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Quantifying the performance of a top–down natural ventilation Windcatcher™

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ABSTRACT

Estimating the performance of a natural ventilation system is very important if one is to correctly size the system for a particular application. Estimating the performance of a Windcatcher™ is complicated by the complex flow patterns that occur during the top–down ventilation process. Methods for predicting Windcatcher™ performance can currently be separated into simplistic analytic methods such as the envelope flow model and the use of complex and time consuming numerical methods such as CFD. This article presents an alternative semi-empirical approach in which a detailed analytic model makes use of experimental data published in the literature for 500 mm square Windcatchers™, in order to provide a fast but accurate estimate of Windcatcher™ performance. Included in the model are buoyancy effects, the effect of changes in wind speed and direction, as well as the treatment of sealed and unsealed rooms. The semi-empirical predictions obtained are shown to compare well with measured data and CFD predictions, and air buoyancy is shown only to be significant at relatively low flow velocities. In addition, a very simple algorithm is proposed for quantifying the air flow rates from a room induced by a Windcatcher™ in the absence of buoyancy effects.

1. Introduction

A Windcatcher™[1] is a top–down, roof mounted, omni-directional device used for naturally ventilating buildings. The Windcatcher™ protrudes out from a roof and works by channelling air through a series of louvers into a room under the action of wind pressure, and simultaneously drawing air out of the room by virtue of a low pressure region created downstream of the Windcatcher™. The Windcatcher™ concept has been around for centuries and is common in the Middle East [1,2]. This concept has been applied commercially in the UK for at least 30 years, see for example the review of Windcatchers™ and other related wind driven devices by Khan et al. [3]. The cross-section of the Windcatcher™ may be of any shape, although it is important to try and maximise the pressure drops on the leeward side and so current commercial designs are either circular or rectangular. Experimental studies have shown, however, that a Windcatcher™ of rectangular cross-section outperforms other designs, see for example Refs. [4] and [5]. For a rectangular Windcatcher™, the cross-section is normally split up into four quadrants so that one or more quadrants act as supply ducts to a room and the remaining quadrants act as extract ducts. The key indicator of performance for a Windcatcher™ is the rate at which fresh air is delivered into the room and the rate at which stale air is extracted. Accordingly, it is very important to be able to predict ventilation rates prior to choosing the appropriate size of a Windcatcher™ for a particular building. This article addresses this issue by developing a simple semi-empirical model suitable for estimating Windcatcher™ performance as a function of wind velocity and cross-sectional area.

It is common to predict natural ventilation flow rates using simple envelope flow models, see for example Refs. [6–10]. A major factor that influences the performance of a natural ventilation system is the losses incurred as the air passes through an opening. For envelope flow models it is normally assumed that these losses can be modelled using an equivalent coefficient of discharge, and values similar to those measured for orifice plates are commonly used [6,9]. However, a Windcatcher™ represents a far more complex opening than, say, a window and such an approach is unlikely to capture the true performance of a Windcatcher™ over a range of parameters. Therefore, in order to realise a more accurate understanding of the energy losses inside a Windcatcher™ it is necessary to study the air flow in more detail. Experimental and theoretical investigations into Windcatcher™ performance have been reported in the literature, although data on Windcatchers™ is not as prevalent as that seen for other types of natural ventilation. The measurement of Windcatcher™ performance has generally been restricted to laboratory conditions and very few studies have

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[1] Windcatcher™ is a proprietary product of Monodraught Ltd.

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examined performance *in situ*. For example, Elmualim and Awbi [5], Parker and Teekeram [11], and Elmulalim [12] all used a wind tunnel to measure the performance of a square Windcatcher™ divided into four quadrants and connected to a sealed room; later, Su et al. [13] performed similar wind tunnel tests but for circular Windcatchers™. Parker and Teekeram focussed on measuring the average coefficient of pressure (C_p) over each face of the Windcatcher™ for wind of normal incidence. Elmualim [12] also measured C_p values, but extended the study to wind incident at different angles in order to build up a more general picture of a Windcatcher's™ performance. The experimental data reported by Elmualim [12] is based on measurements taken using only two pressure tappings placed on the centre line of each Windcatcher™ face, which may introduce further errors and is significantly fewer in number than the pressure tappings used by Parker and Teekeram [11]. Kirk and Kolokotroni [14] also measured the performance of rectangular Windcatchers™, but chose to measure the ventilation flow rates for multiple Windcatchers™ operating *in situ*. Kirk and Kolokotroni measured the decay of tracer gas in order to estimate ventilation rates and for an office environment they observed a linear relationship between extract volume flow rate and the incident wind velocity. A linear relationship was also observed by Shea et al. [15], who measured a net flow out of the Windcatcher™ indicating that there is air infiltration into the room to compensate for the mass shortfall.

The values measured for C_p clearly demonstrate the action of the Windcatcher™ in that those quadrants with positive values of C_p act as supply ducts, whereas those with negative values act as extract ducts. This is also confirmed by observations taken using smoke tests, see for example the measurements of Elmualim and Awbi [5]. To corroborate laboratory measurements, Elmualim and Awbi [5] developed a CFD model for both circular and rectangular Windcatchers™, and for the windward quadrant under normal incidence good agreement between predicted and measured C_p values was observed for the rectangular Windcatcher™. However, a comparison between prediction and measurement for the leeward faces is less successful, although this is, perhaps, not surprising given the complex and highly turbulent nature of the air flow around a typical Windcatcher™. Whilst the measured C_p values are important in dictating the magnitude and direction of the flow velocities into and out of a room, they do not on their own quantify the ventilation rates. Here, ventilation rates also depend on the losses within the Windcatcher™, which must be quantified before a complete picture of Windcatcher™ performance can be realised. The ventilation rates for a 500 mm square Windcatcher™ were measured by Elmualim and Awbi [5] under controlled conditions in a wind tunnel. Later, Elmualim [12] used CFD to predict ventilation rates in a square Windcatcher™, although only limited agreement with measured data is observed. Li and Mak [16] also used CFD to examine the performance of a 500 mm square Windcatcher™ and demonstrated good agreement with Elmulaim and Awbi's [5] data, although this is limited to overall ventilation rates. Recently, Hughes and Ghani [17] used CFD to calculate net flow rates through a 1000 mm square Windcatcher™, and by normalising their results they obtained predictions that were within 20% of those generated by Elmualim [12]; see also an earlier CFD study by the same authors [18].

Whilst CFD models have been shown to be partially successful in capturing the performance of a Windcatcher™, the difficulty of using CFD to generate predictions covering a wide range of parameters, as well as the time taken to generate and solve these models, means that CFD is not so useful as an iterative design tool. Moreover, the very function of a Windcatcher™ depends on high levels of turbulence and early boundary layer separation, an area that not surprisingly causes CFD problems. Accordingly, it appears to be sensible to investigate an analytic approach with a view to developing simple algorithms based on the use of empirical data to estimate the losses due to turbulence. To this end, Elmualim [12] used a so-called explicit model in order to estimate Windcatcher™ performance and represented the losses within the Windcatcher™ using an equivalent coefficient of discharge. This approach is very similar to the envelope flow model described by Etheridge [7], although good agreement with experiment is observed only under limited conditions. Moreover, the method uses two heuristic constants that appear to bear very little relation to the Windcatcher™ itself and it is not clear why certain values were chosen, nor how one should go about identifying these values for different Windcatcher™ designs. Accordingly, there is a clear need for a simple analytic model from which Windcatcher™ performance can be quickly and reliably estimated. This article addresses this need by developing an analytic model that explicitly includes experimental data for the Windcatcher™ as part of the modelling methodology, as well as adding other phenomena such as buoyancy. Here, experimental data is used to quantify the losses in the Windcatcher™ rather than using CFD or heuristic constants. Furthermore, the model is extended to address both sealed and unsealed rooms and will also deliver results for wind incident at two different angles, something that is omitted in the explicit model of Elmualim [12]. Accordingly, in Section 2 that follows an analytic model is developed based on conservation of energy and mass. Experimental data reported in the literature and obtained under controlled laboratory conditions is then used to identify appropriate C_p values in Section 3; by comparing prediction and experiment appropriate loss factors are also calculated and a semi-empirical model formulated. In Section 4 the semi-empirical predictions are compared against other data available in the literature and a very simple relationship between Windcatcher™ ventilation rates, incident wind velocity and Windcatcher™ area is presented.

2. Analytic model

A Windcatcher™ is normally either rectangular or circular in cross-section, although a Windcatcher™ of rectangular cross-section is known to significantly outperform one of circular cross-section [5] and so the analysis that follows is restricted to rectangular cross-sections. The cross-section is assumed to be divided up into four quadrants, where each quadrant contains louvers at the top and dampers plus a grill at the bottom, see Fig. 1. The Windcatcher™ experiences wind of velocity u_w incident at an angle of θ degrees, see Fig. 1a. The Windcatcher™ has cross-sectional dimensions $d_1 \times d_2$; the length of the louver section is L_T and the length of the section from the louvers to the bottom is L.

To model the performance of a Windcatcher™ conservation of energy and mass are enforced using a method similar to that reported by Etheridge and Sandberg [6], and CIBSE [8]. In the analysis that follows, the wind is assumed to have zero angle of incidence ($\theta = 0^\circ$) as this will simplify the discussion; however, a value of $\theta = 45^\circ$ will be included in Section 3. For a quadrant that faces into the wind, flow will be from the outside into the room and here conservation of energy yields [6],

$$\Delta p_{in} = p_E - p_I - \Delta\rho g z_I + p_w, \tag{1}$$

where p_E and p_I are the external and internal pressures, respectively, and Δp_{in} is the pressure drop over the Windcatcher™ quadrant (assuming that all losses between the room and the surroundings are attributable solely to the Windcatcher™). In addition, $\Delta\rho$ denotes the change in air density between the room and the surroundings, z_I denotes the height of the entrance to the