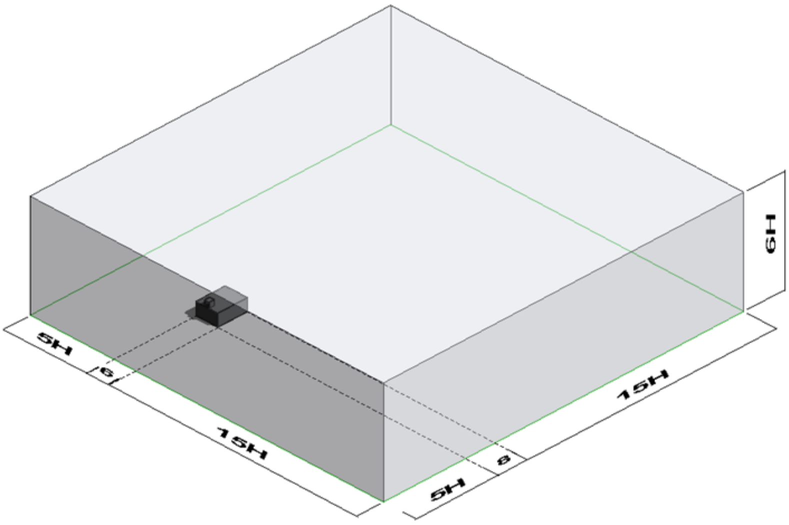


Figure 3 Perspective View of External Volume

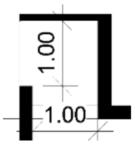
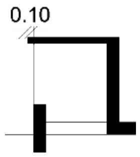
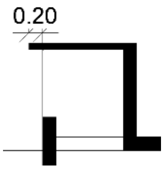
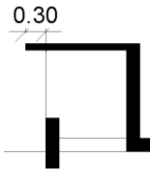
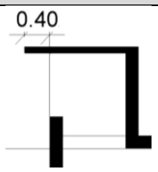
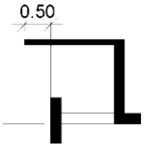
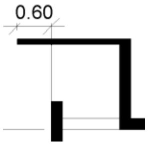
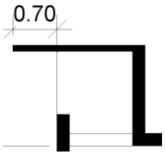
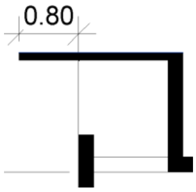
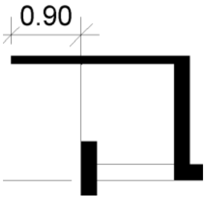
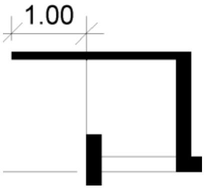
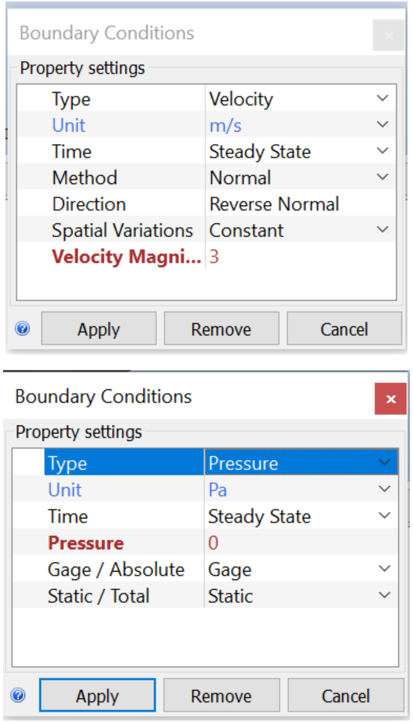
Length	0 cm	10 cm	20 cm	30 cm
Projection	 Case 01	 Case 02	 Case 03	 Case 04
	40 cm	50 cm	60 cm	70 cm
Projection	 Case 05	 Case 06	 Case 07	 Case 08
	80 cm	90 cm	100 cm	
Projection	 Case 09	 Case 010	 Case 011	

Figure 4 Geometry of windcatcher with different projection length

1.1 CFD study for windcatcher performance

In this phase, the windcatcher performance was studied in low wind speed conditions with regard to air velocity, airflow distribution and the other factors of IAQ. The flow equations and simulations were solved by employing the Autodesk CFD with three-dimensional computations. [25]

- Building materials: for simulation purposes, the selected material for model and windcatcher walls is brick with 25 cm thickness, while the material for floors and roofs (both model and windcatcher) is concrete with thickness 20 cm. the internal and external volumes are natural air.
- Boundary conditions: At the inlet of the domain, neutral atmospheric boundary layer inflow profiles of mean wind speed 3m/s. and at the outlet of the domain the pressure is 0 pa at steady state. **Figure 5**
- Mesh sizing: Model meshing is a very complex process; thus, many meshing configurations were tested for different geometric models. After many considerations, a mesh comprised only of tetrahedrons was selected. [7]

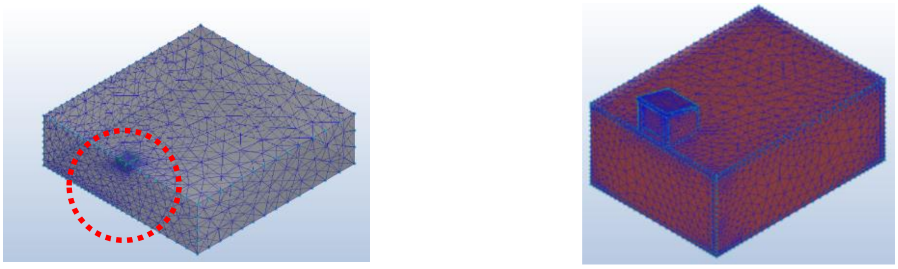


Type	Velocity
Unit	m/s
Time	Steady State
Method	Normal
Direction	Reverse Normal
Spatial Variations	Constant
Velocity Magni...	3

Type	Pressure
Unit	Pa
Time	Steady State
Pressure	0
Gage / Absolute	Gage
Static / Total	Static

Figure 5 Boundary conditions

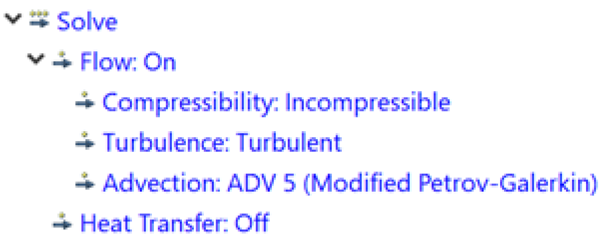
- By selecting the Auto size meshing, the simulation software Autodesk CFD performs a comprehensive topological interrogation of the analysis geometry and define the optimum mesh size and distribution for every edge, surface, and volume in the tested model. **Figure 6** while the process of assigning sizes and mesh distributions for each element, the geometric curvature, gradients, and proximity to neighboring geometry is taken in consideration during the process [5]. The mesh is discretized according to [24],[15].



a- External volume mesh **b- Tested model mesh**

Figure 6 The Mesh of the Model

- Solve settings: the model was tested with Iteration to run 200 and the main solve settings are shown in **Figure 7**



Solve
Flow: On
Compressibility: Incompressible
Turbulence: Turbulent
Advection: ADV 5 (Modified Petrov-Galerkin)
Heat Transfer: Off

Figure 7 Solve settings

Figure 8 shows the different horizontal and vertical planes in which the parameters of indoor air quality were tested for evaluating the windcatcher's ventilation performance. The inlet (vertical outside (1) and horizontal (4) inside the space), 1.1 m horizontal plane (2) and vertical (3) plane at the center of windcatcher and outlet were used to calculate and display the contours of different IAQ factors. The opening plane (2) was defined as the start time of air traveling from windcatcher to outlet through the model for mean age of air (MAA) calculation. The length of the extruded roof was the parameter for the wind catcher design in the current work by testing ten different lengths starting with 0 cm up to 1 meter with 10 cm interval. The inlet plane (1) and 1.1 m horizontal plane (2) were used to calculate the different IAQ factors.

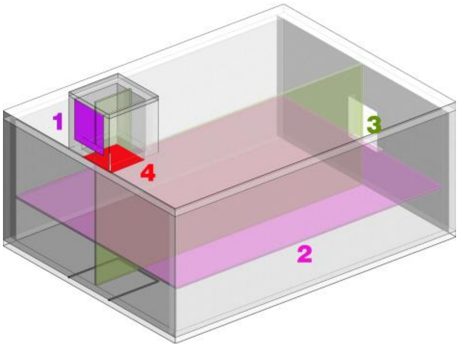


Figure 8 The positions of planes used for calculations

plane (2) was defined as the starting time for air traveling from the inlet to outlet through the tested model for mean age of air (MAA) calculations.

3. Results

The results of CFD simulation, which were obtained from the performance of the windcatcher, are presented in this part of the paper. Windcatcher with different length of wing roof top and slop were assessed. The main aim to analyze the effect of different length and slop of wing top roof of windcatcher on the indoor air quality factors.

1.2 The effect of top roof length on Air Flow in inlet (windcatcher opening)

The ventilation efficiency of different lengths of top roof was evaluated and compared by calculating the average of airflow velocity for plane (4) within the windcatcher inlet, which supplies the fresh air inside the model. **Figure 9** shows the simulation results for the tested model's inlet air velocity in various roof top (plane 4) lengths from 0 cm to 100 cm with 10 cm increments in outdoor wind speed of 3 m/s.

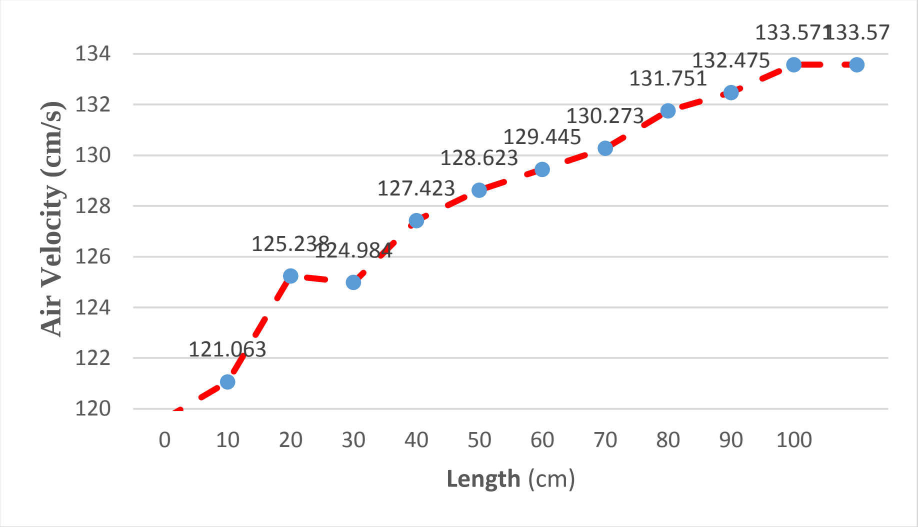


Figure 9 The simulation results for various roof top lengths

According to Figure 9, the air velocity pattern shows a steady increasing in air velocity with the increasing in roof top length; thus, the maximum (1.34 m/s) was observed in model with 100 cm top roof length. The distinction between maximum and minimum values was 12%.

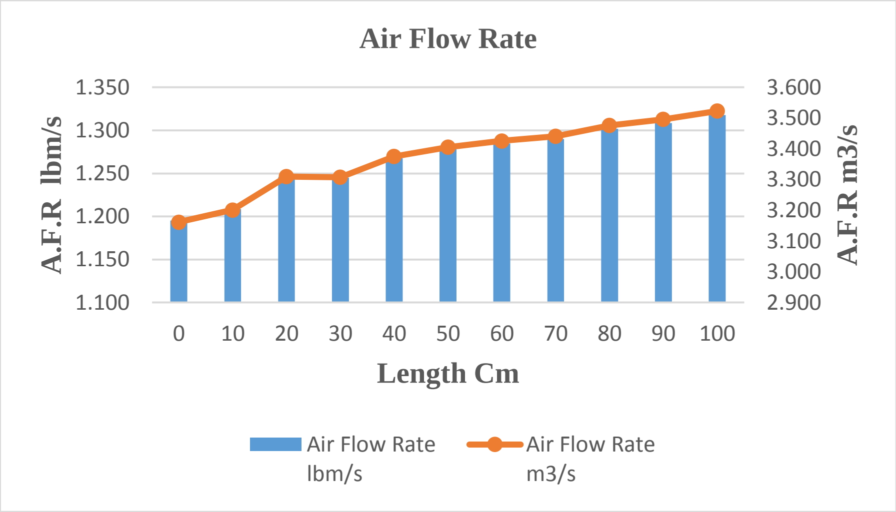


Figure 10 Air flow rate and air flow rate per m^3 in different top roof lengths

Figure 10 shows the air flow rate and air flow rate per cubic meter of the tested model with different roof top lengths. Since the air flow rate is considered as a function of inlet air velocity so, the air flow rate and inlet air velocity pattern are similar. In another words, as the roof top length increased, the air flow rate also increased and reached its maximum value at 100 cm (3.5 lbm/s and 1.3 m3/s).

Figure 11 shows the air change rate per hour (ACH) for different roof top length of windcatcher, the pattern of ACH is similar to the pattern of air velocity as it is directly associated with inlet air velocity, so as the roof top length increased, ACH also increased and reached its maximum value at 100 cm (33.1 per hour).

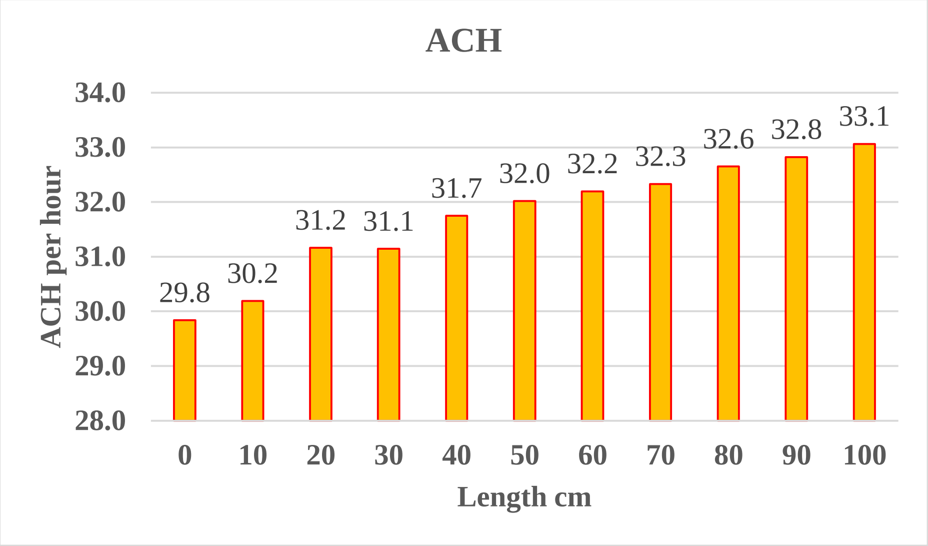


Figure 11. ACH in different top roof lengths

3.2 The effect of top roof length on IAQ (Indoor Air Quality)

In this part of the current work, the main parameters of IAQ of the tested model are assessed in plane 2 (horizontal plane at height 1.1 m from floor) and plane 3 **(Fig. 8)**. The main measured parameters are: air velocity, mean age of air (MAA) and air change effectiveness (ACE). The air velocity contours inside the occupied zone (the breathing height at sitting position) are presented in Figure 12 and 13.

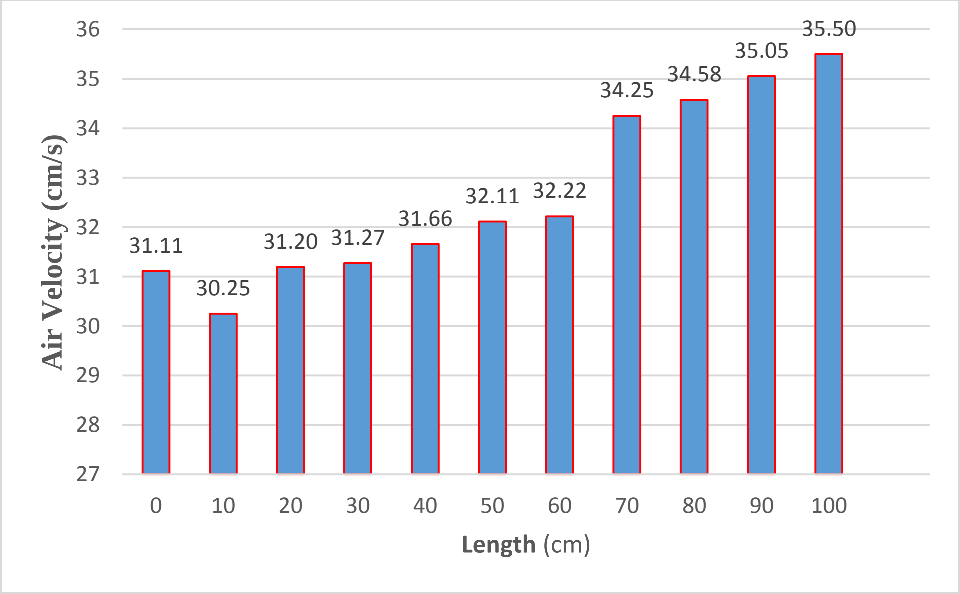


Figure 12 The average of air velocity in 1.1 m horizontal planes in different wing wall lengths

Slop / length		0 cm	10 cm	20 cm	30 cm

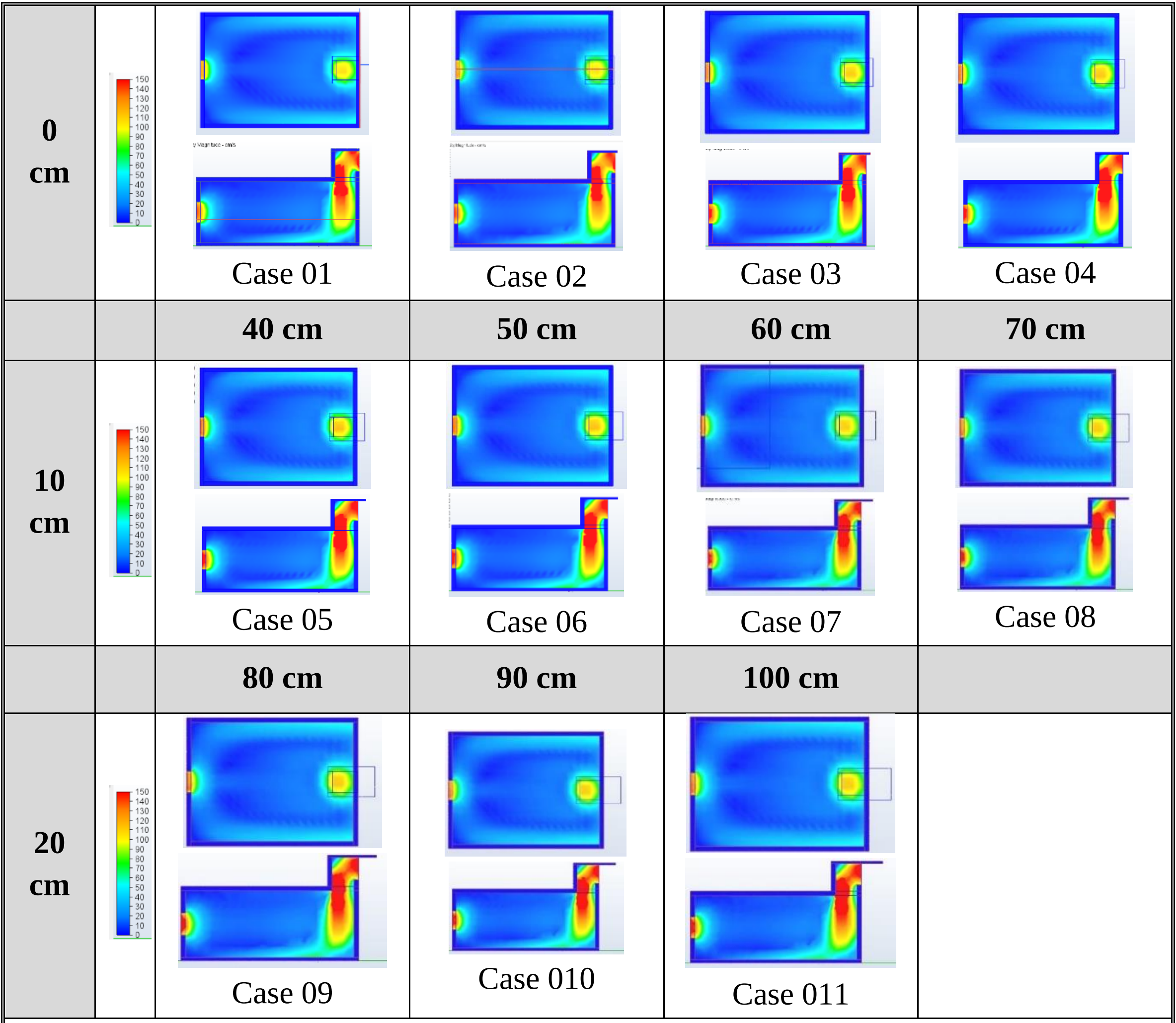


Figure 13 The air velocity contours inside the occupied zone

Figure 13 shows that the pattern of inlet air flow is similar to the pattern of air flow inside the occupied space inside the tested model.

Mean Age of Air

Mean age of air (MAA), which is defined as the needed time since the air enters an indoor space [29].

Figure 14 shows the different calculated values of MAA in 1.1 m horizontal plane at different top roof of windcatcher length where the lower values is preferred. The maximum MAA in 10 cm length was 12% higher than the minimum MAA in 100 cm length. It seems that the MAA become greater by decreasing in top roof length of the windcatcher.

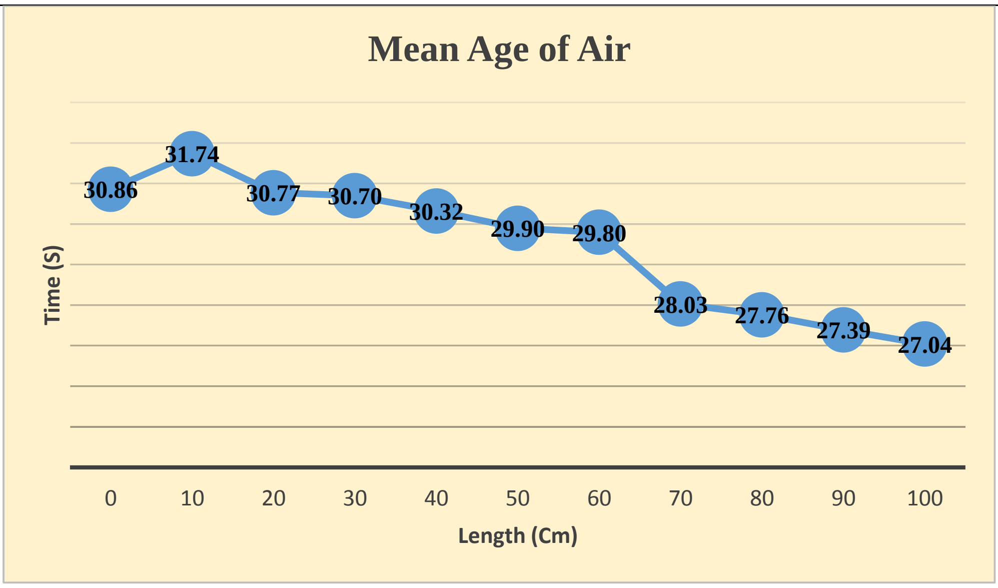


Figure 14 The Mean age of air of horizontal plane in different length

Air change effectiveness

The ratio of a nominal time constant to a mean age of air is defined as Air change effectiveness (ACE) [26]. The ratio of the tested model volume (8 * 6 * 3 m3) to the flow rate of supply air volume (m3/s) to the tested model is the nominal time constant [29]. The ACE calculated values at 1.1 m horizontal plane shown in Figure 15 ranges between 0.87 and 1.45

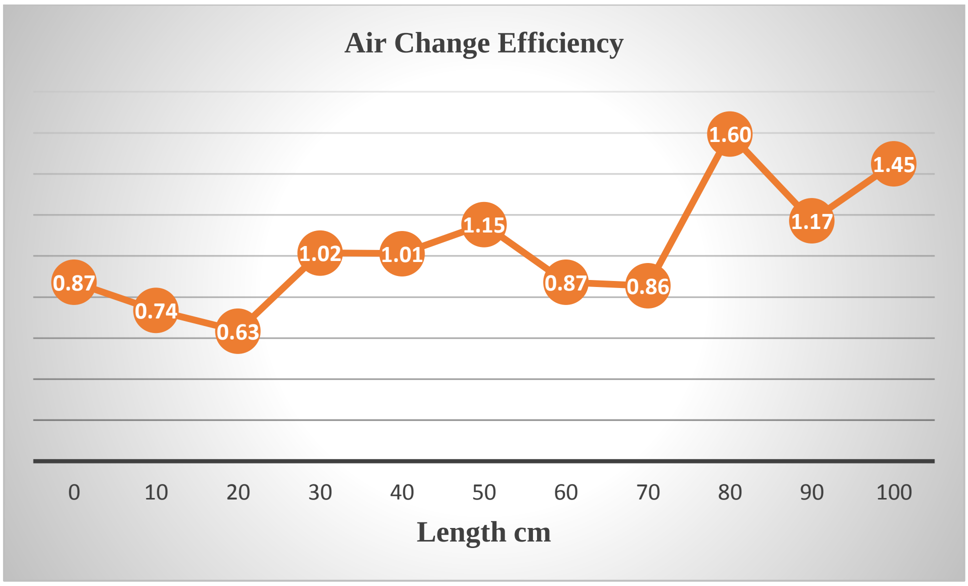


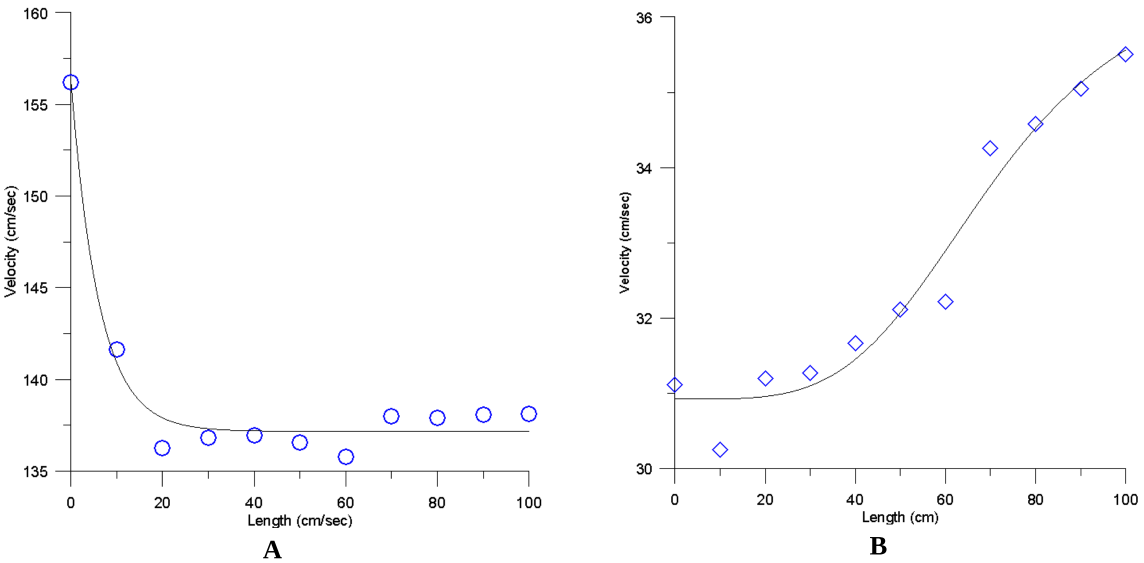
Figure 15 The air change effectiveness of horizontal plane in different length

The data for the average velocity inside room is correlated in equations [1] and [2], respectively. Figure 16 is showing the validation of the equations with the numerical data for AVA at inlet and AVA inside the tested model for plane 3, respectively

$$V_1 = 19.13 * (7.17 + e^{-0.163L}) \qquad [1]$$

$$V_2 = 30.92 + \frac{5.788 * L^{4.032}}{70.67^{4.032} + L^{4.032}} \qquad [2]$$

The proposed equations describe the change of the air velocity as a function of the windcatcher top length. Equation (1) is predicting the average velocity at the inlet V1 while Equation (2) is calculating the average velocity through the tested model. The AVA (V1) is decreasing asymptotically from about 156 cm/s to a fixed value of about 137 cm/s for all windcatcher lengths higher than 30 cm. The AVA (V2) started to increase from about 31 cm/s till the maximum value of 35.5 cm/s as the windcatcher length increased five times from 20 cm to 100 cm.



A B

Figure 16 The validation of the predicted models with the numerical results; a) AVA at inlet b) AVA inside the tested model

4. Conclusions

Enhancing the (IAQ) indoor air quality by achieving the standard of natural ventilation leads to consume the used energy in ventilation purposes. Windcatcher is one of the famous traditional solutions for achieving natural ventilation inside buildings. In this work the length of top roof of windcatcher was evaluated at low wind speed (3 m/s wind speed) by variation of the top roof length. This study focused on the length as one of the other design factors to investigate the effect of the top roof length on the indoor air quality (IAQ), factors such as air velocity at level 1.1 meter from height, air flow rate (AFR) for inlet, air change rate (ACR), mean age of air (MAA) and air change effectiveness (ACE). Different top roof lengths from 0 cm to 100 cm were assessed and it was found that increasing the length of top roof of windcatcher leads to upswing the different indoor air quality factors. The findings highlighted that the increasing of the top roof of windcatcher to 100 cm leads to increase the AVA with 10.5%, increase AFR with 190%, increase ACH with 11% at inlet. Also increase AVA with 14%, decrease MAA with 14% and increase ACE with 67% inside the tested model. The results of this study can be implemented for tropical climate or dense urban areas. In summary, windcatcher roof coupled with top length 100 cm represents the maximum Indoor Air Quality (IAQ) parameters inside building, and hence it helps increasing air velocity inside the building spaces as shown in Figure 17.

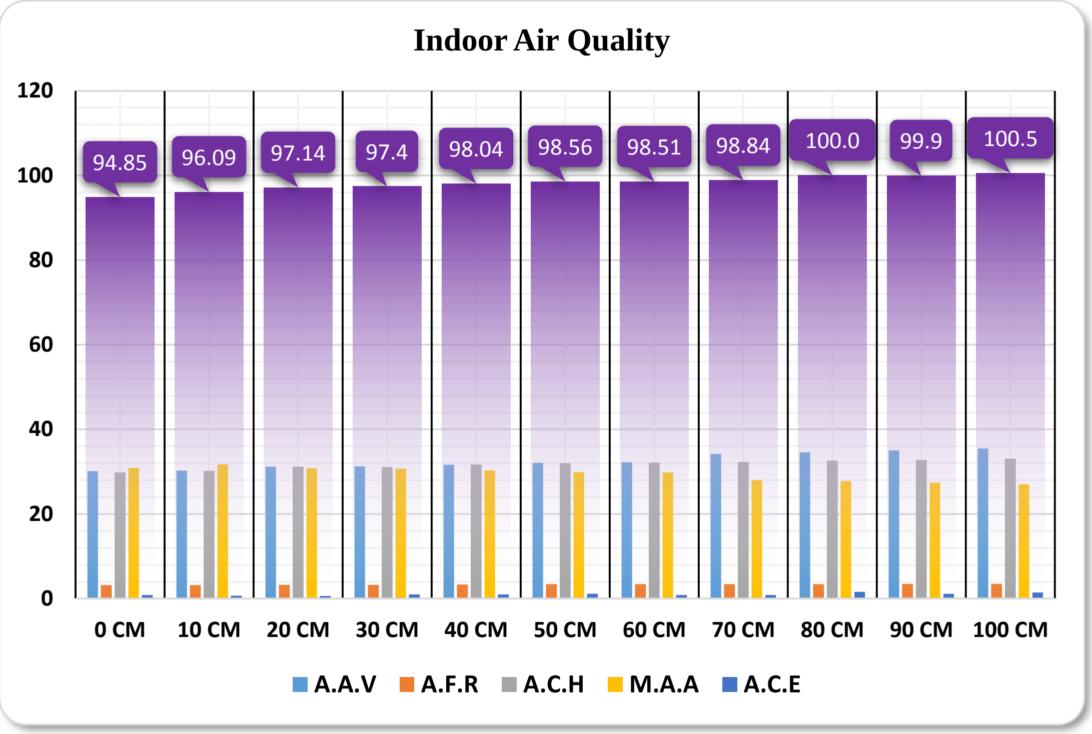


Figure 17: Indoor Air Quality for different top roof lengths

5. Nomenclatures

IAQ	Indoor Air Quality	The purity of the air in a specified area, which is determined by the level of dust, suspended particles and pollutants.
AAV	Average Air Velocity	The average of air velocity (distance traveled per unit of time) in a certain plane or volume of a space distance traveled per unit of time.
AFR	Air Flow Rate	The actual volume of air passing through the windcatcher per unit of time.
ACR	Air Change Rate	Is a measure of the air volume replaced within a defined space by ventilation?
MAA	Mean Age of Air	The average time that air has spent in a space of the building accumulating contaminants.
ACE	Air Change Effectiveness	A description of the air distribution system's ability to deliver ventilation air to a building, zone or space, and measured as the ratio of a nominal time constant to the mean age of air.
CFD	Computational Fluid Dynamics	The use of applied mathematics, physics and computational software to visualize the gas or liquid flow in buildings, zones, spaces and objects.

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