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Wind Driven Ventilation for Enhanced Indoor Air Quality

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1. Introduction

The last century has seen tremendous progress in technological development that is underpinning the progress of the modern day human civilization. Unfortunately, however, such progress is giving rise to unwanted problems of grave consequences that have the potential to destroy the very environment which sustains life. There is now a real eagerness and greater awareness in the general public to look for alternative natural energy systems and products to help alter the present energy use patterns that have lead to this dilemma.

United Nations' conferences in Rio in 1992 and Johannesburg in 2002 have brought the issue of environment sustainability to the forefront in international circles. Subsequently the organization has defined goals that buildings should seek to achieve in order to obtain green building recognition that include goals such as increase in reliability, increase in indoor air quality, decrease in natural resource use, considerable decrease of energy costs over the lifetime of the building, improving comfort due to improved energy efficiency in building and raise of employment as a result of increased activity in energy improvements in buildings. These benefits will theoretically take care of any type of increase (typically 3-5%) in construction costs and making improvements will have a direct positive impact upon life-cycle costs.

The present chapter is an attempt to advance the cause of sustainable living and improve the quality and comfort of human existence through the greater use of environment friendly wind driven ventilation. Most of the materials presented are based on the author's experimental and numerical computational works carried out at the School of Mechanical Engineering at the University of New South Wales of Australia with a particular focus on the development and production of highly efficient wind driven rotating ventilators for domestic and industrial use.

1.1 Significance of ventilation

In the past, the building codes and policies of most of the developed nations were implemented to ensure the safety and adequate sanitary conditions for occupants and protect the public from hazards such as fire, electrical problems, sewage disposal, etc. It is more recently that emphasis has been placed on energy efficiency and sustainable buildings. Issues have varied over time, but recently the catalyst for such policy changes has come about as a result of rising greenhouse gas emissions from energy consumption, as well as

land use practices such as deforestation. Thus governments around the world are grappling with ideas regarding building policies and the potential benefits to not only the people that use them but the environment in which the buildings exist.

Generally speaking, a movement or circulation of the air within an enclosed space in any ventilation system is essential to ensure that the temperature and humidity be maintained within a range that allows adequate evaporation of perspiration from the skin. There is evidence to show, that the deleterious effects result largely from interference with the heat-regulating mechanism of the body. Lack of air currents and the increase in relative humidity and temperature, especially noticeable in crowded or poorly ventilated places, prevent normal evaporation of perspiration and loss of heat from the surface of the skin. Under requirements to maintain a safe working environment, many dwellings and factories now need adequate fresh air exchange to remove gaseous, process emissions and/or heat buildup. The high priority placed on indoor air quality from health considerations has prompted New York in the USA to pass legislation effective from December, 2008 to require landlords to notify tenants and building occupants of indoor air test results.

Good ventilation is a key element in maintaining a healthy environment for people within the confines of a building. Failure to provide adequate ventilation in a building can result in problems with moisture, unpleasant smell, lack of oxygen, and unacceptable content of poisons gases such as CO which cause medical conditions for tenants. Contaminants such as formaldehyde or radon can also accumulate in poorly ventilated homes, causing health problems. Due to fact that every person's resistance to pollutant varies, it is hard to obtain an accurate quantitative measurement of the impact of ventilation on human beings (Hanssen 1997). However, some method was proposed based on the consideration of the factors such as direct medical costs and lost earnings due to major illness as well as increased employee sickness days and lost productivities while on the job (European Collaborative Action report 2000). For example, Brooks and Davis (1992) calculated that productivity loss in the United States of America attributed directly to indoor air quality (IAQ) is around 14 minutes per day; Pillgram Larsen (1991) estimated loss in Norway is of 1 to 1.5 billion of euro per year which is equivalent of 250 to 350 euro per inhabitant. For Finland, a more detailed estimation was given by Seppanen and Palonen (1998) where the potential economic impact of indoor air pollution was estimated to be tens of billions of dollars per calendar year (see Table 1.1).

Building Type	Maintenance Costs (Billion Finnish Marks)	Energy Costs (Billion Finnish Marks)	Costs of poor indoor climate (Billion Finnish Marks)
Houses	12.7	7.2	7.0 (Mould allergies)
High-rise residential building/office buildings/schools/hospitals and other buildings	37.3	7.0	10.6 (Radon cancers, decreases in efficiency, poor learning, hospital infections)

Table 1.1. Cost due to poor indoor air quality

Ventilation is also an effective means of ameliorating the internal environment (Billington 1982). This is usually achieved in three prime motive forces: mechanical means (fans, pumps, HAVCS), heat (stack effect) and wind pressure. The use of mechanical ventilation system consumes a significant amount of energy in a building. For example, electricity bills for residential buildings in the United States of America is approximately US\$140.8 billion in 2006 (U.S. department of energy 2006), and the energy consumed by heating, ventilating and air conditioning system (HVAC) accounts for 40 to 60 percent of the total energy. For example, the energy cost has risen 30% in the state of New South Wales since 2009 (IPART website 2009). Due to the rising fossil and energy costs, people's awareness have increased and attention is focusing towards the use of an alternative solution. Under such concern, natural ventilation becomes a viable and sustainable method in providing suitable environment and is increasingly considered in many building designs.

2. Brief overview on different modes of ventilation

In general, natural ventilation can be induced by cross ventilation or stack ventilation and they can be either passive or active in nature. Cross ventilation technique use the natural wind force to direct the air movement through a building. When wind impact on a building it produces positive pressure on the windward side and relative negative pressure on the leeward side and these difference in pressures drive the airflow through the building. In order to achieve good cross ventilation effect, openings such as windows, doors and other openings are required at the different facings of the building. The stack ventilation technique utilizes the temperature between inside and outside of a building. When the room temperature is greater than outside, the warm indoor air will rise and exit and cooler, denser air from below can enter.

The natural ventilation can be further enhanced by wind driven ventilation technique. These techniques can be either passive or active in nature however the primary driving force for providing ventilation are primarily caused by wind.

2.1 Passive wind driven ventilation techniques

2.1.1 Window openings/vents

This is probably the simplest form of its kind. Through strategically placement of openings, the potential natural ventilation in a building can be optimized to cut down the need for artificial cooling (Mochida et. al. 2005, Karave et. al. 2005). In conjunction with the window openings, static vents can also be placed at the planned location where window openings are not required. There are various of types of vents that are commercially available as shown in Fig. 2.1. Due to the relative cost effective and sustainable benefits, a large number of experimental and numerical investigations have been conducted to study the benefit of this technique (Greeno 1997, Heiselberg et al., 2001, Olsen & Chen 2003, Faye et. al. 2005, Asfour & Gadi 2007).

The low-tech nature and manual operability of window openings/static vents technique are acceptable in domestic dwellings. However, a major limitation of naturally ventilated technique in general is the unpredictability of the driving force. Wind pattern and availability for different region varies according to seasons and more over for large buildings some physical limitations exists. Hence its application on its own cannot be considered to be a primary ventilation method.



Fig. 2.1. Common types of roof/attic venting

2.1.2 Atria and courtyards

Courtyard is an effective way of providing natural ventilation and can be found in many architectural designs across the globe for thousands of years. A courtyard provides a relatively enclosed space to channel and direct airflow into some openings and results in convective natural ventilation within and around the building. Some studies have been conducted to study the effect of atria and courtyards on energy performance (Rajapaksha et. al. 2003, Aldawoud & Clark 2008). These studies generally confirmed that the wind driven ventilation can be enhanced by using atria and courtyards and are more effective for low rise building. However, the passive nature of this technique indicates that its effectiveness depend largely on the availability of its driving force.

2.1.3 Wind towers

Wind towers have been used in conjunction with courtyard and atria for centuries in many middle-eastern architectures. They work on the principle of both wind driven and stack effect ventilation. Wind enters via the windward side that has a positive pressure coefficient and was redirected through the tower into the building. These winds disperse through the building and exit through relative negative pressure areas. The exit paths can be multiple, either through the tower or openings that was carefully designed. Multiple wind towers have also been used to maximize the effect as can be seen from Fig. 2.2. Wind towers can also benefit for modern buildings and have been the subject of several studies (Bansal et. al. 1994, Bahadori 1994, Kolokotroni et. al. 2002, Badran 2003) through the following considerations: (1) Tower with evaporated cooling columns can increase the cooling potential of incoming air. (2) Natural ventilation principle can dictate the extract height and cross section of the towers to accommodate for the targeted number of occupants. (3) Solar collectors can be used to enhance the stack effect ventilations in times or areas of little wind. A modern modification of wind towers is a device known as the wind catcher. These devices capture the wind at roof level and direct it down to the building. The working principle and their application of these devices are shown in Fig. 2.3.

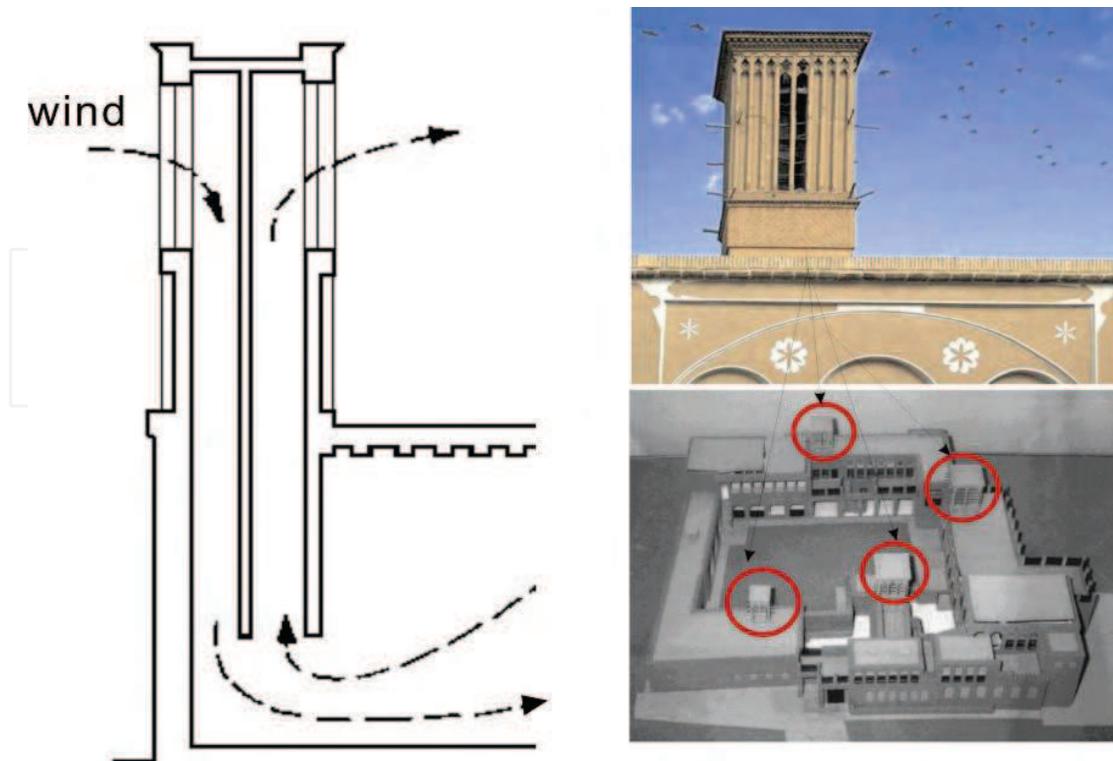


Fig. 2.2. Wind tower design in Middle Eastern building

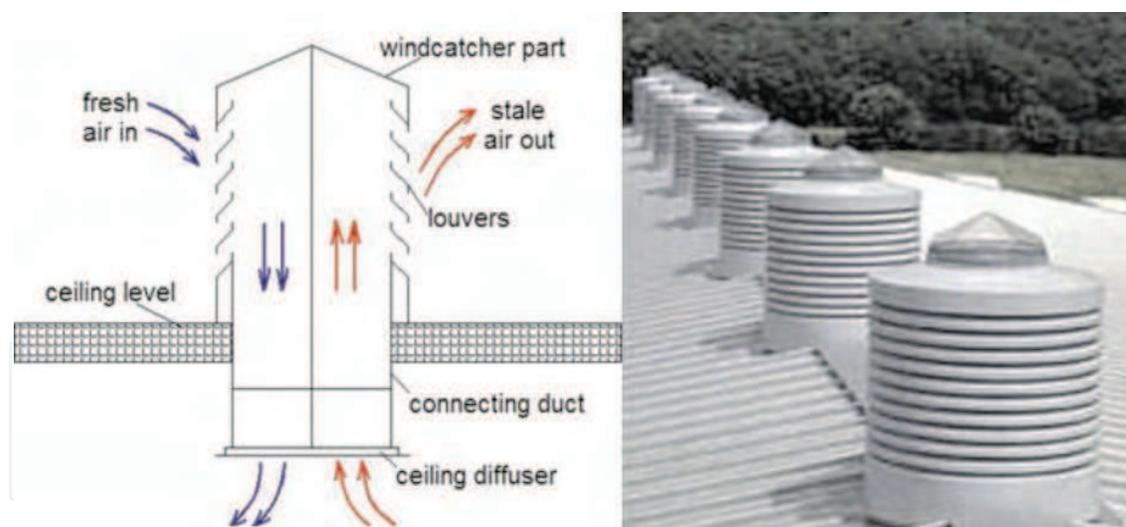


Fig. 2.3. Operation principle and application of wind catcher system

Since the introduction of this technique in 1990 there have been a number of studies associated with its performance both experimentally and numerically (Kolokotroni 2002, Li & Mak 2005, Elmualim 2006). These studies points put that the performance of a wind catcher system is influenced by a number of factors: the outdoor wind; temperature difference between indoor and outdoor environment and location of other openings and windows.

The studies surrounded the wind tower technique not only indicates that the principle works, more importantly they highlighted the needs of redundancy via another source when using wind driven ventilation technique such as active system.

One major concern of the passive natural ventilation technique is that the driving forces are variable and the minimum required ventilation rate is hard to be ensured in still air conditions (no wind or stack effects). Hence several alternative engineering solutions are formulated to maximize and control the effect of natural ventilation. For example, the roof mounted rotating turbine ventilators can be used or in conjunction with the natural ventilation techniques. The rooftop ventilators are commonly found in most countries of the world where they are mounted on the roof and rotate with the slightest breeze and generate a powerful updraft to effectively pump the air out of the room.

2.2 Active wind driven ventilation techniques

2.2.1 Turbine ventilators

Turbine ventilators are available commercially with various blade designs, sizes and materials. They usually rotate in its vertical axis to create updraft inside the turbine which extracts air and in the absence of wind, they can still facilitate ventilator using the stack effects. These types of installations are usually on the top of the roof where higher wind speeds are available for most buildings and these are shown in Fig. 2.4.

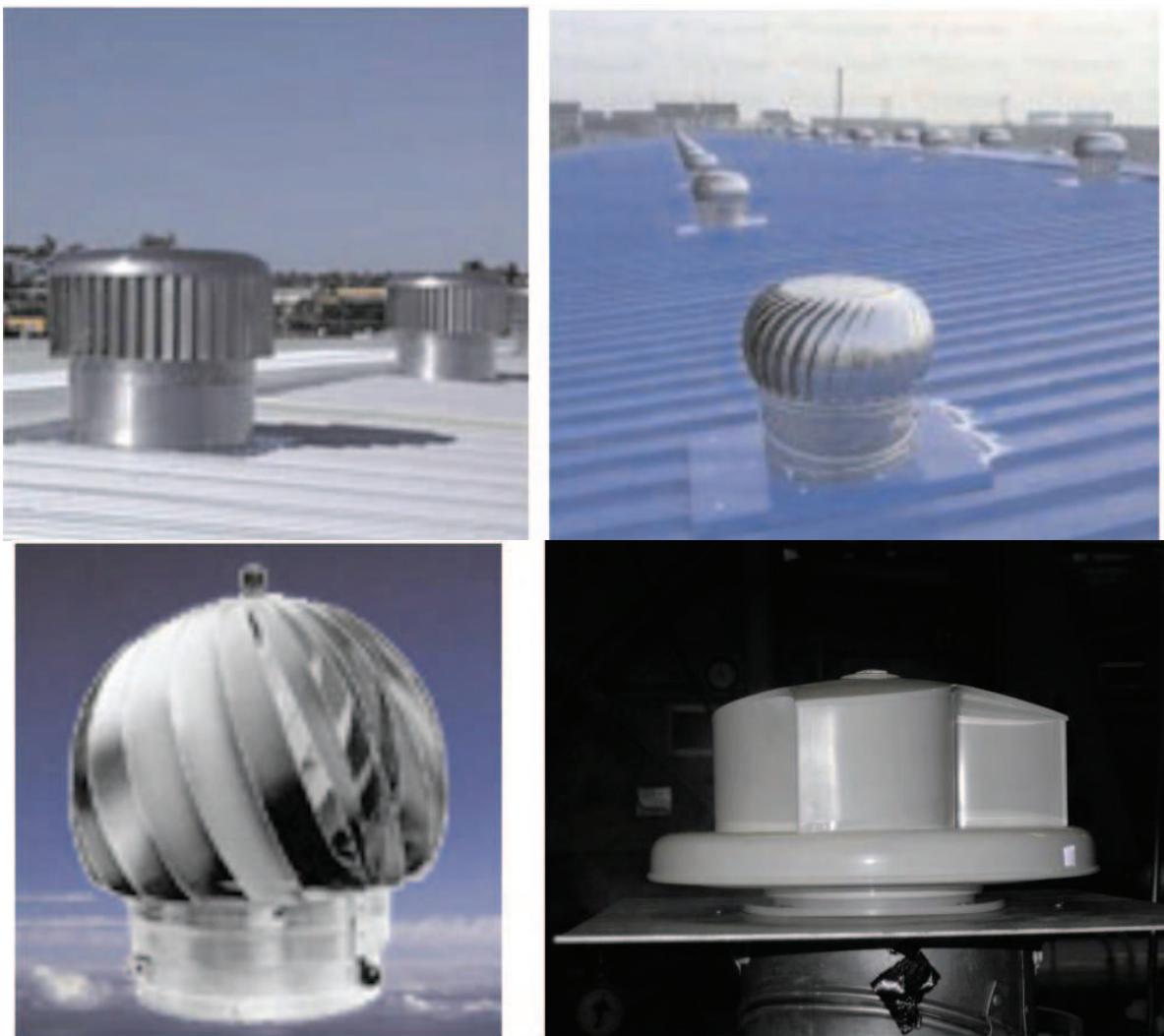


Fig. 2.4. Various blade design of turbine ventilators

The concept of a turbine ventilator was originally patented in 1929 by Meadows and its commercial production was started by Edmonds of Australia since 1934. Although these types of devices have been on the market for many decades, there were only limited quality aerodynamic researches available in open literature.

The first series of investigation into the aerodynamics of a turbine ventilator was reported by Lai (2003). His flow visualization study on three different sized turbine ventilators of 6, 14 and 20 inches respectively showed the airflow pattern around a turbine ventilator. Another experimental study by Flynn and Ahmed (2005) also confirmed the flow pattern. These studies suggested that the larger diameter ventilators induce greater mass flow extraction rates.



Fig. 2.5. Installation of multiple stacked ventilators at UNSW

The performance studies of a turbine ventilator are usually associated with the air extraction rates (Revel 1998, Khan et. al. 2008). These studies suggested that the performances of such devices are significantly influenced by the blade design as well as the construction material and the sizes significantly affect producing higher exhaust mass flow rate. On the other hand, the aerodynamics forces acting on a turbine ventilator have also been studied by Rashid and Ahmed (2003). It was concluded that the operation of a ventilator without the effect of inclined rooftop is more efficient at lower wind speeds. At higher wind speeds larger flow separation was induced on the blades and this reinforced the need of greater attention to optimize blade designs so that they are capable of operating over a wide range of wind speeds.

2.2.2 Hybrid ventilators

As the performance of the traditional turbine ventilators largely depend on the local wind conditions and the ventilation rates are cannot be guaranteed, hence various of forms of hybrid system are purposed to boost its performance to comply with the increasing building

regulation. In this section only three examples of ventilation systems that rely purely on wind power or renewable power source are discussed.

The first such ventilator system considered has been proposed by Lai (2006). This ventilator combines the traditional turbine ventilator with a small DC fan in the base duct which is powered by solar cell as presented in Fig. 2.6. This system was found to be effective in enhancing the ventilation rate at low wind speeds.

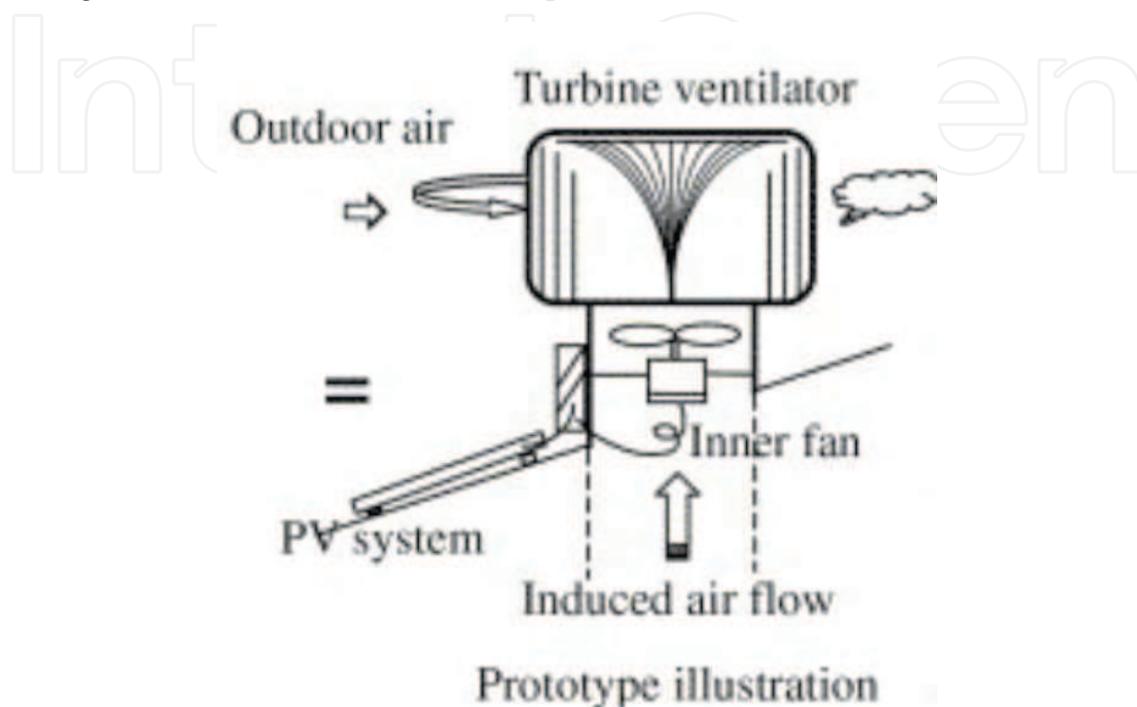


Fig. 2.6. Prototype turbine Ventilator (Lai, 2006)

The second ventilator system considered uses a different approach. It can be easily demonstrated that any obstruction in the throat of a wind ventilator can produce significant noise and reduce vent performance, and this performance reduction can be as high as 40% (West 2001, Khan et. al. 2008) indicates than under normal wind load. The UNSW research team under an Australian Research Council Grant in active collaboration with CSR Edmonds, Pty Ltd, therefore, proposed a model (Ahmed, 2010), the EcoPower, which has no motor and fan blade in the throat of the vent. The model utilises an electronic commutating (EC) motor installed in the head of the ventilator to enable motorised boost during periods of low wind speed or special ventilation needs. The motor can also be programmed and activated by digital measures, such as temperature, humidity gas concentration level etc or by manually switch. The research behind this device also indicates a significant improvement of ventilation rate at low wind speeds. The EcoPower is now commercially produced and marketed worldwide by CSR Edmonds, Pty Ltd.

The third approach mentioned here is the hybrid system proposed by Arup. This device incorporates a vertical axis wind turbine that produces renewable energy to drive the fan which is located directly underneath the turbine to produce the desired ventilation. A photograph of this device is presented in Fig. 2.8. This first full scale model was constructed and installed at the Harrare International School in Zimbabwe. It was found that the room

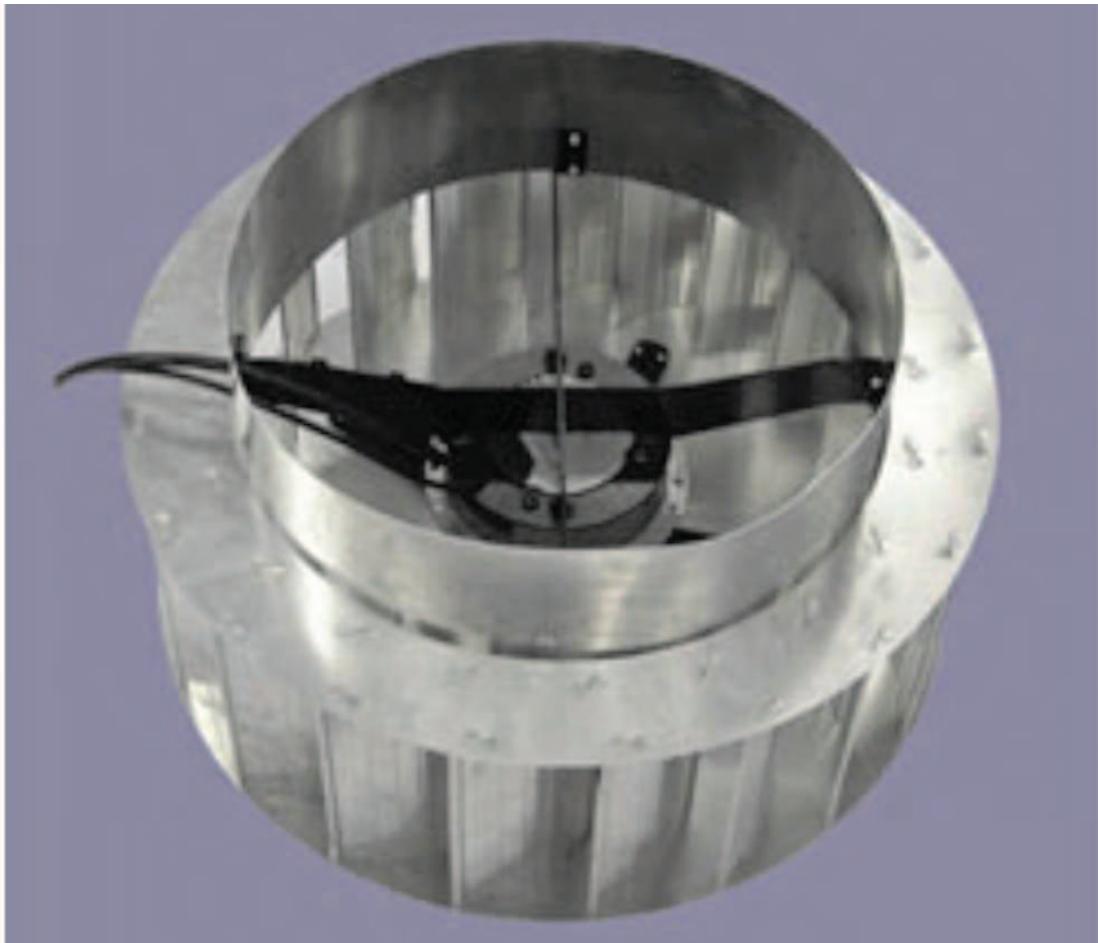


Fig. 2.7. EcoPower Ventilator (CSR Edmonds, Pty Ltd)



Fig. 2.8. Vertical axis Wind Extractor (Arup, Zimbabwe)

temperature in the classroom is significantly cooler (up to 80 C) during the day than without the system installed. However there is very little academic literature on the flow rates and performance associated with this device.

3. Towards enhanced wind driven ventilation technique

In this section some recent studies on means to enhance the performance of wind driven ventilator by the authors at University of New South Wales have been summarised.

3.1 Physical experimentation

The physical experimentation were conducted in a 76mm diameter open return, 0.2% turbulence intensity open test section wind tunnel of the Aerodynamics Laboratory of the University of New South Wales. The experimental setup is shown in Fig. 3.1.

A five-hole pressure probe was used in this investigation. Recent advances in using multi hole pressure probe techniques (Pisasale & Ahmed, 2002-2004), makes it possible to obtain the velocity vector and static pressure field in a highly three dimensional flow field. A step by step procedure of how to obtain the velocity vector and pressure terms can be obtained is detailed in reference 21. A Furness FCO510 micromanometer and a box consisting of seven channels of Honeywell transducers were used to measure the pressures on the five-hole pressure probe. The manometer and the pressure transducer provided measurement in the range that varied from -2000 Pascal (Pa) to 2000 Pa with an accuracy of $\pm 0.1\text{Pa}$.

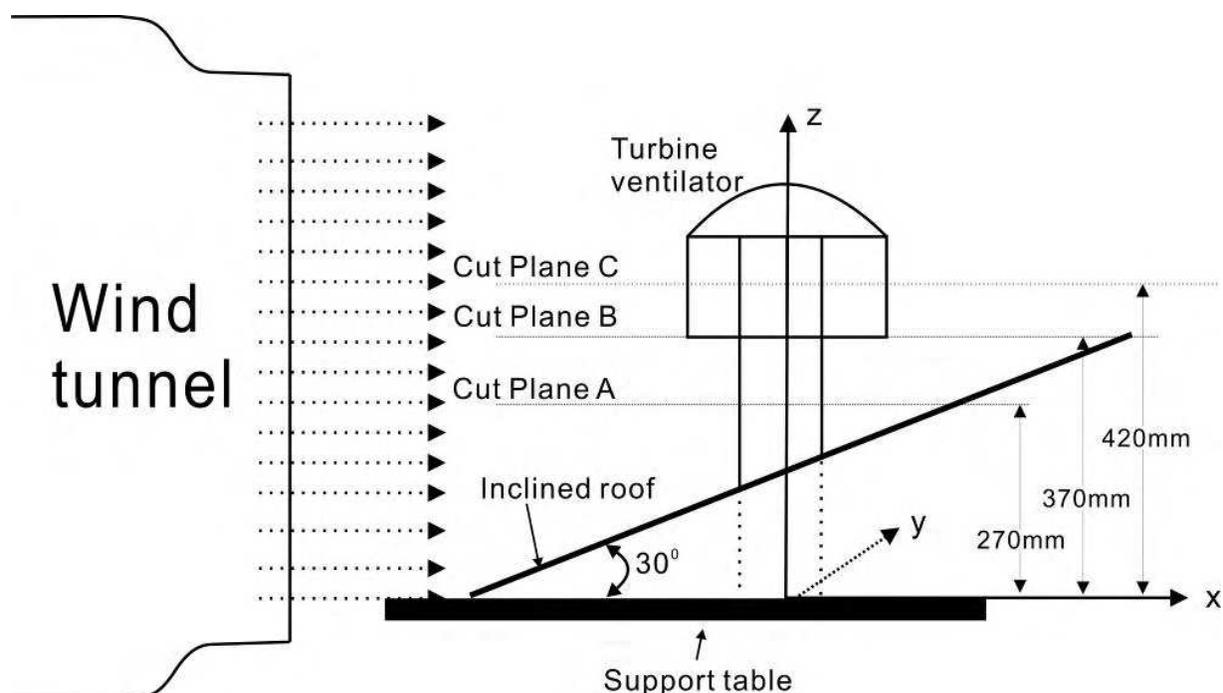


Fig. 3.1. Schematic of experimental setup

Apart from the forces obtained directly from the force balance, pressure and skin friction distribution were used to determine a flow features of the system. Since these parameters contribute largely to the aerodynamic forces acting on a body. In the present investigation, the effects of the inclination angles on the performance of a rotating ventilator were

investigated in a wind tunnel. The Reynolds number, $Re_x (= xU_\infty/\nu)$, used was based on, x , the distance measured from the leading edge of the plate, U_∞ , the free stream velocity and ν , the kinematic viscosity of the fluid. Re_x values ranged between 7×10^4 and 1×10^6 .

3.1.1 Effect of inclination angle on forces on a ventilator

The force components in the x , y and z directions as well as the total force acting on the rotating ventilator at different inclination angles were examined against free stream velocities and presented in Figures 3.2a to 3.2d.

From these Figures, the force acting on the turbine ventilator is found to increase with free stream velocity. The increasing trend is more pronounced in the x direction signifying that the inclination angle has greater effect on F_x which largely contributes to the drag than on the side and normal components of the force that contribute to both lift and drag (Rashid & Ahmed, 2003).

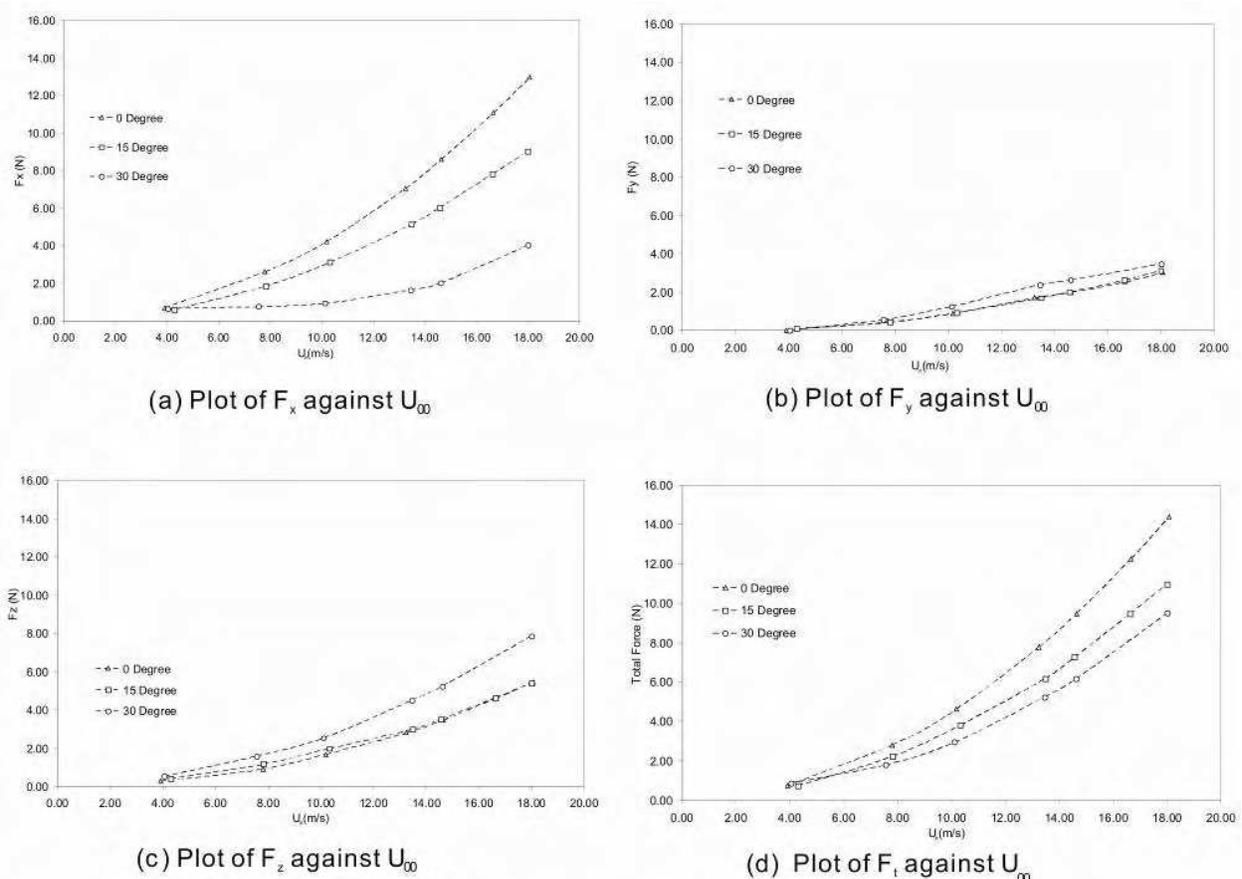


Fig. 3.2. Force acting on the turbine ventilator at various inclination angles.

Some additional features may be elucidated if the total and its component forces (F_t , F_x , F_y , F_z) are examined in non dimensional forms or force coefficients (C_t , C_x , C_y , C_z) against Reynolds number of the flow (Re_d) based on the rotor diameter. The total force and its components were normalised by $0.5\rho U_\infty^2 A$, where ρ is the density of air, U_∞ is the free stream velocity and A is the total wetted area of the ventilator. The wetted area was calculated based on the total area exposed to the flow (see Fig. 3.1). The results are shown in Figures 3.3a to 3.3d.

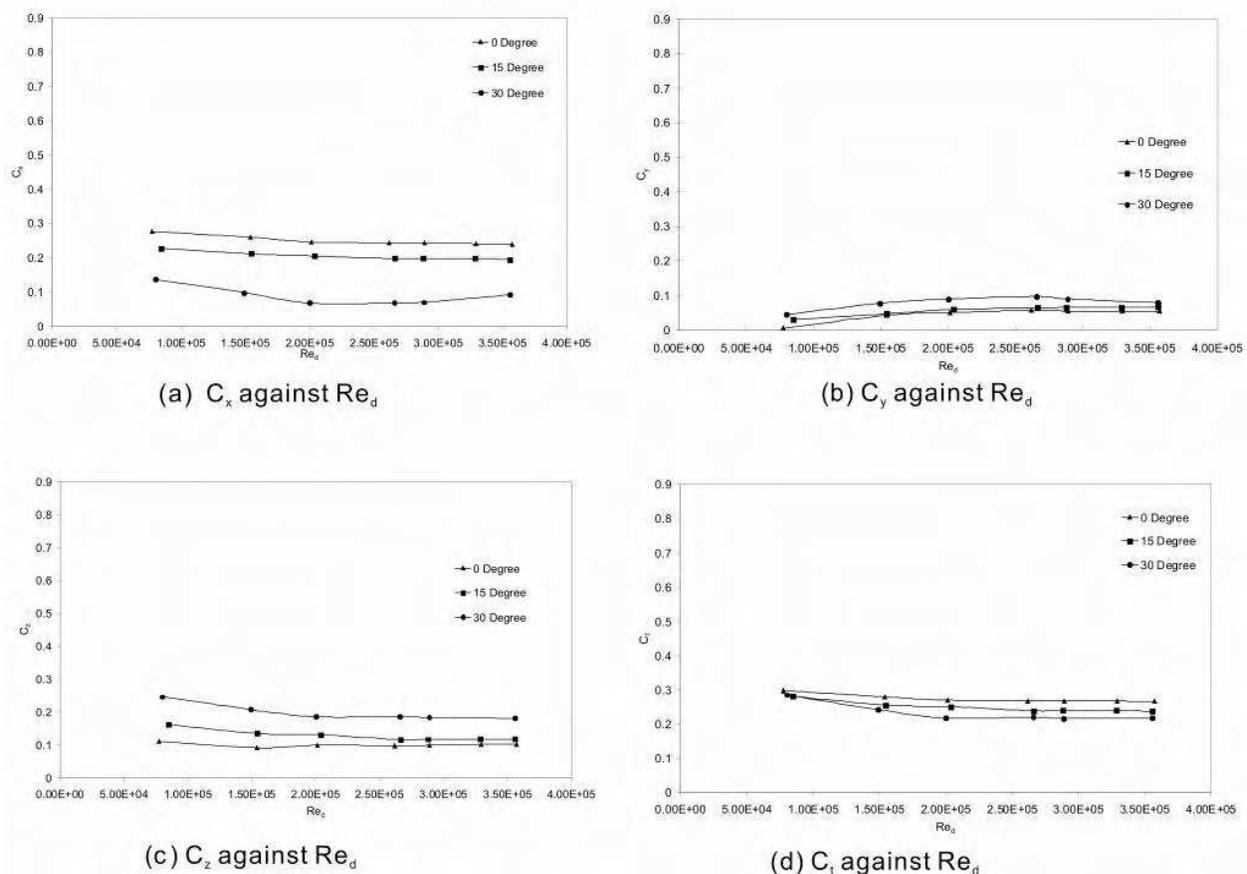


Fig. 3.3. Coefficient of force at various inclination angles.

It is evident that the C_x value decreased with the increase in inclination angle while the C_z value showed the opposite trend. The inclination angle, however, showed little or minimum effect on the C_y values. Consequently, the total force coefficient, C_t , acting on the ventilator reduced with increases in inclination angle and converged towards a constant value beyond Reynolds number of 2×10^5 . This is significant as it implies that the force acting on the ventilator is independent of the Reynolds number beyond a certain rotational speed and may be highly relevant during the operation of a turbine ventilator at lower wind speed. A hybrid system that incorporates other power source such as solar power may provide additional means to efficiently overcome the inertia and friction forces acting on the body to initiate adequate rotation at low wind speed.

3.1.2 Effect of inclination angle on rotational speed of a ventilator

The overall effect of the roof inclinational angle on the operation of a turbine ventilator was further examined against its rotational speed. The results are shown in Fig. 3.4. The results indicate that the rotation speed of the turbine ventilator showed a linear relationship with the free stream velocity (Flynn & Ahmed, 2005; Rashid & Ahmed, 2003; and Khan et al., 2008). Additionally, it also indicates that the high inclination angle lowers the rotational speed of the ventilator that is more noticeable at higher free stream velocity suggesting that the inclination angle has minimal impact on the total mass flow extracted at lower wind speeds. This is also a significant observation since the operation of these ventilators are designed for low wind speeds and as such will not suffer greatly from adverse effect of the high inclination angle.

The Australian regulation stipulates that for the safety of operation, the turbine ventilator must be able to withstand wind loads from speeds of 200km/hr without suffering deformation. As such loads are directly proportional to ventilator rotation, at high wind speed safety in operation become more of a priority than mass extraction rate. Thus, the lowering of rotation due to increasing inclination angle of roof may thus be usefully exploited to reduce wind loads and hence extend the safety margin.

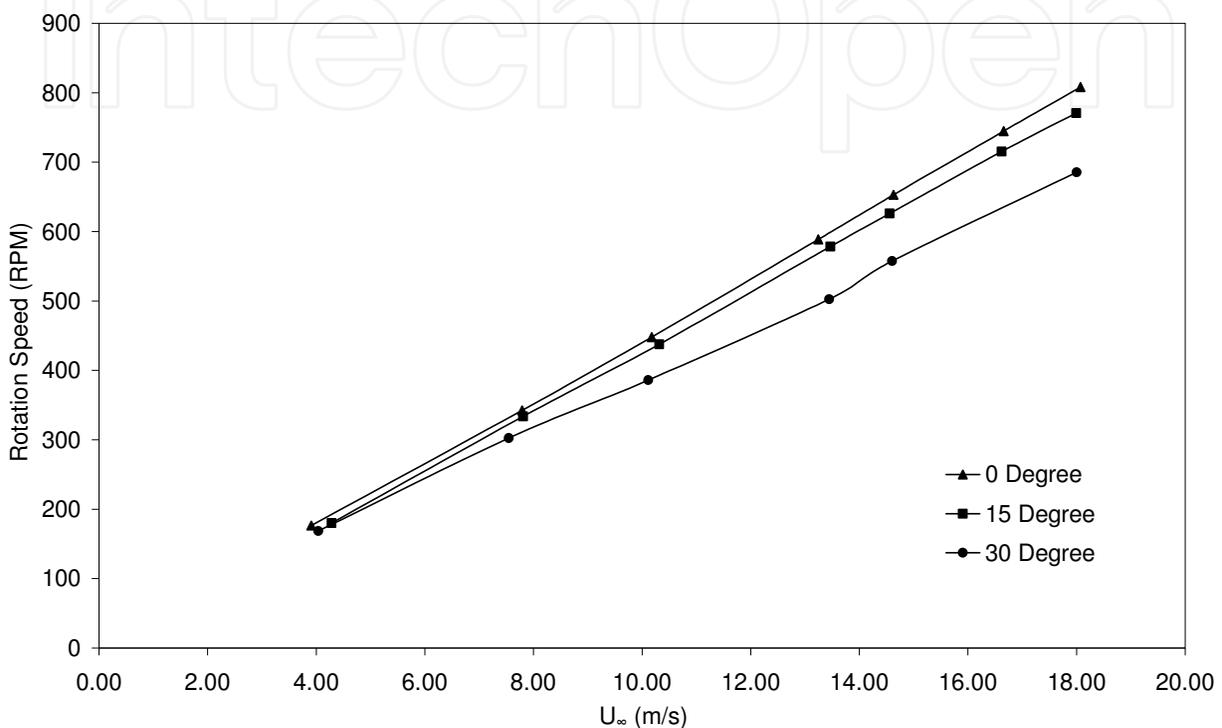


Fig. 3.4. Rotation speed of the turbine ventilator at various inclination angles.

3.1.3 Normalised static pressure distribution on the roof

The results of static pressure distribution in non-dimensional form, C_p , under various inclination angles on the inclined roof without the turbine ventilator are presented in Figures 3.5a to 3.5c, where $C_p = (p_s - p_\infty) / (0.5\rho_\infty U_\infty^2)$, p_s is the static pressure measured at each static ports on the surface and p_∞ is the static pressure of free stream flow. The results obtained when the turbine ventilator present are shown in Fig. 3.5d to 3.5f. An advantage of such representation is that the C_p values can range from +1 to any negative value. A positive C_p values generally suggests that the flow is slowing down until reaching the limiting value of +1 or the stagnation or zero velocity condition, while any negative C_p value means that the flow is experiencing acceleration, with higher negative C_p signifying higher acceleration.

The inclined roof at its leading edge imposed pressure gradient to the oncoming flow and forced it to slow down producing a C_p distribution that had values moving towards +1 with approximately a symmetrical distribution in the spanwise direction. The C_p values at the leading edge for 0, 15 and 30 degrees of inclination were found to be 0.05, 0.19 and 0.42 respectively that decreased towards zero value in the streamwise direction.

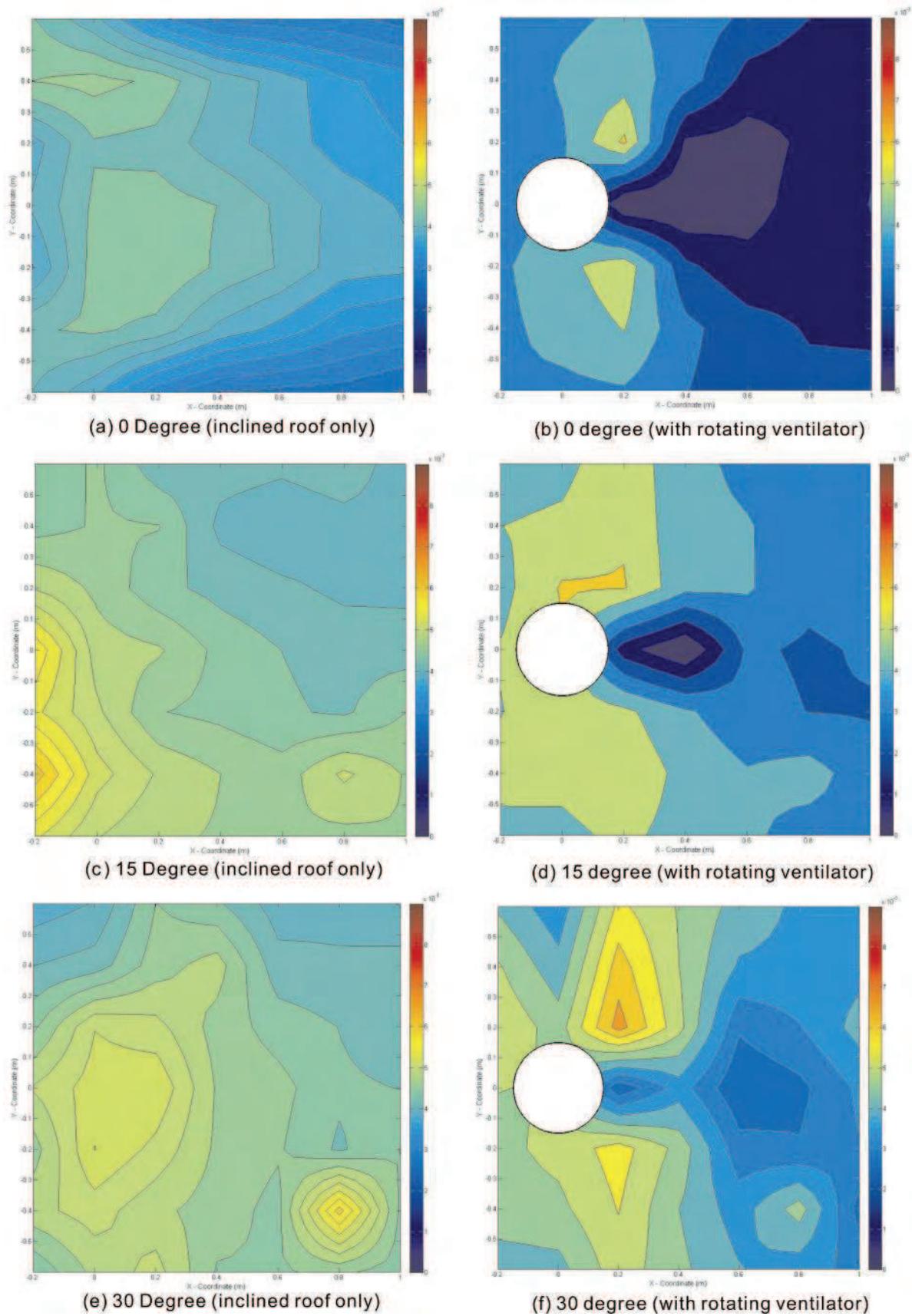


Fig. 3.5. Static Pressure distribution on the roof, where $U_{\infty} = 10 \text{ m/s}$

On the inclined plane, the addition of the ventilator imposed further pressure gradient that slowed the incoming flow even further. From Figures 3.5d to 3.5f, the C_p values at the leading edge increased to more positive C_p values due to the presence of the ventilator while maintaining symmetrical distribution for the upstream flow as expected. Similar trends were also observed for flows at 5m/s suggesting that the Reynolds number appeared to have negligible effect on the overall pressure distribution.

3.1.4 Skin friction distribution on the roof

Recent advances (Pisasale & Ahmed, 2002-2004, Lien & Ahmed, 2003) in using multi hole pressure probe have greatly aided in the quest of measuring the velocity and surface skin friction distribution in a complex flow field. Following the procedure outlined in Lien & Ahmed (2003), a five hole pressure probe was used to measure the skin friction distribution at each measuring station.

The skin friction distributions on the roof at different inclination angles 'without the ventilator' are shown in Figures 3.6a to 3.6c and 'with the ventilator' present are shown in Fig. 3.6d to 3.6f.

From tests conducted at the two wind tunnel speeds of 5m/s and 10m/s and at the three different inclination angles of 0, 15, and 30 degrees, the skin friction distributions were found to become progressively lower downstream of the ventilator. This reduction in skin friction values appears to be a consequence of reduced free stream velocity due to the momentum deficit occurring behind a bluff body. Since skin friction varies with square of the free stream velocity (Baskaran & Bradshaw, 1993), it is not surprising that the trend is more apparent at higher wind speeds.

On the other hand, with the ventilator placed on the roof, the skin friction distribution on the roof increased significantly with increases in the roof inclination angle. Since the skin friction signifies losses in the flow, it is expected that the increase of this quantity appears to emanates from the overall reduction of the forces acting on the ventilator that produces lower rotational speed.

3.2 CFD modelling

After gaining insights of flow physics around the ventilator and on the inclined roof, Computational Fluid Dynamic software is also utilised to extend the performance study of rooftop ventilator under the effect of inclined roof.

The turbine ventilator used in this investigation is a Hurricane H100 produced by CSR Edmonds Australia Ltd. It consists of a rotating portion (Rotor) with 8 curved blades and a stationary portion in the form of a cylindrical base. The dimensions of the various components of this ventilator are shown in Fig. 3.7.

This numerical simulation of flow characteristics of the turbine ventilator used in wind tunnel tests were then performed using FLUENT. The equations for the conservation of mass, momentum and turbulence scales are solved in FLUENT using the control volume method in a three-dimensional body-coordinate system.

The geometry is created in Computer Aided Three-dimensional Interactive Application (CATIA) and exported to GAMBIT (the pre-processor) for meshing. For modelling of the rotating motion of the turbine ventilator, the multiple reference frame (MRF) meshing in FLUENT was adopted as they have been successfully applied in flows with rotating objects (Luo et al., 1994). This meshing allows multiple moving reference frames to be solved in a

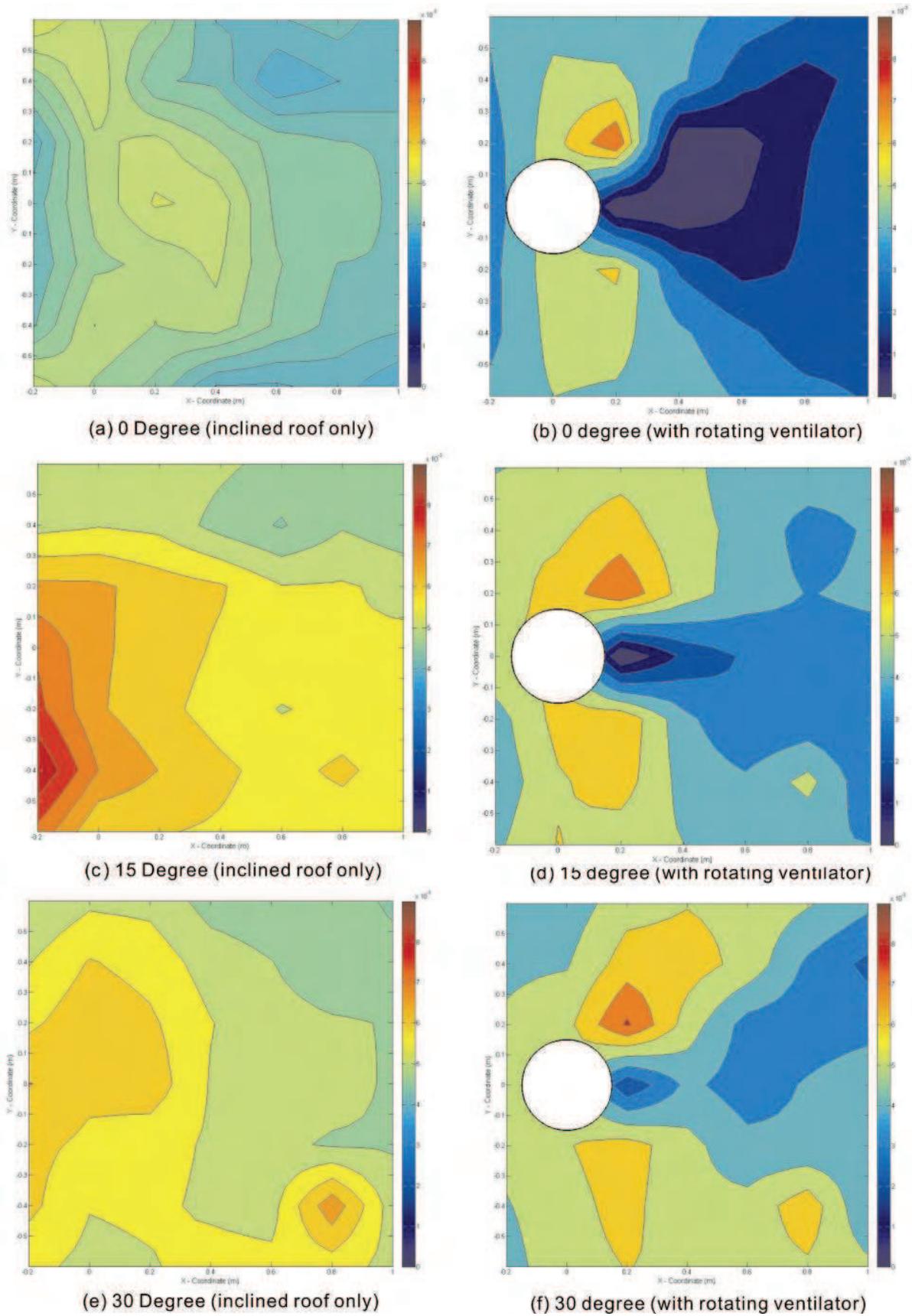


Fig. 3.6. Skin friction distribution on the roof, where $U_{\infty} = 10 \text{ m/s}$

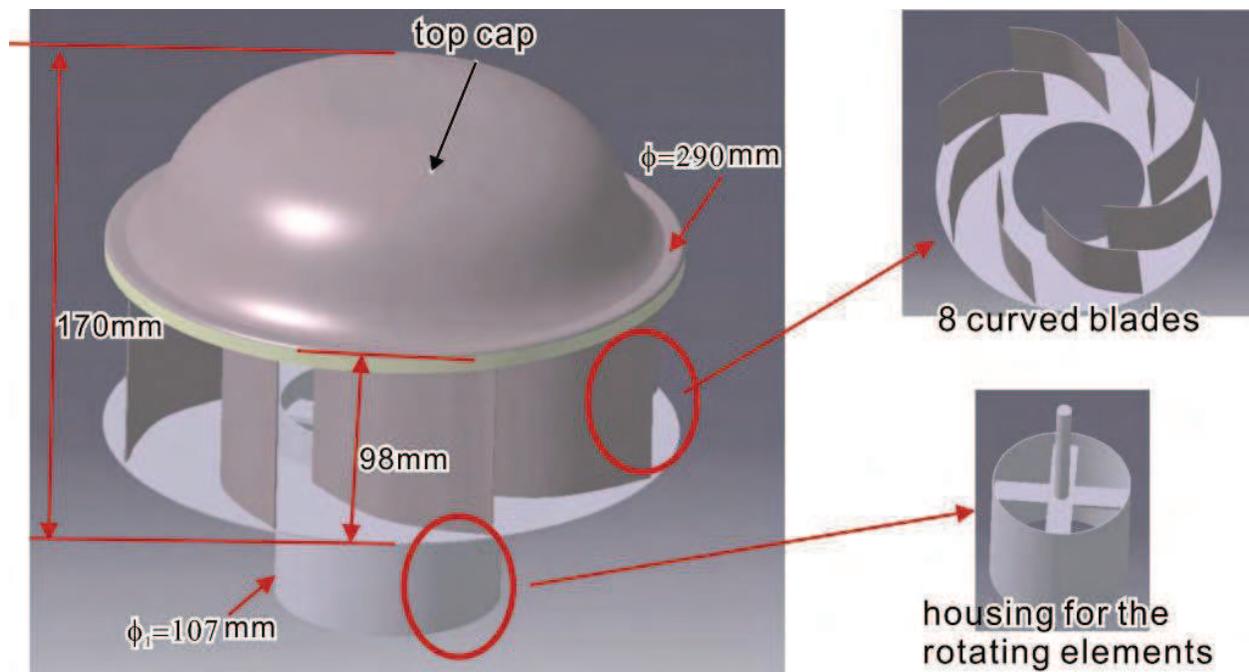


Fig. 3.7. Modelling of turbine ventilator

single domain. MRF is normally used for steady state condition and the individual cell zone can move at different rotational speeds and provide solution using the moving reference frame equations. Grid sensitivity test was performed by examining the effect of different number of mesh grids and the total number of grids was determined when grid independence was established. The final total number of grids used in the present simulation was determined to be approximately 1,200,000. The maximum and minimum grid volumes were approximately $1.8 \times 10^{-4} \text{ m}^3$ and $2.4 \times 10^{-9} \text{ m}^3$ respectively. Mesh quality was checked in GAMBIT to ensure the skewness of the three dimensional grids was less than 0.8.

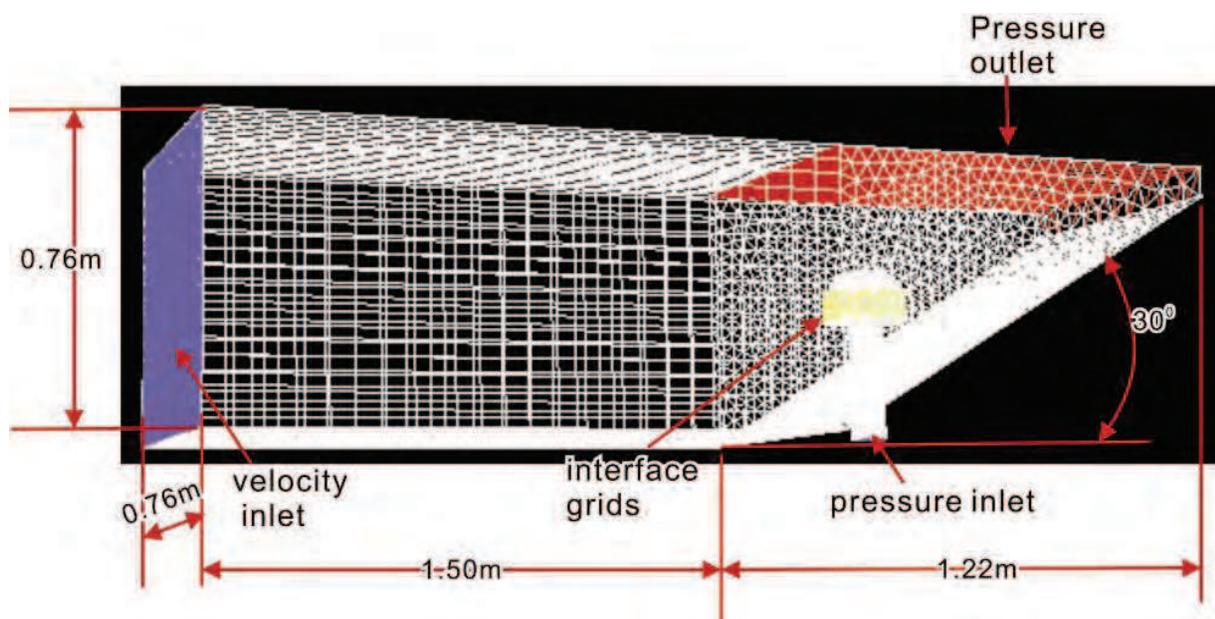


Fig. 3.8. Modelling of domain and dimension

3.2.1 Performance investigation of rooftop turbine ventilator

The major function of a rooftop turbine ventilator is to create suction and move air out from an enclosed building. The performance of a wind driven ventilator is generally gauged against its exhaust mass flow rate. However, before exhaust flow rate was determined, an attempt was made to explore the nature of the flow associated with the rotating ventilator particularly those inside the rotor.

CFD results can provide clear image of the external and internal flow on the entire ventilator in terms of the three dimensional path lines. This provided a qualitative description of the general flow pattern. This is shown in Fig. 3.9. Two distinct streams of the flow can be observed. The left hand-side flow follows the direction of the turbine rotation while the flow direction of the right-hand side flow is contrary to the turbine rotation. The right hand side flow becomes the deflected flow field that acts against the rotation of the turbine. This results in the formation of secondary circulation between the separated flow and the blades on the right-hand side flow.

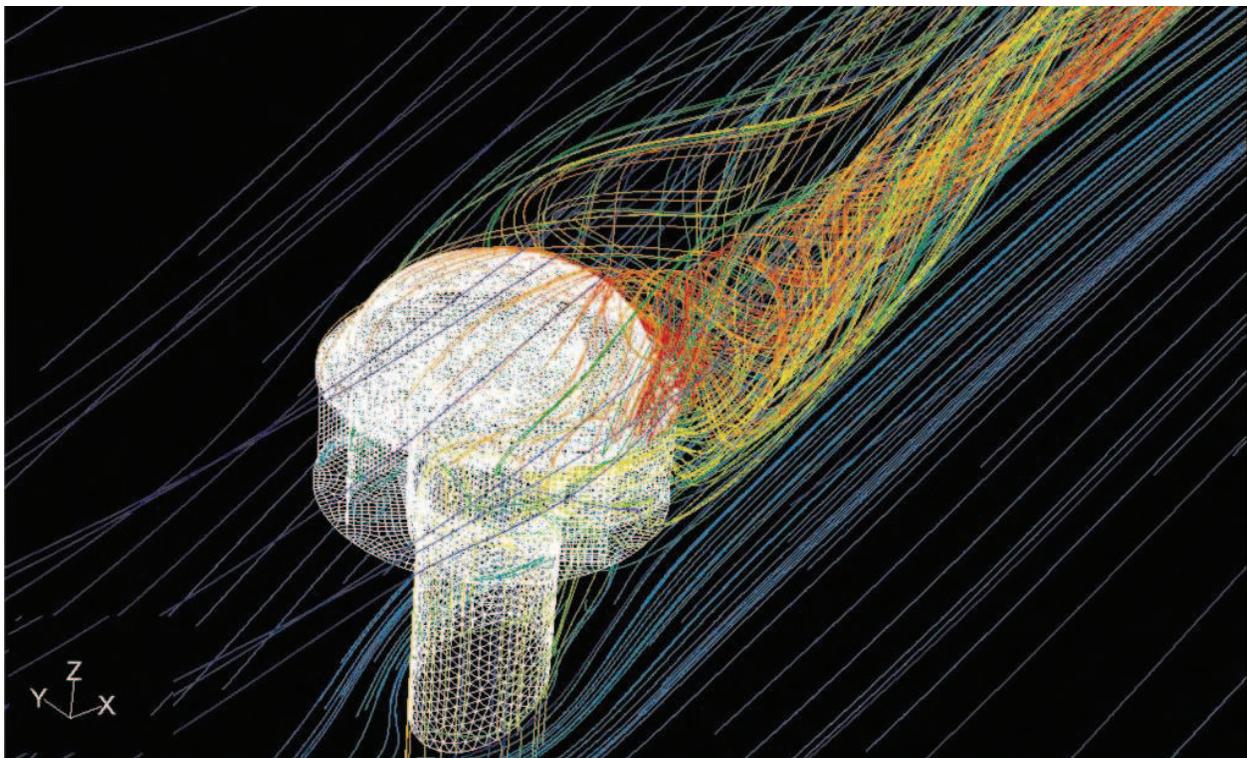
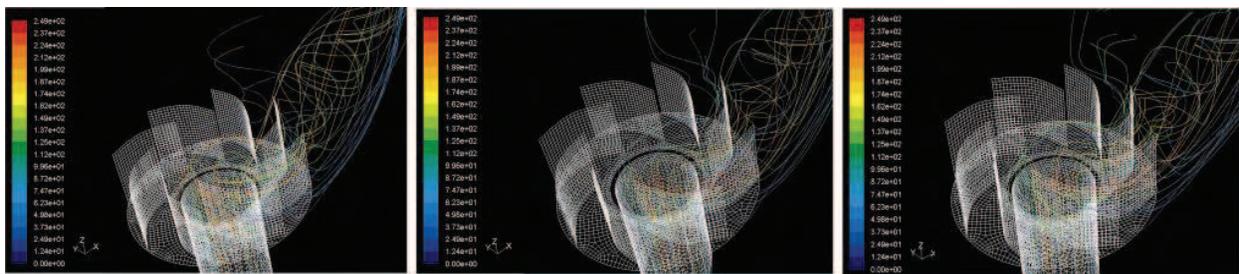


Fig. 3.9. Three dimensional path line of the flow associated with the rotating ventilator at 10m/s.

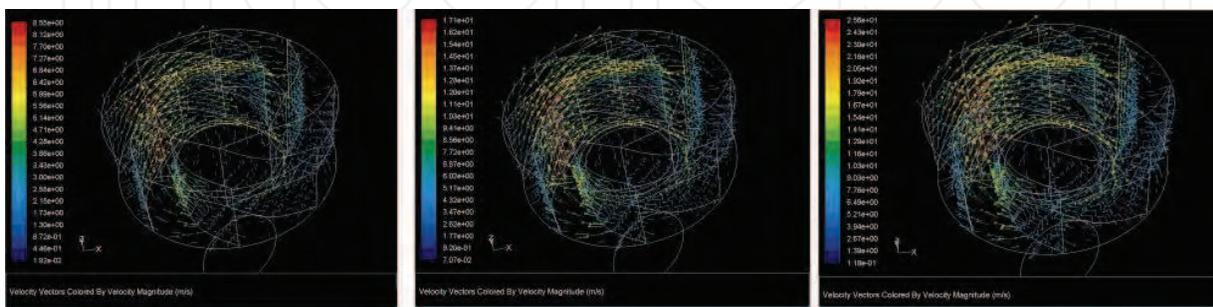
The CFD software can further observe the features of the behaviour of the flow as they are extracted and exhausted by the ventilator as shown in Fig. 3.10. The path lines of the flow at different wind speeds within the rotor and downstream in the wake are shown. The rotor cap is removed from this Fig. for greater clarity. It is clear that at various wind speeds tested, the rotation of the turbine creates updraft.

The flow interactions within the rotor can be shown using vector plots in three dimensions and the results are shown in Fig. 3.11a to 3.11c. The path line in the duct (base) and the rotor also indicates that the flow swirls upwards and mixes with the secondary circulation of the wake region downstream of the ventilator.



(a) Free Stream Velocity = 5m/s (b) Free Stream Velocity = 10m/s (c) Free Stream Velocity = 15m/s

Fig. 3.10. Three dimensional path lines of flow within and downstream of the rotor.



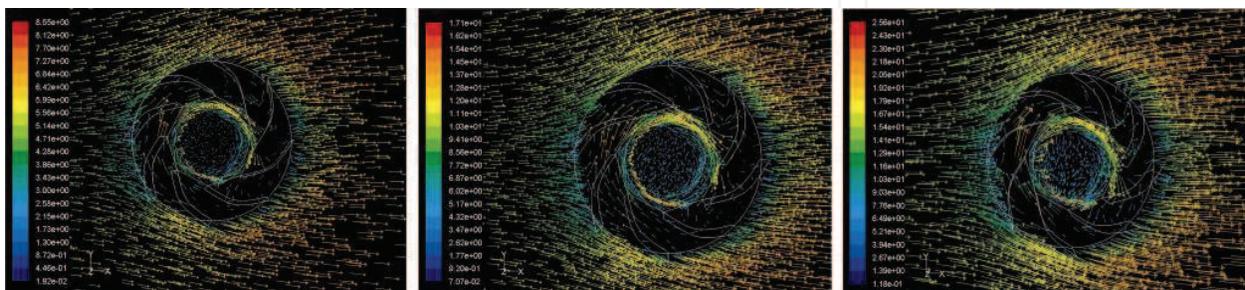
(a) Free Stream Velocity = 5m/s (b) Free Stream Velocity = 10m/s (c) Free Stream Velocity = 15m/s

Fig. 3.11. 3D velocity vector inside the ventilator

It is evident that as the ventilator rotates in the clockwise direction, the air flow extracted through the base swirls up and mixes with the oncoming wind entering the ventilator from the left. The resulting mixed air exhausts from the right half of the ventilator. These Figures also show that with increasing wind speed there is a corresponding increase in swirl flow within the rotor suggesting subsequent increase in exhaust mass flow rate.

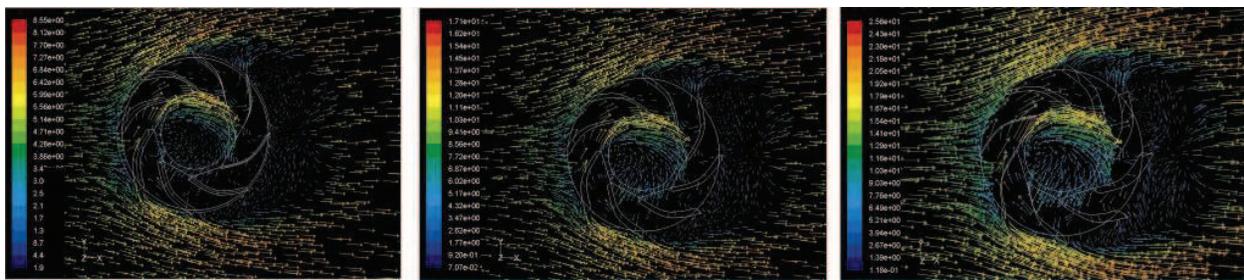
To provide further insight, the flow features within and around the rotor at the two cut planes of B and C at three wind speeds are presented in Figures 3.12 and 3.13 respectively. The results are given as two dimensional vector plots.

Figures 3.12 and 3.13 indicate that with increasing wind speeds, the flows at the left side of the ventilator are higher than at the right side. The extracted air swirls in clockwise direction. Figures 3.13a to 3.13c further indicate that the wake behind the rotor increases in size with increases in wind speeds that produces the increases in suction and hence the increases of swirl component within the ventilator. These observations are in good agreement with the flow visualisation experiments conducted by Flynn & Ahmed (2005) and Lai (2003).



(a) Free Stream Velocity = 5m/s (b) Free Stream Velocity = 10m/s (c) Free Stream Velocity = 15m/s

Fig. 3.12. Velocity vector field at cut plane B at different wind speeds



(a) Free Stream Velocity = 5m/s (b) Free Stream Velocity = 10m/s (c) Free Stream Velocity = 15m/s
 Fig. 3.13. Velocity vector field at cut plane C at different wind speeds

To explore the capability of the CFD modeling approach as an initial design tool, the exhaust flow rate was determined against a range of wind speeds between 3m/s to 15m/s. Numerical computation were performed by assigning boundary condition of 'pressure inlet' at the bottom of the pipe set as ambient pressure.

Once the exhaust mass flow rates for various cases were obtained, the effect of blade heights on performance of a turbine ventilator was explored. Three blade heights H , $1.5H$ and $2H$ were considered, with $H = 98\text{mm}$. The computed exhaust mass flow rates for varying wind speeds are shown in Fig. 3.14.

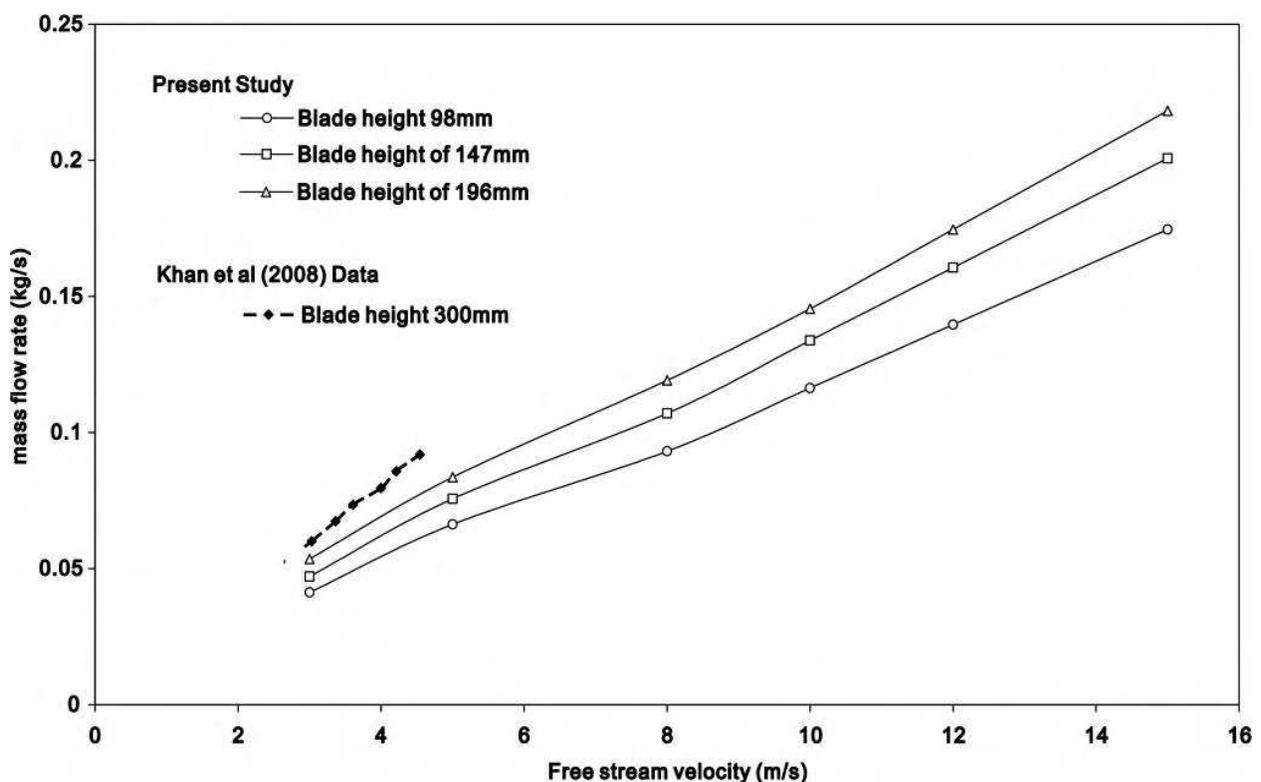


Fig. 3.14. Effect of free stream wind speed on exhaust mass flow rate

It is clear that the exhaust mass flow rate has a near linear relationship of increasing in value with increases in the incoming wind speed. The same trend has been observed by Khan et al., (2008) where four different geometry ventilators were tested in a wind tunnel.

Additionally, the wind tunnel results of Flynn & Ahmed (2005), Khan et al., (2008) indicate that the rotational speed of the ventilator also increases linearly with increases in wind

speed suggesting a linear increase in mass flow rate with increasing ventilator size (diameter or blade height). With 50% and 100% in the ventilator blade height, the improvement of exhaust mass flow rate was found to be 15% and 25% respectively.

Due to the absence of adequate performance data on turbine ventilator in open literature, the data from the experimental results of Khan et al., (2008) on Hurricane turbine ventilator of 300mm diameter and 300mm blade height were extrapolated to provide some comparison against the CFD results. The results are presented in Fig. 3.15.

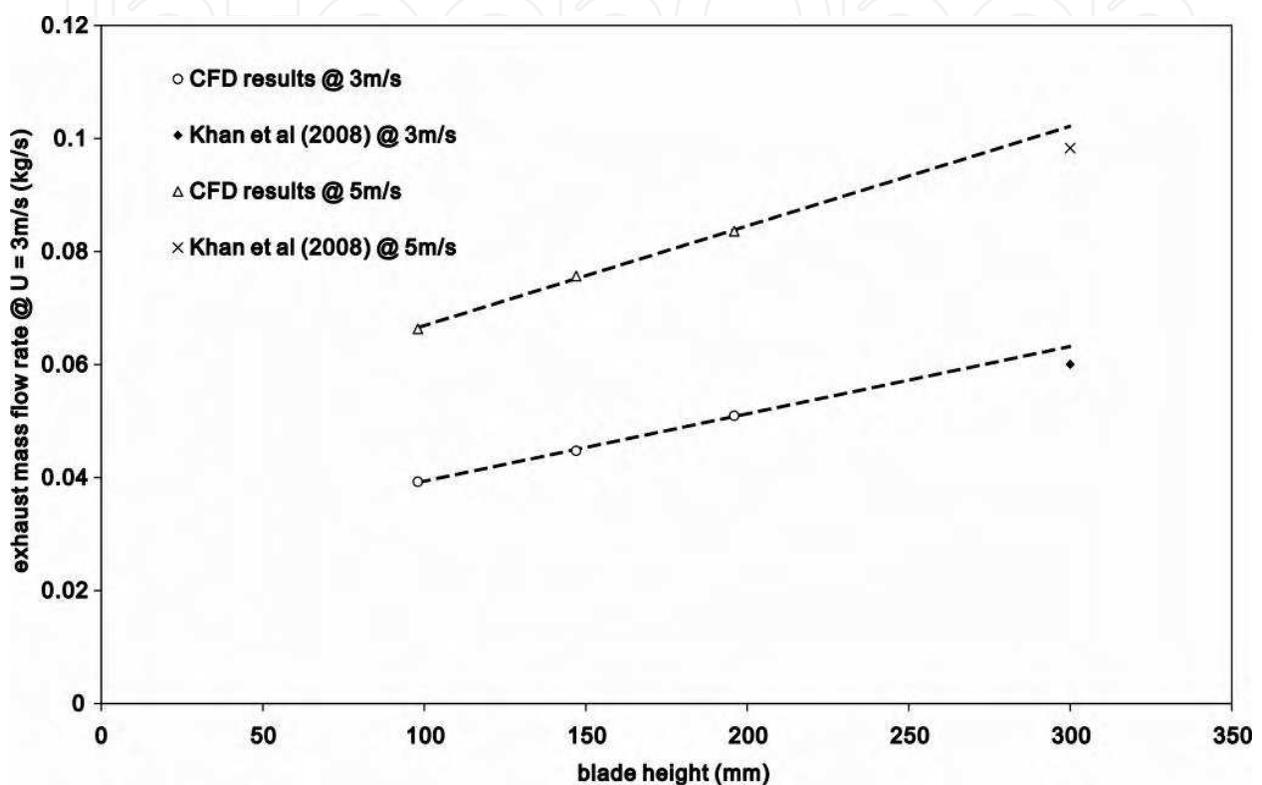


Fig. 3.15. Effect of blade height on exhaust mass flow rate ($U_{\infty} = 3\text{m/s}$ and 5m/s)

Again from Fig. 3.15, a linear relationship between exhaust mass flow rate with blade height was observed. A slight overprediction when compared against Khan et al.,(2008)'s data was observe. Given that the comparison was with extrapolated value and also for the fact that CFD results were from an inclined roof, the small discrepancies are not surprising. However, based on the observations that the similar trends were observed for the exhaust mass flow rate as well as the external and internal flows associated with a rotating ventilator on a 30° inclined roof, it appears that the roof inclined at such angle did not have a significant effect on the overall trend in ventilation performance of a rotating ventilator.

4. Conclusions

Wind driven ventilation systems that utilize wind as a natural energy to provide improved air quality within buildings have been considered in this chapter. Since the wind driven turbine ventilator has proved to be one of the most efficient such device, it has been the primary consideration in this chapter. However, the performance of wind driven ventilation depends largely on prevailing winds. This has necessitated efforts of the authors to

concentrate on exploring the basic flow physics around and within such wind driven ventilator that are detailed in this chapter. The results indicate that the efficiency and reliability of a ventilator operation may require boosting by a hybrid system by incorporating other power sources such as solar power to overcome the inertia and friction forces acting on the body to initiate ventilator rotation at lower wind speed.

Numerical analysis using computational fluid dynamics (CFD) was also employed to investigate both internal and external flows around and within a rotating ventilator. A promising conclusion that can be drawn from these studies is that CFD analysis could be used alongside physical experimentation, as a cost effective aid to enhance operational performance and safety features in the future design and development energy efficient natural wind or wind/hybrid powered ventilation systems to improve air quality and comfort within buildings.

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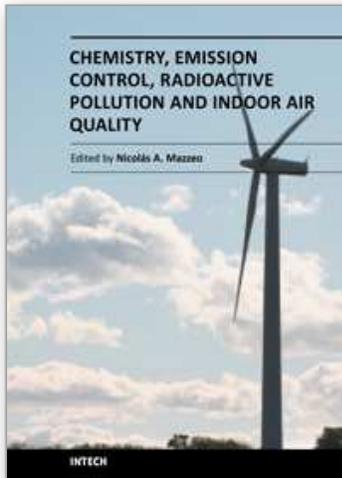
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The atmosphere may be our most precious resource. Accordingly, the balance between its use and protection is a high priority for our civilization. While many of us would consider air pollution to be an issue that the modern world has resolved to a greater extent, it still appears to have considerable influence on the global environment. In many countries with ambitious economic growth targets the acceptable levels of air pollution have been transgressed. Serious respiratory disease related problems have been identified with both indoor and outdoor pollution throughout the world. The 25 chapters of this book deal with several air pollution issues grouped into the following sections: a) air pollution chemistry; b) air pollutant emission control; c) radioactive pollution and d) indoor air quality.

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