21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Simulation of Buoyancy Driven and Winddriven Ventilation Flow in a Three Dimensional Room Fitted with a Windcatcher

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Abstract

Natural ventilation is the process of supplying and removing air through an indoor space by natural means. There are two types of natural ventilation occurring in buildings: winddriven ventilation and buoyancy driven or stack ventilation. Combining the wind driven and the buoyancy driven ventilation will be investigated in this study through the use of a windcatcher natural ventilation system. As stack driven air rises leaving the windcatcher, it is replaced with fresh air from outside entering through the positively pressured windward side. To achieve this, CFD (computational fluid dynamics) tool is used to simulate the air flow in a three dimensional room fitted with a windcatcher based on the winddriven ventilation alone, and combined buoyancy and winddriven ventilation. A three dimensional real sized room with a length of 5 m, a width of 4 m and a height of 3 m fitted with a windcatcher is modeled in this study using Ansys Fluent. The combined, buoyancy driven and winddriven ventilation, has provided approximately 3.16% increase in the total air flow rate, when heat flux of 500 W/m^2 is applied at the front and bottom walls of the windcatcher's outlet compared to the winddriven ventilation only. The pattern of air flow through the room has provided full ventilation at 1.2 m height where most of the human occupancy occurs.

Introduction

Natural ventilation uses fresh cool air from outdoors for cooling and ventilation. The introduced air replaces contaminated heated indoor air. Building design is essential in producing energy efficient buildings. The natural ventilation design approach improves up to 9.7% the building energy performance [10, 13]. It is especially important to provide architectural designs and engineering approaches in the context of an overall environmental design strategy [16]. Natural ventilation has several benefits including contamination removal and providing fresh oxygen, thereby promoting good indoor air quality [17]. Solar chimney is regarded as an effective and economical design method however it is noted that with only a solar chimney there seems to be limited potential to induce sufficient natural ventilation and to satisfy indoor thermal comfort [18]. The most efficient design for a natural ventilation building would make use of both types of natural ventilation, namely the winddriven ventilation and buoyancy or stack ventilation [4].

Combining the winddriven and the buoyancy driven ventilation will be investigated in this study through the use of a windcatcher natural ventilation system. Figure 1 shows a representative model of the three dimensional room studied.

Air with higher inside temperatures have lower density and thus will rise above the cold air to exit and be replaced by cooler denser air which creates an upward air stream [11]. Winddriven ventilation is mainly the primary driving force [7] yet stack ventilation can offer several benefits. Stack ventilation is less dependent on wind and its direction. Solar chimneys are an innovative passive design [12] that contributes to an increase in efficiency for residential space heating and cooling in addition to a considerable reduction of greenhouse gas emissions.

In a combined winddriven windcatcher and buoyancy driven solar chimney, air enters through the wind tower and exits through windows, doors and through the solar chimney. At low wind speed, the solar chimney creates natural air flow since the fresh air enters through the wind tower as the warm air exits through the solar chimney [4].

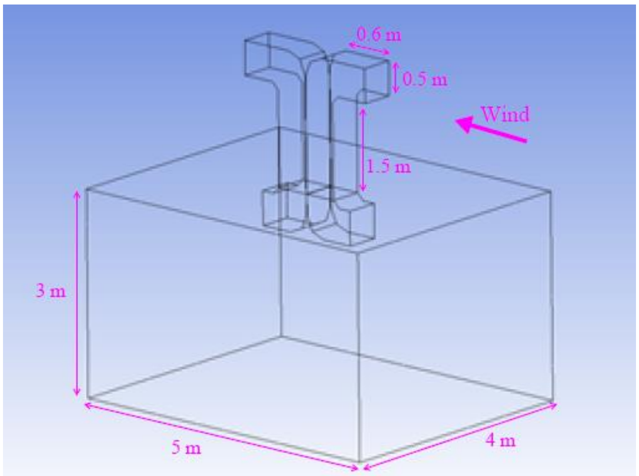

Figure 1. Three dimensional room fitted with a windcatcher

The review of the literature reveals a gap related to the effect of the architectural design of the windcatcher and how it affects the air flow and human comfort [6]. A recent study of the same authors has investigated the effect of the windcatcher's inlet design at a constant wind speed of 3 m/s [2], a previous study [1] has also investigated the effect of combining buoyancy driven and winddriven ventilation in a two dimensional room. The combined, buoyancy driven and winddriven ventilation, has provided at least 10% increase in the total air flow rate, when heat flux of 600 W/m^2 is applied compared to the winddriven ventilation only.

Modelling and computation

A three dimensional real sized room shown in Figure 1 with a length of 5 m, a width of 4 m, and a height of 3 m fitted with a windcatcher is modeled in this study using Ansys Fluent [3]. The height of the windcatcher is assumed to be 2 m from the roof of the room up to the top of the windcatcher.

The size of the inlet and outlet openings of the windcatcher is taken to be 0.5x0.5 m^2. They are perpendicular to the flow direction. Niktash and Huynh [14] has investigated the effect of two sided windcatcher inlet / outlet on ventilation of a three dimensional room. This research has concluded that when the inlet / outlet cross section is perpendicular to the wind direction it satisfies the human comfort requirements for having proper indoor ventilation and it leads to enhancing the performance of windcatchers. The chimneys entrance geometry significantly affects the ventilation rate as found by Huynh [8] who computationally studied the natural ventilation flow through a real sized 3 dimensional room and found that a rounded entrance results in higher flow compared with sharp entrance.

The windcatcher length inside the room is taken to be 0.1 m and the inside opening size is also 0.5x0.5 m^2. Niktash and Huynh [15] has studied the ventilation flow through a two dimensional room fitted with a windcatcher and concluded that the shape of the windcatchers bottom and its length strongly affects the flow pattern and flow velocity and that a good combination is achieved by a shorter bottom length which also does not obstruct the access through the room. It has been also found that when the windcatcher is located in the middle of the roof there is more uniform circulation in the lower parts of the room.

To simulate a free ventilation air flow the addition of a surrounding domain that contains wind is considered. Wind is driven from the right side at a velocity of 3 m/s distributed uniformly over a height of 20 m; the air inlet is at a distance of 15 m away from the right edge of the room. The total width of the surrounding domain is 35 m, its depth is 28 m and its height is 20 m. The room is fitted in its center as shown in Figure 2.

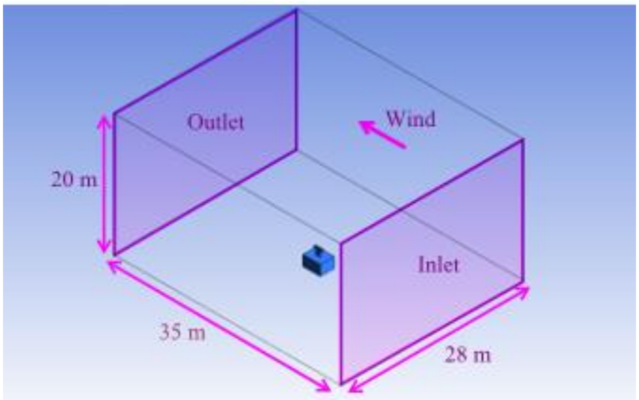

Figure 2. Schematic representation of the surrounding domain showing its dimensions and the direction of the wind. The room with the windcatcher is shown in blue at its center.

The right side of the surrounding is a velocity inlet, where the speed of air is set to 3 m/s. The left side is an outlet with pressure set to zero gauge. The room, the windcatcher's walls and the remaining sides of the surrounding are all set to be a stationary wall with no slip shear condition.

For meshing the geometry, tetrahedral have been used with a face sizing applied at the room and windcatcher of 0.05 m and a growth rate of 1.2.

To make sure that the grid pattern used is adequate, a grid convergence test was performed. The velocity magnitude and the pressure were compared at two points, one within the room at 1 m high, 1 m deep and located at 3 m from the room's left wall. The second point was in the surrounding at 6 m high, 1 m deep and located at 5 m from the room's left wall. As the number of elements increased from 2284215 to 3361886 to 5752078 by decreasing the body mesh sizing of the room and windcatcher from 0.05 m to 0.06 m to 0.03 m, the pressure and velocity at the first point changed by approximately 1.5% as shown in table 1. Similar results were observed at both points.

No. of Elements	Mesh Size (m)	Velocity (m/s)	Velocity Change %	Pressure (Pa)	Pressure Change %
2284215	0.05	0.156417	--	2.50713	--
3361886	0.04	0.158785	1.49%	2.50195	-0.21%
5752078	0.03	0.156016	-0.26%	2.54719	1.57%

Table 1. Mesh convergence study at a point 1 m high and located at 3 m from the room's left wall

Before the surrounding dimensions were selected, simulations using a surrounding with larger dimensions of length 65 m, a height of 35 m and a width of 52 m were conducted. The pressure and velocity at a point close to the windcatchers inlet, differed by less than 1%.

The simulation in this study is performed assuming the air properties to be constant, corresponding to air temperature at 288 K and air standard pressure at sea level at 101.3 kPa. The values for the air density and the dynamic viscosity are assumed as follows:

$$\rho = 1.23 \text{ kg/m}^3; \qquad \mu = 1.79 \times 10^{-5} \text{ Pa s};$$

For defining turbulent flow the realizable k - ε model is used. The k – ε model is robust and stable and it is considered the default modeling option for handling turbulent flow in many commercial codes. The flow is turbulent as Reynolds number Re estimated at the chimney`s exit for one condition corresponding for an inlet velocity of 3 m/s is approximately 80000. The turbulence intensity at the flow domain's inlet has been assumed as 5%, and the turbulent viscosity ratio as 10. As the turbulence intensity changed from 5% to 2% and 1% the results of the average velocity only differed by less than 1% which indicates that turbulence intensity imposed at the flow domain's inlet did not have a significant effect.

To simulate the buoyancy driven effect, heat flux is applied at the windcatchers outlet in the part above the roof. A fixed value of 500 W/m^2 is applied as shown in figure 3 on the front surface (A) and on the bottom of the outlet (B). The applied heat flux is estimated to be due to solar heated elements with high heat storage capacity.

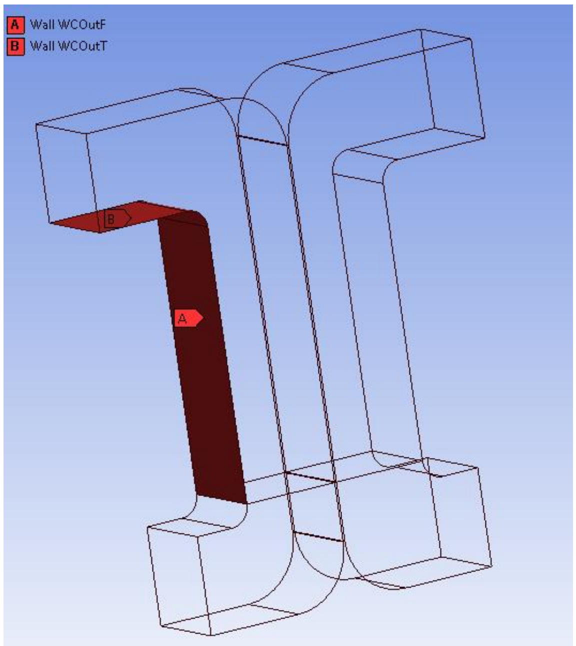

Figure 3. Heat Flux locations at the windcatchers outlet applied on the bottom and front surfaces.

Goriel et al [5] have investigated a two dimensional model of a solar chimney and concluded that the warmer the outer panel of the solar chimney the higher net air mass flow rate. Huynh [9] has found that the ventilation rate increases quickly with increasing heat flux when Q is low, but more gradually as Q becomes high.

Gravity is selected for the body forces in the y direction only, the boussinesq approximation is applied with a reference temperature of 288 K and the volumetric coefficient of thermal expansion α_v = 0.003 1/K [3]. The thermal parameters used are the specific heat C_p and the thermal conductivity K_t as follows:

C_p = 1006 J/(kg K); K_t = 0.0242 W/(m K)

In all the simulations the simple scheme and the second order spatial discretization have been used. The convergence criteria is 0.0001.

Results and discussion

The total flow rate inside the room is investigated in each of the following cases:

1. Winddriven ventilation alone
2. Combined winddriven and buoyancy driven ventilation with 500 W/m^2 heat flux applied to the windcatchers outlet wall.

The average velocity of air entering the windcatcher tunnel is obtained and the corresponding air flow rate is thus calculated in each of the above two cases. The average velocity of air inside the room at a height of 1.2 m from the floor is also obtained.

The results are viewed using Ansys CFD-Post [3] after simulation is run by Ansys Fluent. The maximum number of iterations is set to 50000 and the convergence criteria to 0.0001.

For the winddriven ventilation only, the average velocity magnitude passing through the windcatcher's inlet is 1.9 m/s thus providing a flow rate of 0.475 m^3/s. The problem converged in 7185 iterations. Figures 4 and 5 show the distribution of the air velocity in the windtunnel at 4.1 m high and inside the room at a height of 1.2 m from the floor. The average velocity at 1.2 m high in the room is 0.189 m/s and it is evident that the higher speeds are located close to the walls and the minimum speeds are in the middle of the room where the majority of human occupancy occurs.

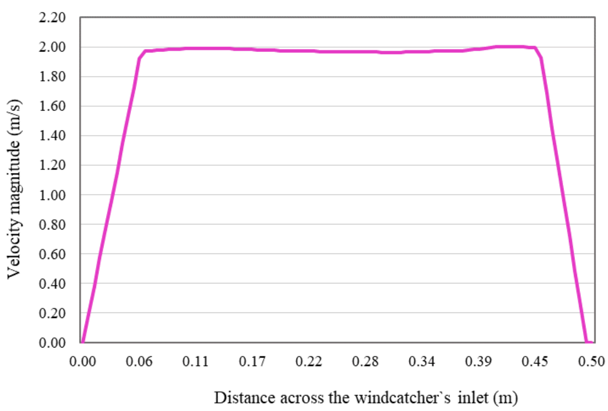

Figure 4. Velcoity magnitude across the windcatchers inlet

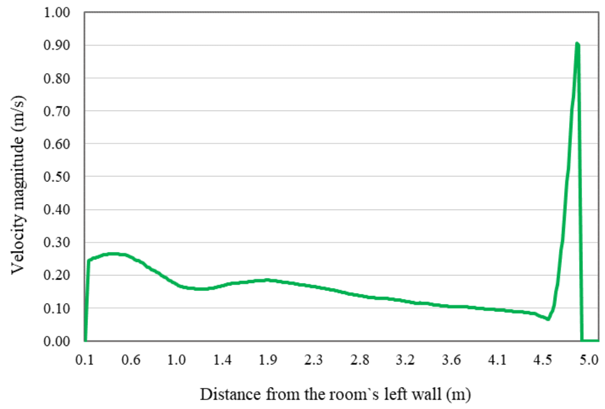

Figure 5. Velocity magnitude across the room at 1.2 m height

For the combined winddriven and buoyancy driven ventilation with heat flux of 500 W/m^2 at the windcatcher outlet, the average velocity magnitude passing through the windcatcher's inlet is 1.96 m/s thus providing a flow rate of 0.49 m^3/s. The problem converged in 8594 iterations. The distribution of the air velocity in the windtunnel and inside the room at a height of 1.2 m from the floor are similar to the winddriven ventilation alone shown in Figures 4 and 5. Figure 6 shows the pattern of the air flow circulating through the three dimensional room providing full ventilation inside the room and especially at 1.2 m height. This pattern is similar for both winddriven alone and combined winddriven and buoyancy driven ventilation. The velocity in the wind tunnels inlet and outlet are much higher than inside the room.

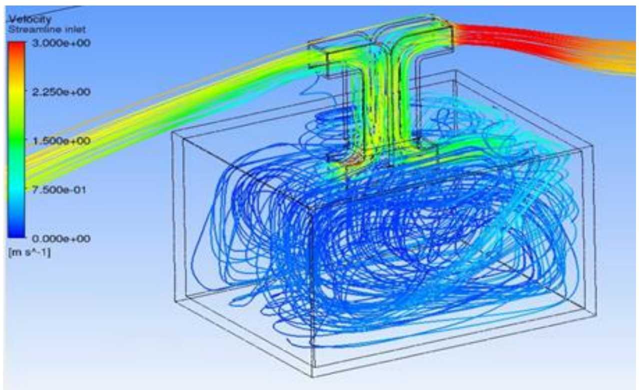

Figure 6. Air flow pattern through the three dimensional room

Table 2 shows the average velocity and total flow in both cases. The combined winddriven and buoyancy driven ventilation has provided 3.16% increase in the total air flow rate, when heat flux of 500 W/m^2 is applied compared to the winddriven ventilation only.

	Winddriven only	Combined winddriven and buoyancy driven Heat Flux 500 W/m2
Average velocity magnitude m/s	1.9	1.96
Flow Rate (m3/s)	0.475	0.49
Increase (%)		3.16%

Table 2. Average velocity magnitude and total flow rate passing through the windcatcher's inlet and the percentage increase of the combined windriven and buoyancy driven ventilation compared to winddriven ventilation alone.

With the addition of the heat flux the air temperature within the windcatcher outlet has increased. Figure 7 shows the variation of the temperatures at a section of windcatcher outlet with a maximum temperature of 380 K at the external front wall.

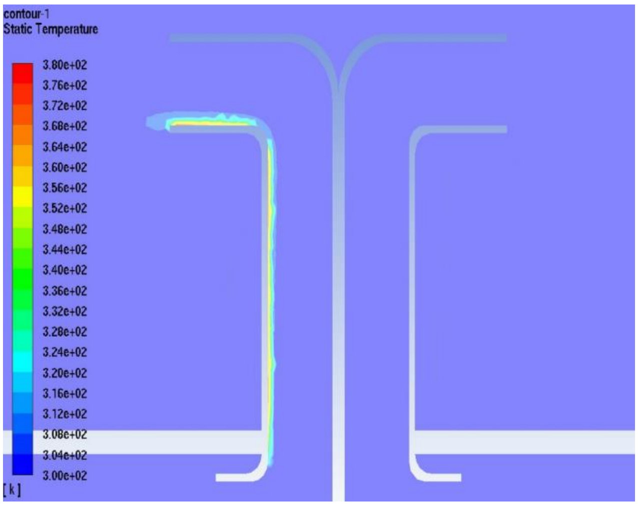

Figure 7. Contours of the static temperature with a maximum of 430 K at the windcatcher's outlet when 500 W/m2 heat flux is applied

Further study related to the effect of applying heat flux at other parts of the windcatcher's outlet such as the sides and the top is to be conducted as well as experimental validation where the heat flux would be induced using solar heated elements.

Conclusions

Computation of average air velocity magnitude through a three dimensional room fitted with a windcatcher was conducted. Cases for winddriven ventilation and combined winddriven and buoyancy driven ventilation have been simulated using Ansys Fluent with a constant 500 W/m^2 heat flux applied at the windcatcher's outlet.

The combined, buoyancy driven and winddriven ventilation, has provided approximately 3.16% increase in the total air flow rate, when heat flux of 500 W/m^2 is applied compared to the winddriven ventilation only.

Three dimensional simulations which reflect real life situation have been conducted and the results showed the pattern of air flow through the room provides full ventilation at 1.2 m height.

Acknowledgments

This research is supported by an Australian Government Research Training Program Scholarship.

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