A review on wind driven ventilation techniques

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Abstract

Natural ventilation has gained prominence in recent times as a bespoke method of ventilating buildings. The two fundamental principles of natural ventilation are stack effect and wind driven ventilation. This paper reviews miscellaneous wind driven ventilation designs with respect to traditional means such as wind towers and more modern techniques including turbine ventilators and wind catchers. A distinction is made between specific types of wind driven ventilation techniques depending on their operation and mode of engagement with the wind. For example, a static wind catcher is classified as passive; a rotating wind cowl as a directed passive technique and a rotating turbine ventilator is classified as outright active due to its constant rotation with the wind. A table summarising the review is presented at the end with corresponding references.

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1. Introduction

Ventilation is changing of air in an enclosed space. Air should continuously be withdrawn and replaced by fresh air from a clean, external source to maintain good indoor air quality which may be defined as a state where no known contaminants are present in harmful concentrations [1]. A lack of ventilation can cause excessive humidity, condensation, overheating and a build-up of odours, smokes and pollutants. In commercial and industrial buildings ventilation is a part of HVAC (heating, ventilation and air-conditioning) systems which are very energy intensive; usually comprising of large fans, ductwork systems, air-conditioning and heating units. In domestic buildings the primary ventilation method is renewable in the form of air infiltration and natural ventilation through windows and openings [2].

2. Natural ventilation

Natural ventilation uses the natural forces of wind pressure and stacks effect to aid and direct the movement of air through buildings. It is applicable only to a limited range of climates, microclimates and building types, perhaps best suited to a mild climate [3]. Wind incident on a building face will produce a positive pressure on the windward side and a relative negative pressure on the leeward side. This pressure difference as well as the pressure differences inside the building will drive airflow. Strictly speaking wind driven ventilation itself consists of two parameters. The first is the mean driving pressure at the opening. Straw et al. [4] elaborate on the fluctuating component which is the second parameter in wind driven ventilation. Fluctuating pressures can cause unsteady flows around an opening and these are based on three key constituents:

- Broad banded airflow is the influence which fluctuating surface pressures at the opening have on the airflow.
- Resonant ventilation is caused by effects perpendicular to the opening, in particular driven by differential internal and external pressures [4] elaborates that these are significantly influenced by the opening geometry and compressibility of the fluid flowing through that opening.
- Shear layer ventilation is an artifact of ‘eddies in unstable shear layers’ caused by flow through an opening (orifice).

Stack effects are caused by temperature differences between the inside and outside of buildings. When the inside building temperature is greater than the outside, warm indoor air will rise and exit thus being replaced by cooler, denser air from below. The stack effect is dominant during periods of low wind speed and reduces in summer periods when temperature differences are minimal.

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HVAC in buildings accounts for 60–70% of total energy use in non-industrial (commercial and domestic) buildings. This includes heating and cooling requirements as major contributors. Of this 30–50% is related to ventilation and infiltration. The building sector takes up as much as one third of national energy use in the UK. As such it is not immune to widespread efforts in reducing the energy impact of major sectors including transport, the built environment and power generation. To minimize the environmental impact of the building sector we need a multi pronged strategy which includes the use of renewable energy, energy recovery and demand-control and energy efficient technologies [1–3.5].

Natural ventilation is now one of the fundamental methods in the energy efficient design of buildings. This paper will review various wind driven ventilation techniques used in low energy building design, and they will be classified as passive; directed passive and active.

3. Passive wind driven ventilation

This section looks at devices and methods which are passive in nature and primarily use wind-induced effects as motive forces for providing ventilation. By passive we mean those devices which generally have no moving parts although some recent modifications and innovations have integrated moving or controlled additions.

3.1. Window openings

It is well known that in low rise buildings in summer the airflow through windows and openings is mainly wind driven; thus, this has become a centerpiece for ventilation strategies in such buildings [6]. Purposefully designed and positioned openings are used in the building envelope to draw in and expel air. This strategic placement of openings is described by Mochida et al. [7] and Lee et al. [8] both of whom point out the wind flow patterns around a building and its effects on the openings used for ventilation. In concert with this view, Heiselberg et al. [9] have described the change in ventilation flow rates, efficiency, thermal comfort and indoor air quality due to varying configurations of window and opening positions. Asfour and Gadi [10] have presented mathematical network and CFD models for predicting wind driven ventilation in buildings using varying configurations of opening and wind speed and direction. Etheridge and Chiu [11] have elaborated on the discharge coefficients of two types of natural ventilation opening; air vents and chimney stacks. Present methodology in ascertaining these discharge coefficients are centered around laboratory tests under still air conditions which do not reflect wind effects that may cause ‘unsteadiness’ of the velocity and pressure profiles around the building. Their study developed on the uncertainties of envelope flow calculations for natural ventilation design and greatly added to understanding wind driven ventilation. A complementary study [12] aimed to investigate unsteady wind flow effects on natural ventilation stacks using wind tunnel and theoretical envelope flow modeling; the aim was to aid in the design of sitting natural ventilation openings to avoid any possible flow reversal due to unsteady flow effects.

A major limitation of naturally ventilated techniques in general is the unpredictability of the driving forces. Wind data used in the design process is usually based on modal and averaged data for a particular area. This hampers ventilation requirements during periods of relatively extreme conditions and could have a significant impact such as causing flow reversal, although wind-induced ventilation is capable of being enhanced as seen by e.g. wing walls. Similarly stack effects can be enhanced and concentrated to suit a specific application. Both wind and stack effect therefore necessarily require an element of redundancy in their respective systems such as electrical fans for periods of low driving forces. Having said this there are examples where naturally driving forces are the sole motivators for ventilation in buildings.

Window openings are acceptable in dwellings due to their low-tech nature and manual operability. However they are somewhat limiting for larger buildings and on their own are not considered to be a primary ventilation method.

3.2. Atria and courtyards

A common natural ventilation and thus cooling technique is the use of atria and courtyards. The latter have been used for thousands of years and are common architectural features in many areas including the Middle East and Mediterranean. Both are used as centerpieces in buildings and are in direct contact with the outside environment. A courtyard can provide a relatively enclosed space to channel and direct the airflow which is promoted by large openings (gates, doors, arches, etc.) and results in convective natural ventilation in and around a building. To quote [31] “Courtyards are transitional zones that improve comfort conditions by modifying the microclimate around the building and by enhancing the airflow in the building”. An atrium works in a similar way and is used to provide comfort through a progressively acceptable transmission of the external environment to the inside. An extensive list of references is presented in [31] including simulation and experimental studies, a detailed literature review and classification system of atria. Also included are tools for design and estimation of atria size and the associated airflows.

A comparative analysis of the energy performance of atria and courtyards is presented in [13]. A central courtyard and atrium of the same geometric dimensions were simulated against varying climatic and glazing conditions. The general conclusion was in favour of open courtyards for smaller height buildings as being more energy efficient. At increasing building height, the ‘enclosed atrium’ became more energy efficient. Although the study did not actively examine ventilation in atria and courtyards, air infiltration and outdoor climatic conditions were taken into account and can thus give some measure of ventilation potential of the two, under the category of total energy performance used in the study. Since ventilation presents a large proportion of the energy loss in buildings, this is a significant development.
Using a courtyard to provide wind-induced natural ventilation and so prevent overheating indoors was the subject of [14]. A courtyard and its passive cooling potential were examined for a single storey dwelling using field studies and simulation. The airflow patterns around the dwelling due to openings and the courtyard determined the heat exchange between the walls, indoor space and the outside environment and thus had a direct impact on internal comfort conditions. When the courtyard ‘funnels’ air to the open sky, i.e. providing natural extract ventilation, the improvement in conditions is judged better than when the courtyard provides supply ventilation from the open sky into the building. Due to near still air conditions at night in the tested location, stack effects were also investigated and observed in the courtyard, most significantly at night, although the overall influence of stack effects was minimal and close to invisible when ventilation was wind driven through the courtyard. Consequently, the airflow patterns were examined using CFD techniques based on wind driven boundary conditions only.

Fig. 1 illustrates the CFD results. It was found that when the courtyard ventilated the building while other openings were closed (Case 1), a suction zone formed and sucked in air from the open sky to supply air into the courtyard. Some of this supply air may try and escape from the same way it entered, creating a vortex. In case 2 with openings 1 and 2 allowed to ventilate, the courtyard became a funnel which directed air out of the dwelling. Evidently the airflow pattern was influenced by the make up and functions of the openings in the building envelope. Full results can be found in [14].

In summary wind driven ventilation can be enhanced using courtyards and atria. The airflow pattern will determine the potential of natural ventilation. Stack effects can also help especially in atria where the vertical height is usually greater. Atria and courtyards are confined to particular types of architecture and again depend on changeable driving forces.

3.3. Wing walls

A wing wall is usually used to aid single sided ventilation on windward facing windows. The objective is to explicitly induce positive and negative pressures on either side of two protrusions emanating from the window, thus enhancing the flow rate on an already handicapped single sided system [15] cites results claiming that when wing walls are used the average air velocity in the room is 40% of the outside incident wind velocity whilst without one it is only 15%. And another citation refers to full scale experiments which again corroborate the considerable improvement of flow rate with the use of a wing wall [15]. The same study presents numerical simulations of wing walls using CFD techniques and then compares them to already published data. Fig. 2 illustrates the airflow through a single sided opening room with the enhancement due to a wing wall. The wing wall dimensions used in the study [15] are shown in Fig. 2.

The results are favourable. ‘Air circulation’ in and out of the two lateral openings into the room is increased via increased and opposing pressures developed on either side of the wall. Best performance is seen during incident wind angles of 45°, 2D and 3D CFD modeling confirms this. It is also reported based on simulation that the relative size of a wing wall for a given room size approaches a value, above which the size of the wing wall yields no further improvement in performance.

Wing walls have been shown to be effective in [15] although their major limitation appears to be architectural integration and more specifically their use may tend to block sunlight. One way around this could be to use materials of a transparent nature which could doubly act to enhance and/or direct sunlight into the building. There is currently little research on the topic, perhaps due to the limited single sided target although they could be adapted anywhere where distinct and opposing pressures are needed.

3.4. Chimney cowls/exhaust cowls

Exhaust cowls are an effective means of facilitating ventilation. All have the goal of dissipating exhaust air into the atmosphere; secondary objectives include prevention of down draughts, rain, insects, etc. into the building. The
additional negative pressure created by rotating cowls may also be present in some fixed cowls, however fixed cowls are not normally designed for this and the effect is minimal. This suction effect is dependent upon three primary factors; prevailing wind conditions, type of cowl (discharge coefficient) and also the flow rate.

Roof outlets or exhaust cowls typically come in the arrangements seen in Figs. 3 and 4. The first cowl is designed to prevent downdraught into the stack or chimney. The second cowl is commonly used to safeguard against birds, pest, insects, etc. but has a limited downdraught prevention capability (www.topstackchimneys.co.uk).

The suction characteristics of cowls are investigated for hybrid ventilation systems in [16] using CFD techniques. Considering a chief feature of hybrid systems is the low pressure in the system, the suction performance of the cowl becomes singularly important in this context. The study aimed to present four methods for determining cowl performance in terms of the flow rate encountered in the ducts and also the flow field on the roof due to wind induction only. It also classified the cowls investigated into three main types relative to an open duct reference model:

- A cowl benefiting the pressure and flow stability in the duct.
- A cowl inhibiting the pressure and flow stability in the duct.
- Cowls which benefit the pressure and flow stability in some conditions and inhibit them in others.

A typical Chinese hat style cowl was presented as an example of the third type of dual characteristics dependent upon local wind conditions.

Results show that the suction of a wind cowl was a result of the wind speed and wind angle. For example, the Chinese hat style cowl, performed well for descending wind angles and unfavourably for ascending winds relative to a horizontally placed cowl. Consequently, accurate flow field modelling on roofs is encouraged and some advice is given on this. In designing cowls it is essential not to impede airflow too much otherwise an unbeatable resistance in the duct and cowl will significantly handicap airflow. Consequently, design guides are available from many bodies for example CIBSE in the UK.

Research has suggested that wind direction is a critical factor to the effectiveness of wind driven ventilation, this is also true for cowls. Hence a general conclusion one can draw is that stationary devices lack the complete spectrum of abilities to fully utilise the wind resource, thus rotating cowls will be dealt with later on.

Gadi [17] used a form of suction cowl adapted from traditional African design in a new system. In some African homes there is a dome or vaulted roof (Fig. 5). Gadi stated that during summer days this domed roof would have up to 40% of its area shaded from the sun due to its domed shape as opposed to a flat roof. This would mean that parts of the domed roof were cooler than others. A ventilation opening was placed at the apex of the roof to foster ventilation as shown in the diagram. This acts much like a suction cowl in that it creates a negative pressure over the opening and extracts indoor air. A study [18] illustrates the basic concept of a new energy conscious system for passive cooling and heating. Among the two principle concepts used are the doomed roof and roof vent evaluated in various configurations as illustrated in Fig. 6.

The dome allows long wave radiation heat loss from the house during summer nights and short wave transfer of solar radiation during winter days. In addition the roof vent permits air movement around the house. The design was integrated into a typical North African house and then modeled and mounted inside a wind tunnel for natural ventilation simulations. Tests were run using different configurations of open/closed windows...
and vents (Fig. 6). The wind speed and direction was also varied. Results showed the importance of the dome for creating suction, i.e. negative pressure coefficients were observed distinctly at the dome region. The maximum airflow rate achieved for the model was 490 l/s which is equivalent to 6 air changes per hour (ACH) for the system. Wind tunnel results showed that introducing the retrofitted dome system onto the house has resulted in a 6-fold increase in airflow through the building as compared to the reference house without the system attached and all openings closed. Full details of the system are in [17].

Wind driven ventilation is analyzed with respect to a crop protection structure for tropical regions in [19]. A 1:15 scale model of a greenhouse was made and tested in a flume tank filled with water which simulated wind flow through the model. Four different ventilator configurations (Fig. 7), again like a wind cowl/scoop were tested experimentally and using CFD:

1. Firstly the greenhouse with a roof ventilator and two side openings (7a).
2. The leeward side opening and windward roof vent opening were closed (7b).
3. The windward side opening and the leeward roof vent opening were closed (7c).
4. Both side openings were closed and only the roof ventilator was operational (7d).

In configuration ‘a’ it is visible that the air moves in a jet like manner from the windward wall to the leeward wall opening and at the same time creates a modest anti-clockwise circulation which is ventilated partly via the roof ventilator.

The effect of the roof ventilator is minimal as the flow seems to be short circuiting by entering one opening and exiting the next without any proper mixing. Air velocity is greatest at the jet and almost 0 at the centre of the structure. The velocity field for configuration ‘b’ has a diagonal jet which expands as it forms and travels from the windward wall opening to the leeward roof opening. This is a good example of how a cowl works. The leeward roof opening creates a slight negative pressure which draws air from the room. Expelled air is then replaced by an opening lower in the room. There appears to be more mixing than in the previous case although the ventilation rates were reportedly lower. These results provide us with a flow visualization schematic of how a suction cowl extracts air. Configuration ‘c’ which is the opposite of ‘b’ can in a way demonstrate the operation of a pressure cowl. Positive pressure is formed at the windward opening of the roof ventilator and this forces air into the room. Air is then extracted via another opening. Contrasting configurations ‘b’ and ‘c’ show us the airflow patterns around the two types of cowl; pressure and suction. The cowl is an effective measure of providing ventilation in this case and can easily be installed on similar buildings due to its simple nature. It may encounter problems when faced with buildings which have partitions and many floors and rooms, as the airflow will most likely encounter more resistance. A general criticism for this type of cowl exists when there is little or no driving force from the wind. Counting on this cowl to provide the sole means of ventilation for drying applications is severely limiting.

3.5. Wind towers

3.5.1. Past and modern

Wind towers have traditionally been used in Middle Eastern architecture for many centuries. The primary attraction of wind towers is that they are passive in nature, requiring no energy to operate [31]. They work on the principles of natural ventilation, employing both wind driven and stack effect ventilation. Wind
enters via the windward side which has a positive pressure coefficient. It is then directed through the tower into the building. Airflow will follow the pressure gradients within the structure. It will disperse through the building and exit wherever negative pressure coefficients exist relative to where the air entered. Wind flowing around the building causes separation of flow which creates this negative pressure at the leeward side of the building and tower. Exit can be through openings in the tower itself or more normally through purposefully designed openings to encourage cross flow and mixing (Fig. 8).

Wind pressure coefficients at various openings of a wind tower have been determined by testing a scale model of the structure in an open boundary wind tunnel [20]. These coefficients were investigated at various wind angles and two topographies, suburban and open country. Determining factors were found to be the incidence angle of the wind at the tower openings and also the leeward opening of the tower; which was found to hinder airflow through the building. The study recommended that automatic control dampers be used to block the leeward opening of the towers to prevent any short circuiting.

“A wind tower airflow system is ‘analogous’ to air supply systems comprising main and secondary ducts” [21], during its distribution, air will traverse the ducts overcoming resistances, bends, obstacles, etc. Motive forces acting on the air due to pressure differences will be used up in kinetic energy of air and to overcome resistances in the system.

During the day the warm outside air is cooled by the tower structure which itself is slightly cooler internally than its surroundings through irradiative transfer with the environment. At night the cool air will flow through the building and deposit its coolness in the building mass, this is night time cooling and makes use of ‘free’ meaningful cooling which reduces the cooling load the following morning. Essentially, because the air inside is cooler and hence denser, this creates a reversed chimney effect where airflows into the building.

Ref. [20] argues that the sensible and evaporative cooling potential of conventional wind towers is limited due to their design. Other factors limiting conventional wind towers:
- Dust and insects may enter the building.
- There is very little control of the volumetric flow rate.
- Cooling stored in the tower will be limited due to the low specific heat of traditional materials.
- Areas of low wind speed make wind towers unsuitable.

Modern designs of wind towers have integrated advanced building principles and technology. For example:

- Towers with evaporative cooling columns can increase the cooling potential of incoming air. This may require small pumps to feed the moisture into the system which can reduce the passive advantage of wind towers.
- Natural ventilation principles can dictate the exact height and cross section of the towers to accommodate for the target occupants in any building.
- Tower heads can accept wind from any direction without the airflow short circuiting.
- Control dampers and diffusers can modulate the volumetric flow rate.
- Solar collectors can be used as aids to promote stack effect ventilation in times or areas of little wind speed.

Refs. [21] and [22] describe designs of wind towers which use control dampers and solar collectors to enhance the airflow around buildings. They also provide detailed methodology for designing and siting a wind tower.

A study [21] investigated a wind tower coupled with solar chimney design (Fig. 9).

The system consisted of a uniform cross sectioned wind tower which connects to the rooms to be ventilated. Solar chimneys were used to enhance stack effects for exhausts at purposefully designed exits. The analysis involved using predetermined values of pressure and loss coefficients through the system taken from engineering standards on duct and ventilation systems. The overall transport of air is a combination of aero motive and thermal forces. In the wind tower itself it was concluded that thermal effects were negligible whereas in the solar chimney the reverse was true. This study aptly illustrated the dominance of wind driven ventilation and the need for redundancy via another source, in this case stack effects for periods of low wind speed. Results reflect this principle; at low wind speeds the solar chimney dominates, however this pattern is reduced considerably with increasing winds. The wind tower alone, provided up to 20 ACH (air changes per hour) at an ambient wind speed of 1 m/s; this can reach 60 ACH using the combined system. With evaporative cooling these values can be 35 and 73 ACH, respectively. The overall conclusion of the study was that the system is extremely satisfactory as a ventilation and cooling system. Another study in Jordan [23] looked at wind towers and evaporative cooling in contrast to a simple wind tower providing sensible cooling only. The performance of a wind tower was investigated in various parts of Jordan including Amman and warmer desert areas. The design in question was presented by [24].

The tower head in Fig. 10 has four openings to allow air from any wind direction. Assuming air enters through opening 1, i.e. the windward side, it then follows onto Section 2 containing clay conduits. As air passes through these conduits, it loses heat to the clay mass which has been cooled overnight. Water spraying pipes also allow for evaporative cooling in this section. Air then enters the rooms at 5 and 8 and exits via the openings on the opposing side of the ventilated rooms. The pressure difference $\Delta p$, driving the airflow is given by:

$$\Delta p = 0.5(C_{pi} - C_{pe})\rho v^2$$
where $C_{pi}$ and $C_{pe}$ are the wind pressure coefficients at the tower inlet and building exit, respectively, $\nu$ is the wind speed and $\rho$ is the density of air. $C_{pi}$ is positive and $C_{pe}$ is negative. These values were determined by wind tunnel experiments as described in [20]. Results and analysis showed that some traditional wind towers were unnecessarily high at 15 m; the study illustrated that the required dry bulb temperature and air velocity decrease would not change significantly with a tower height of more than 9 m. In fact a tower height of 4 m and cross section 0.57 m $\times$ 0.57 m can produce an airflow of 0.3 m$^3$/s and cool the internal dry bulb temperature from 36 to 25 $^\circ$C.

### 3.5.2. Double skinned facades

Modern buildings with a double-skin façade also exhibit wind tower characteristics as described in [25] and illustrated in Fig. 11.

Natural ventilation is possible through extraction of air via the double-skin and as such this constitutes a form of wind tower application. The diagram shows a multi storey building from a study in Belgium with a double-skin façade. Cross flow ventilation is used with the double façade imitating a stack and the dominant driving force is wind driven. On the diagram the façade is on the leeward side and acts much like a wind tower surrounded by a region of negative pressure able to extract air. Solar radiation provides some stack effect to increase ventilation. This is a difficult strategy to employ and is an emerging theme within double-skinned facades. The configuration and control of openings is crucial to the effective operation of the ventilation system. Similar to the results on wind towers and cowls it is found that wind speed and direction are influential factors in determining the ventilation efficiency. The study determined the way in which double skinned windows should be sized and opened to achieve the required 4 ACH in various wind conditions.

A similar study investigating passive and active stack ventilation in high rise buildings in Singapore [26] presented a hybrid model of the classic wind tower stack. The objective of the study was to assess the present disposition of the natural ventilation system in a four room, high rise, public housing building and then to develop a passive or active stack ventilation system to enhance efficiency. Different stack sizes were tested in a scale model, wind tunnel experiment. It is found that the passive stack working under buoyancy driven forces alone, cannot enhance the airflow in the building thus requiring an extra motive force. This motive force used a DC fan to extract air and was placed on top of the stack to create a suction effect. A considerable improvement in the airflow rate was achieved. It is worth noting the inability of stack effects alone in providing adequate ventilation hence adding weight to the use of wind driven ventilation. In this case a hybrid solution was used via a DC fan powered by solar PV panels to reduce energy consumption. Wind towers in general are limited to where they can be easily located. For example, it is not ideal to have a wind tower in a dense urban city area with high rise buildings surrounding it although the double skinned façade described above is a way around this. Full results can be found in [26].

### 3.6. Wind catchers

Wind catcher or Windcatcher was also another name for wind tower, but here it means a specific wind driven ventilation device. A wind catcher can capture the wind at roof level and direct it down to the rest of the building. Air is also extracted for ventilation purposes. The Monodraught windcatcher was launched in 1990. It is a complete natural ventilation system and is a further development of the vertical balanced flue arrangement used in boiler rooms to provide ventilation.

Fig. 12 shows the basic operational principles of a wind catcher system. Fresh air is drawn in at the windward side and is directed into the building. Weatherproof louvers protect the interior of the building and volume control dampers are used to moderate flow. Stale air is extracted at the leeward side, which is also the passive stack due to a partial negative pressure created by wind siphonage and stack effects. The differential air temperature and hence pressure inside and outside the building force warmer air to rise and exit through the extract quadrants or passive stack; the system is normally divided into four quadrants which run the full length of the body and become air intakes or extractors depending on wind direction thus making the wind catcher system less vulnerable to periodic wind changes and negating the need for any possible rotation to face the wind [27]. Because air is supplied to the building this slightly pressurizes the inside, again aiding the stack effect by forcing warmer air out. Night cooling is an integral part of the ventilation strategy. This ‘free cooling’ occurs during summer months when the control dampers are fully opened to allow the cool night air to invade the building. Thus the building is cleansed of any stale air during the night ready for occupant use in the morning. Fig. 13 shows Monodraught Windcatchers installed on a warehouse.

![Fig. 11. Wind tower application in a double skin Façade.](image-url)
Multi floor and deep plan ventilation is also possible using larger sized windcatchers such as in the three floored Peckham Academy in London where windcatchers alone were used to provide sustainable low energy ventilation and cooling solutions, also utilising the thermal mass of the building to promote night time cooling [27].

A standard 500 mm square 1 m high wind catcher system was evaluated using CFD in [27]. It was connected to a room of 3.6 m by 3.6 m by 2 m. The simulation evaluated windcatcher at four different wind directions from 0° to 45° at intervals of 15° and over wind speed range of 0.5–6 m/s. The general result as expected was that ventilation performance is primarily influenced by wind speed and direction, i.e. angle of incidence on the quadrants (Fig. 14). A more specific result testifying to the efficiency of the system was that the speed of air entering the ventilated room is close to the actual incident wind speed externally. This result illustrates the capability of a windcatcher to literally catch the wind and use it as required. The results show the airflow rate into the room at various external wind speeds and directions. Direct wind (0°) supplies 106 and 145 l/s at wind speeds of 3 and 6 m/s, respectively.

Detailed results (Fig. 15) show a linear relationship with increasing wind speed and extract flow rate. The same is not true for inflow after 2 m/s. At an average wind speed of 3 m/s the air supplied was 106 l/s and air extracted was just over 80 l/s. These results bode well for the windcatcher system in providing adequate ventilation.

However, irrespective of wind speed the flow rates do change according to the wind direction as shown by the results. This may imply a lack of tolerance to turbulent wind conditions and also present unpredictability when calculating flow rates for sitting and sizing purposes. It could also limit the locations...
of windcatchers to open rooftops with flat roofs to provide a wind direction parallel to the roof.

These CFD results have been validated against wind tunnel testing of windcatcher by the same study group and are in favourable agreement with errors up to 22% between simulated and experimental results.

A more detailed study [28] conducted wind tunnel, flow visualization and CFD modeling tests on commercially available windcatchers. The specimen was again a 500 mm square system although slightly larger at 1.5 m height and was connected to a test room inside an open section wind tunnel. Tests were for a range of wind speeds although the wind direction was limited to 0° incidence. The exact wind tunnel set up was simulated in a CFD simulation to cross examine the results and CFD technique validity. As before, it was found that ventilation performance depends upon wind speed and direction relative to the quadrants. Dampers were tested regarding volume flow rate control and a heat source was used to simulate stack effects.

It was found that with the damper on a fully open position the supply flow rate was reduced by 50 and 20% at wind speeds of 1 and 3 m/s, respectively as compared to having no damper at all. Similarly the extract flow rates were correspondingly reduced by 29 and 33%, respectively. Thus the general conclusion is that installing the dampers and associated eggcrate grille will reduce the volume flow rate as opposed to a windcatcher without any additional controls. The heat source tempered the room up to 32°C with outside temperatures of 20°C. This increase in temperature would naturally cause enhanced stack effects to increase the ventilation rate and this occurred most especially at low external wind speeds. This pattern conforms to natural ventilation principles where the stack effect will dominate in the absence of wind, this pattern reversing itself with increasing wind speed. Again at 1 and 3 m/s wind speed the ventilation flow rate increased to 54 and 7%, respectively. For extracted flow these figures were 38% increase at 1 m/s and a 2% decrease at 3 m/s. Another finding was that the system reduced the internal temperature by almost 6°C given an 8°C differential temperature. In conclusion on these results the windcatcher is appropriate for reducing cooling loads in summer and more than adequate for providing ventilation. However these results are based on wind tunnel and CFD simulations and the absence of much field data is an incentive for further research. One study which has conducted field research [29] investigated the effectiveness of a windcatcher system installed in an open plan, two storey office building in the UK. Ventilation measurements were carried out using tracer gas techniques, temperature and indoor air quality was also recorded. The primary ventilation mechanisms of the offices are operable windows for cross ventilation and also windcatchers installed on the roof. Windcatchers here are designed to work with the windows and as such the airflow is primarily influenced by:

- Outdoor wind speed.
- Temperature difference between indoor and outdoor environment.
- Use of other openings such as windows.

And this is also true in general. The windcatcher induces air from one or more of the quadrants as described earlier and will exhaust air from the remaining quadrants. The results are summarized in the table below for tests carried out over two days on the ground (GR) and first (1st) floors.

As can be seen from the results in Table 1, the windcatcher on its own provided relatively little ventilation. Only once the windows were opened, the rates increased considerably. This is a result common to all 6 tests and is an undeniable observation. The first floor results showed a higher ventilation rate and this can be explained by shorter duct lengths from the windcatcher on the roof to room level, thus lower resistances for airflow. Tests 6 shows a markedly greater ventilation rate because of open windows and a greater temperature difference which causes stack effects to become noticeable. There was also a higher wind speed than the previous tests. The general results of this study concur with previous work in that wind speed, temperature differential and duct lengths will affect the delivered ventilation rate. CO₂ levels were kept within regulatory limits at all times due to the ventilation provided by windcatchers thus success in one measure of providing good indoor air quality is observable.

A recent improvement in the windcatcher design is the Monodraught SolaBoost seen in Fig. 16. A solar driven fan assists in bringing in fresh air during periods of high demand in summer months. The 40 W polycrystalline PV panel powers the fan which can additionally bring in up to 260 l/s. In very sunny conditions once 6 V or more is generated by the solar panel, the fan will switch on. When the solar panel reaches 14 V, i.e. this assumes that conditions are very sunny and warm thus requiring more cooling, an intelligent power control device will boost the power to the fan to 25 V resulting in a

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**Table 1**

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Windows status</th>
<th>Outside temp</th>
<th>Inside temp</th>
<th>Wind speed (m/s)</th>
<th>Ventilation rate (Ac/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (GR)</td>
<td>Closed</td>
<td>29</td>
<td>27.1</td>
<td>4.1</td>
<td>1.6</td>
</tr>
<tr>
<td>2 (GR)</td>
<td>Open</td>
<td>29.5</td>
<td>27.8</td>
<td>4.6</td>
<td>5.5</td>
</tr>
<tr>
<td>3 (1st)</td>
<td>Closed</td>
<td>29.5</td>
<td>30.1</td>
<td>4.6</td>
<td>2.7</td>
</tr>
<tr>
<td>4 (1st)</td>
<td>Open</td>
<td>29.5</td>
<td>31</td>
<td>4.1</td>
<td>5.8</td>
</tr>
<tr>
<td>5 (1st)</td>
<td>Closed</td>
<td>16</td>
<td>25.3</td>
<td>5.7</td>
<td>3.8</td>
</tr>
<tr>
<td>6 (1st)</td>
<td>open</td>
<td>16</td>
<td>24.4</td>
<td>5.7</td>
<td>13.4</td>
</tr>
</tbody>
</table>
250% increase in the speed of the fan and hence the flow rate [30].

### 3.7. Wind floor and air inlets

A novel approach to naturally ventilate a high rise building in Japan was the addition of a wind floor. All four sides are open to the environment and winds continuously cross the large openings. This works like a suction cowl in that the whole floor generates a negative pressure which aids the exhaust airflow through the purposefully designed central core which uses the stack effect. A 30% increase in flow rate is attributed to the wind floor although there is too little evidence to draw general conclusions [31].

Air inlets and inlet grilles play a vital role in naturally ventilated buildings by controlling and facilitating airflow. These devices include but are not limited to; differential pressure inlets, including passive and active air inlets and pressure control valves [31].

### 3.8. Example application

The Queens Building at De Montfort University is a prime example of wind driven ventilation in use. It was designed to provide teaching, laboratory and research facilities at the School of Engineering and Manufacture. It was completed in 1993 and designed to maximally exploit natural day lighting and ventilation [32]. As such it uses cross flow ventilation via open able windows for narrow sections of the building and purposefully designed openings and wind towers for deeper parts; these stacks or towers open to exhaust warm, stale indoor air while simultaneous activation of low level louvers and windows allows fresh outdoor air to enter. Roof vents are automatic and initiate when purge ventilation is required during peak times [33].

### 4. Directed passive wind driven ventilation

#### 4.1. Wind cowls/scoops

Wind cowl is a general name for a roof ventilating structure. The terms cowl and scoop are sometimes used synonymously. In [34] the term scoop is used to describe a device which lets air into buildings while a cowl refers to an air extractor. A scoop is typically an open ended, weatherproof device which ‘scoops’ the air and directs it into a building. Scoops can be stationary (Section 2) or rotate about an axis so as to always have the opening facing the incident wind. The same is true for cowls except the opening faces the leeward side. This takes advantage of the partial negative pressure created when winds blow across openings or if the cowl rotates. Wind cowls and scops are usually used in conjunction with wind towers.

Adekoya [34] describes two types of cowl (Fig. 17); the first is a pressure cowl, i.e. those which face the wind and form positive pressures similar to the scoops illustrated above. The second are suction cowls again as described above, which back the wind and develop negative pressures for air extraction. The study cites Kelly et al. in which both pressure and suction cowls were tested in an attempt to compare the two. Significantly, the pressure cowls were found to be better at producing positive pressures than suction cowls were at creating negative pressures. Kelly et al. concluded that pressure cowls were almost two and a half times better at ‘creating a pressure head’ for air movement. Adekoyas’ own research was to determine the suitability of a rotating suction cowl for maize drying applications and more specifically to investigate the static pressures produced by the rotating suction cowl in a farm building in the USA as a function of airflow rate and various wind velocities. The cowl used consisted of a flue, throat and wind vane. The throat and wind vane rotated about a vertical axis, always backing the wind while the flue was fixed. The cowl was 3.65 m above the ground. Wind velocity and flow rate measurements were taken at varying resistance levels which were simulated by different sized holes in plates attached to the
The results are summarised in the graph below. Flow rates vary from 2.1 to 150 l/s for the varying resistances at 6.5 m/s wind speed. And up to 260 l/s maximum at 9 m/s wind speed. It is unclear why there seems to be a spike at 9 m/s which then lowers at a higher wind speed of 10.5 m/s for a lower resistance (Fig. 18). Generally it was found that with decreasing static pressures the airflow rate increased, i.e. the same trend as with fans.

A good example is the ICI chemicals visitor centre in Runcorn, UK. The obvious feature is a rotating wind cowl used for natural ventilation purposes. The cowl sail which is used to turn the cowl into the wind is made of steel and marine sail cloth. The whole cowl stands 9 m tall and turns on steel wheels. Louvers ventilate the building which was designed to harmonise man-made and natural concepts hence the leaf structure of the sail. The wind cowl was installed in 1999 [35]. This is just one example of where rotating cowls can be used on a large scale to enhance natural ventilation. Large cowls can be integrated into building design from a very early stage and can indeed become integral and archetypal features often working with other concepts such as atria or hybrid ventilation systems to perform optimally. Fig. 19 shows the design of a public sector building in Wales. On top is the large rotating wind cowl made of steel and using louvers to exhaust airflow. The supporting structure for the wind cowl is the ‘lantern’ and is used to transmit natural daylight into the building using the inverted funnel structure which benefits both day lighting and natural ventilation. A smaller wind cowl is also visibly attached to a stack running the height of the building. This is for supplementary ventilation in public spaces of the building. Some parts of the building have a mixed mode system also incorporating air-conditioning for necessary operating periods. Natural ventilation is always the preferred and primary mode of ventilation throughout the building which also has ground source heat pumps and a biomass boiler to take full advantage of renewable energy [36].

Buckminster Fuller, a renowned architect and inventor proposed and built the Dymaxion Dwelling machine as shown in Fig. 20 [37].

Of immense interest is the ventilation principle used in naturally ventilating the ‘house’. It is evident from the picture that a wind cowl of sorts is used, referred to as a rotating roof. The operating principle is seen in Fig. 21. A central column supports the essential services of the house including ventilation, plumbing, etc. Regarding ventilation it acts like a stack and aids airflow around the house. Connecting the top of

![Graph of flow rates for 5 resistances on a wind suction cowl.](image)

![Public sector building in Wales.](image)
the column is the rotating suction cowl. A baffle similar to a wind vane keeps the outlet facing away from the wind at all times. A negative pressure is then formed on the leeward side of the cowl which extracts air from the central column. Key to this house was the design of the central column. It was in fact two columns in a concentric arrangement, one smaller placed inside the larger column. Incoming airflows in the larger and outer column whilst the extracted airflows in the inner, smaller column. This also allows for heat recovery as the two airflows at different temperatures pass by each other, the warmer flow loses heat through the metal column whilst never mixing with the cooler fresh incoming air.

Although based on thorough aerodynamic principles, the environmental control aspect of the DDM was not enough to popularise this technology and Fuller’s ideas were never developed further due to funding shortages. One remaining house sits in the Henry Ford Museum in the USA [37].

4.2. Wing Jetter system

A novel natural ventilation system is the Wing Jetter [38] designed by the HASEC Corporation in Japan and pictured in Fig. 22. It uses wing theory to accelerate air on the underside of the system thus causing a negative pressure which exhausts air, much like an inverted aircraft wing. Fig. 23 demonstrates the working principles. The large rudder ensures that the Wing Jetter is always facing the wind in the appropriate direction. A key component is the airfoil section which is inverted and slightly below horizontal to the incident wind. As the wind approaches the front of the system the airflow splits in two. On the upper side drag is created and hence a positive pressure...
distribution develops. Conversely, lift forces create a negative pressure distribution on the underside which is where it connects to the duct.

The system boasts a noiseless and vibration free operation which reflects the 8000 units installed so far. It stands at approximately 1.5 m high by 1.5 m wide and weighs up to 50 kg. Published results under laboratory conditions are shown in Fig. 24.

The above graph compares three natural ventilation devices. The Wing Jetter shows satisfactory performance over a range of wind speeds and reaches 110 l/s at 6 m/s wind speed. However it does not compare favourably with the rotating turbine ventilator which is much smaller having a throat diameter of only 400 mm; making it a third of the size and weighing only 4.5 kg as opposed to 50. More of a direct comparison would be the windcatcher referred to in the results which has a similar size and can provide an extract flow rate up to 115 l/s at the same wind speed. At this point little is known about the Wing Jetter and more importantly the lack of field data makes comparisons with other devices superfluous.

5. Active wind driven ventilation

5.1. Turbine ventilators

A turbine ventilator is a wind-driven air extractor. Its concept was originally patented as early as in 1929 by Meadows [39], who described it as a rotary ventilator and first commercialised extensively by Edmonds of Australia since 1934. A turbine ventilator includes a number of vertical vanes (curved or straight blades) in a spherical or cylindrical array mounted on a frame (see Fig. 25). A weatherproof dome is on top of the frame. A shaft and bearings connect the top moving section to a base duct. When wind blows on the aerofoil vanes the resulting lift and drag forces cause the turbine to rotate. This rotation produces a negative pressure inside the turbine which extracts air. Air enters the turbine axially via the base duct and is then expelled radially. In the absence of wind, a turbine ventilator facilitates ventilation using stack effects.

Havens [40] modelled a turbine ventilator as a combined backward curved centrifugal fan and wind turbine. His rationale for doing this was firstly, the fact that a turbine

Fig. 24. Comparison of windcatcher, Wing Jetter and turbine ventilator.

Fig. 25. Turbine ventilators.
ventilator captures and uses wind power thus the wind turbine approximation. This model presents the tip speed; which is proportional to the ventilator rotational speed, as a function of wind speed. Secondly that it pumps air out of an attic whilst spinning, hence the fan analogy of finding the airflow as a function of rotational speed. The model is presented in detail in [40]. However, the model is heavily dependent on knowing the coefficient of power and torque for a given turbine ventilator. There is very little information on these coefficients and thus this model remains largely unverified.

A flow visualisation study by Lai [41] shows the airflow pattern around a turbine ventilator. The airflow split into two streams when it flowed through the ventilator. One flow was in the direction of rotation and thus became the motive force for rotation whilst the other was in the opposite direction of rotation and dampened the ventilator rotation. The rotating blades threw the extracted air away to mix into these two wind airflows, which converged in the wake region on the opposite side of the incident wind. The same study tested 3 different sized ventilators of 6, 14 and 20 in. diameters under wind speeds of between 10 and 30 m/s in Taiwan. Lai found that larger diameter ventilators would induce greater ventilation rates as expected, but surprisingly the difference between the 14 and 20 in. ventilators was ‘insignificant’. Lai also tried adding an inner vane enhancement which was perceived in Taiwan to add value to the extraction prowess of ventilators. However it was shown there was no significant enhancement to flow rate contrary to popular consumer beliefs although there was some benefit.

An Australian study by Revel [42] compared ventilation rates between two 400 mm turbine ventilators of straight vane and curved vane design. The study concluded that at all wind speeds the straight vane ventilator significantly outperformed the curved vane ventilator. Ref. [43] Found that by increasing the blade height on a given vertical vane ventilator by 50% a 13.5% improvement in flow rates can be achieved. These are called Long Volume Turbines (LVT) and are shown in Fig. 26. For example, ventilators with vane heights of 170, 250 and 340 mm tested at a wind speed of 12 km/h induced approximately 65, 70 and 75 l/s, respectively.

Another study [44] attempts to investigate the flow field and aerodynamic forces around a rotating ventilator. Although a turbine ventilator is quite simple in its design and construction the associated flow is deceptively complex, comprising two separate but interdependent flows, i.e. the free stream air which rotates the ventilator and the extracted air being expelled, as illustrated by Lai [45]. Due to the difficulty experienced in the investigation, the flow field analysis was limited to the wake region where tufts of fine silk on a frame were used to highlight the turbulent wake region. The experiment was conducted at 15 m/s wind speed with the frame being at 250, 400 and 650 mm away from the rotating ventilator which was allowed to rotate; and stalled in another configuration. Although the experiment was limited in scope it did show the overall parameter of the wake region. Its boundaries were discernable as was the rapid decay of the turbulence suggesting a crude three-dimensional shape of the wake region. The relative randomness of the tufts movement indicated levels of turbulence and ‘violent movement and distinct reversal of direction were observed’ pointing to the region where extracted air is expelled from the ventilator. Comparing the wake patterns of the rotating and fixed ventilator it was found that the former had more evenly distributed fluctuations suggesting a better mixed flow and lower drag. The wake also decayed faster for the rotating ventilator. In comparison, Wilson [46] presents a study on the effects of turbulence on exhaust gases’ dispersion from roof level stacks and vents. A primary conclusion is that the exhaust dispersion is strongly influenced by the additional turbulence generated by the upwind and building turbulences. A reasonable guess would be that a field study of turbine ventilators would yield similar results and add to the understanding of flow around a turbine ventilator placed on a building.

The same study [44] aimed to investigate the aerodynamic forces acting on the rotating ventilator by using force/torque transducer measurements. Indicative parameters for the drag and lift experienced by the ventilator were examined, notably the force coefficients on the X and Y direction, respectively relative to the blades. Results showed that the ventilator tested which was of a vertical blade design, was more efficient at lower wind speeds. Increasing wind speeds may have caused

Fig. 26. 3 Long volume turbine ventilators.
‘flow separation’ on the actual blades implying that an improvement in blade aerodynamic design is needed to allow for efficient operation over a greater range of wind speeds. Rotational speed increased linearly with the wind tunnel wind speed and the dome shaped structure was seen to contribute to possible lift in the vertical direction which could cause the ventilator to be sucked off the roof.

This study compliment Havens’ study [40] by providing some force and torque data to verify the presented model. Dale and Ackerman [47] conducted field measurements of a 305 mm diameter turbine ventilator in a house which had two soffit vents with a combined free vent area of 0.08 m² installed for attic ventilation. They found that ventilation enhancements were a function of wind direction with the best being wind with more upwind shelter. They also studied the temperature difference caused by the turbine ventilator in the attic and found this to be negligible with a measured temperature decrease of only 0.56 °C. They concluded that over all wind directions and seasons, the attic turbine ventilator investigated increased ventilation rates by 15% on average as compared to the existing roof soffit vents in the test house.

Lai [48] also investigated the addition of a large turbine ventilator on a dormitory to enhance ventilation for bathrooms, further to the existing extract fans. The conclusions were that the turbine ventilator did add to the ventilation rate significantly and the induced negative pressure helped reduce leakage of odours and moisture to other spaces.

A novel study [45] combined a small DC fan powered by PV cells with a curved vane turbine ventilator to develop a prototype hybrid rooftop ventilator (Fig. 27). The aim of this was to add redundancy in the system by improving the operation and energy efficiency of a standard commercially available ventilator. In context Taiwan having periods of high winds with low sunlight and the converse would help this novel system function. Thus a 16 inch diameter DC fan was placed in the throat area of a 20 inch diameter ventilator.

The optimum rotational speed of the fan was found to be 1500 rpm. The use of the fan was found to be ideal during periods of low wind speeds up to 5 m/s when the enhanced ventilation rate was linearly increasing with the fans rotational speed. At higher wind speeds of 7.5 m/s the effect of the DC fan diminished and at very high wind speeds of 10 m/s the fan did not contribute to the airflow.

5.2. Rotating chimney cowl

Fig. 28 shows a rotating chimney cowl. These are essentially smaller versions of the turbine ventilator, indeed the former are based on these vintage designs. The rotating chimney cowl freely rotates in the wind and extracts air. The major advantage of such a device is the prevention of down draughts into the chimney. The main feature of these devices is the rotating body composed of ‘helicoidal’ blades in a spherical arrangement connected to the bearing assembly and base duct. Often times these are used in chimneys extracting flue gases from combustible processes.

Depending on the wind speed and chimney diameter the flow rate through a rotating chimney cowl can be large. Table 2 shows the respective diameters and corresponding flow rates for one type of chimney cowl [49]. The larger sizes are comparable to smaller turbine ventilators in terms of flow rate.

5.3. EcoPower

A significant new improvement upon the vertical vane ventilator is the hybrid EcoPower turbine ventilator, developed
by Edmonds of Australia (www.edmonds.com.au and www.hybridvent.com.au) [50]. This innovation came as a result of traditional turbine ventilators being too dependent on the local wind conditions thereby not guaranteeing ventilation rates which are expected to comply with ever increasing building regulations. The EcoPower is both a wind driven and motorized ventilator with the ability to operate by wind alone or by both wind and electrical power. It has a motor incased inside the dome. The bearing assembly of the motor is also the bearing assembly of the ventilator which can be activated by any control indicator such as a humidity or temperature sensors. Consequently, periods of low wind speed are compensated for when the motor kicks in thus ensuring adequate ventilation flow rates. Without the motor and under free spinning conditions the EcoPower matches and even outperforms the standard Hurricane Vent of a similar size by up to 15% [Edmonds Report]. An electronic commutating motor provides energy efficient ventilation and maintains the throat open area by being placed in the dome of the ventilator. Other attempts to add redundancy to a turbine ventilator have always focused on

Table 3
Classification of wind driven ventilation techniques

<table>
<thead>
<tr>
<th>Wind driven ventilation type</th>
<th>Feature/application</th>
<th>Typical flow rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>Wind pressure and stack effects</td>
<td>Can be the sole method of ventilation</td>
<td>[2–10,30,31]</td>
</tr>
<tr>
<td>Atria &amp; courtyards</td>
<td>Architectural integration into building</td>
<td>Typically used in warmer climates for cooling</td>
<td>No data available</td>
</tr>
<tr>
<td>Wing walls</td>
<td>Uses wind pressure mostly in domestic buildings, used to facilitate natural ventilation</td>
<td>Up to 40% of outdoor wind speed inside the room, only 15% without</td>
<td>[15,29]</td>
</tr>
<tr>
<td>Chimney/exhaust cowl/roof vents</td>
<td>Placed on top of chimneys and roofs, uses wind induction and stack effect</td>
<td>Various depending on size and application. Can provide whole building ventilation</td>
<td>[16–19,31]</td>
</tr>
<tr>
<td>Wind Towers</td>
<td>Wind pressure/stack effects</td>
<td>Depending on wind speed, direction and height: up to 73 ac/h/300 l/s for 4 m tower head</td>
<td>[20–25,31]</td>
</tr>
<tr>
<td>Windcatcher</td>
<td>Wind pressure/stack effects. Installed in Schools, offices, domestic buildings, industrial buildings</td>
<td>Reported supply of 100 l/s and 80 l/s extract at 3 m/s wind speed</td>
<td>[26–30]</td>
</tr>
<tr>
<td>Wind floors Air inlets</td>
<td>Wind floors are used on top of high rise buildings to facilitate natural ventilation. Air inlets are components of natural ventilation design</td>
<td>Various; little data available</td>
<td>[31]</td>
</tr>
<tr>
<td>Directed passive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cows &amp; scoops</td>
<td>Uses wind pressure and faces into or away from prevailing wind (static)</td>
<td>150 and 260 l/s at 6.5 and 9 ms/wind speeds. Chimney cowl on a hybrid system provided up to 55 l/s</td>
<td>[32–36]</td>
</tr>
<tr>
<td>Rotating roof</td>
<td>Dymaxion dwelling machine with a rotating roof similar to a wind cowl. Used to naturally ventilate whole dwelling</td>
<td></td>
<td>[37]</td>
</tr>
<tr>
<td>Wing Jetter</td>
<td>Uses drag and lift forces to create a negative pressure and extract air</td>
<td>Up to 110 l/s at 6 m/s wind speed in laboratory conditions. Lack of field data</td>
<td>[38]</td>
</tr>
<tr>
<td>Active</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine ventilators</td>
<td>Combined wind turbine and extract fan design. Domestic and industrial use</td>
<td>Depending on size and wind speed up to 300 l/s per unit. 20–50 l/s for domestic buildings for a small sized ventilator. Rotating chimney cowls provided 35–90 l/s dependent on size and wind speed</td>
<td>[39–45,47,48,50]</td>
</tr>
<tr>
<td>Rotating chimney cowl</td>
<td>Small spherical rotating ventilator placed on top of chimneys. Good at preventing down draughts</td>
<td>Between 35 and 87 l/s depending on size and wind speed</td>
<td>[49]</td>
</tr>
<tr>
<td>Vawtex</td>
<td>Vertical axis wind turbine attached to extract fan</td>
<td>No data available. Vawtex is being installed in several buildings on a pilot study</td>
<td>[51]</td>
</tr>
</tbody>
</table>
placing DC fans in the base duct which significantly reduces the extract flow rate.

5.4. Vertical axis wind extractor (VAWTEX)

A novel type of ventilator is the Vawtex machine [51], Vertical Axis Wind Turbine Extractor as shown below (Fig. 29). It is a vertical axis wind turbine which provides electricity free ventilation on a large scale with no fuel cost and no pollution. The special feature on the Vawtex is that it has two wings which produce lift and can operate in very turbulent, urban conditions. The vertical axis of the turbine is attached directly to a fan which rotates with the turbine and extracts air. The first prototype is 10 feet tall and has a cut in speed of 3 mph. It is designed to turn less efficiently in larger winds to reduce potential hazards during storms. The Arts block at the Harare International School in Zimbabwe housed the first Vawtex machine. It is used to remove heat gains during the day and works in tandem with granite chambers underground which cool during the night and keep the building cooler during the day. Noticeable effects are that the classrooms are up to 8°C cooler during the day than without the system installed. The designers, Arup have installed the Vawtex machine in Mozambique and Belgium. However, there is very little academic literature on the flow rates produced by the Vawtex Machine and it remains to be seen whether the design can take off commercially.

6. Conclusion

Miscellaneous wind driven ventilation techniques have been reviewed and categorized. A summary of their features and typical flow rates is given in Table 3. It is worthwhile to mention that it was difficult to find data on flow rates for some large scale devices.

References