Internal airflow sensitivity in a naturally ventilated atrium subject to variation in external wind conditions

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ABSTRACT

Design guidelines for natural ventilation in buildings normally focus on the potential hourly air change (ACH) rates based on the building space parameters. Critically, external airflow design data is often assumed on the basis of a single mean wind speed and an associated prevailing wind direction. This can result in significant variation in ventilation rates and comfort conditions when non-design external wind conditions prevail. This paper examines the influence of variations in external wind conditions on internal building airflows using a CFD model for the atrium space of a naturally ventilated building. External wind speeds from 25% to 250% of the mean site wind speed were examined. For a single wind speed, the relationship between wind direction and air change rates was also found to be approximately linear for wind directions between 0^o and 90^o (orthogonal and parallel) to the vent openings, but non-linear for other directions (90^o to 135^o).

1. INTRODUCTION

A key issue that arises in the design of naturally ventilated (NV) buildings is the assessment of building internal air movements. The increased interest in NV has in recent years has exposed the limitations in existing knowledge relating to the prediction of the performance of NV buildings under the broad range of external weather conditions that a building may experience (Hunt 1999, Lomas 2006). This paper examines this issue by undertaking a detailed study into the affect of different external wind conditions on the airflows induced in a NV building. Existing NV design guidelines, such as those produced by the Chartered Institute of Building Service Engineers (CIBSE 2005), outline recommended room sizes based on three factors, namely; window layout, required air changes per hour (ACH) and internal heat gains. Importantly, external airflow, a parameter directly influencing the driving forces of NV (wind and buoyancy effects), is often ignored in NV design guidelines due to its building specific nature. In designing NV buildings, Omer notes that NV spaces are typically analysed under conditions where steady airflow through the openings are assumed (Omer 2006). However, the effect of changes in the wind speed and direction on the ventilation rate and internal airflow conditions are often not quantified, therefore leaving the designer unsure as to the extent to which conditions inside the building may fluctuate. This research attempts to address this lack of understanding by providing an insight into the effect of external wind conditions on the airflows induced in a NV building.

2. BACKGROUND

Uncertainty continues to exist on the effect of external wind conditions on the induced indoor airflow patterns in NV buildings. Studies by Reichrath & Davies and Watakabe et al. report on the wind induced pressure coefficients on building facades for a single wind condition (Reichrath 2002, Watakabe 2002). Other studies by Burnett et al. (Burnett 2005) extend these investigations further by examining the effect of changing wind conditions on the induced building façade pressures. Nevertheless, research to date does not appear to consider the effect of variations in external wind speed and direction on induced airflows within buildings. This is somewhat surprising given the potential influence that external microclimate can have on NV building internal conditions. Research by van Moeseke et al. (van Moeseke 2005) which utilised an analytical pressure model to establish pressure coefficients on the façade of a multi-storey office building as a function of various external wind conditions, states that the analytical pressure model method has limited ability when applied in an urban environment. Using thermal analysis software to investigate the resulting air change per hour (ACH) rates for an NV building, the study by van Moeseke showed that wind incidence had an influence on the air movement inside the building. As this work did not utilise any discretised numerical techniques such as CFD, the influence on room airflow patterns was not quantified. Little insight on the effects of external wind conditions on the internal airflows in a NV building is evident from the studies mentioned so far. Nonetheless in another study by Kindangen et al., external wind direction was found to have a significant influence on the internal airflow patterns

(Kindangen 1997). Kindangan et al. investigated the effect of roof shape on induced airflows inside and outside a simple cross-ventilated single zone NV building. Although several wind directions were investigated, the work was limited to a single wind speed and therefore does not help address the uncertainty associated with the effect of external wind conditions on the internal airflows in a NV building. Based on these studies, it is clear that wind direction does have a significant effect on internal airflow patterns in NV buildings. Kindangen et al. also found that wind direction had a major influence on the internal airflow patterns for a simplified, single room NV building, while in an other study, Shklyar & Arbel (Shklyar 2004) found wind direction to have a significant effect on the induced airflow pattern in a NV greenhouse. Nonetheless, each of these studies has in some way been limited and few offer any quantitative relationship between internal and external conditions.

3. THE CFD MODEL

3.1 Building Form

The form chosen in this work was based upon the shape of a two-storey NV office building which has been used previously by the authors to examine the use of CFD for predicting internal airflows in NV buildings (Horan 2004). The building consists of a central atrium space, with rooftop openings, surrounded by a series of cellular offices. The external dimensions of the building form, as shown in Fig. 1, were 30 m wide by 20 m long with a roof height of 9.6 m. The atrium space at the centre of the building measured 12.0 m wide by 8.0 m long, and in height extended from floor to roof. Only the airflow in the atrium space was modelled as including the cellular office space was deemed to deviate considerably from the earlier validated scenario, whilst also greatly complicating the modelling processes. Three vents, each with an opening area of 1.0 m^2, were distributed along one side of the building. These vents, along with four top pivot windows on the roof, each with an opening area of 2.6 m^2, acted as the building openings. To investigate the affect that the extent of the vent opening area had on the internal airflows in the atrium, three internal building models were utilised as follows. A triple vent model (TV), which contained three side vents as shown in Fig. 1(b), a double vent model (DV) as shown in Fig. 1(c), and a single vent model (SV) as shown in Fig. 1(d).

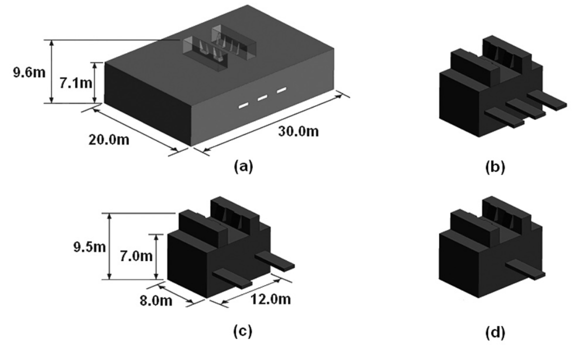

Figure 1: (a) The external form of the building model, (b) the internal form of the triple vent (TV) model, (c) the internal form of double vent (DV) model, and (d) the internal form of the single vent (SV) model.

3.2 CFD Model

A coupled CFD simulation, modelling both the internal and external building airflows, can result in excessive computational demand, whilst the selection of the turbulence model may be an issue, as the same turbulence model must be used to model both the internal and external airflows. By decoupling the CFD model, and solving the internal and external airflows in separate models, the computational hardware requirements can be greatly reduced, although, the separate external and internal simulations considerably increase computational time. In this work, a coupled approach is selected thereby removing any uncertainty associated with a de-coupled approach. On the basis of data obtained from a nearby meteorological station, five wind speeds were chosen for investigation; 3.0 $m.s^{-1}$, 5.0 $m.s^{-1}$, 7.0 $m.s^{-1}$, 9.0 $m.s^{-1}$ and 11.0 $m.s^{-1}$. Five CFD models were developed to provide more detailed inlet flow fields for all five inlet velocities. The airflow at the computational domain inlet was defined using a logarithmic velocity profile. Profiles of the velocity, turbulent kinetic energy and the turbulence eddy dissipation at the outlet of the domain were obtained from the results. To reduce the number of simulations in this work, all five wind speeds were applied to the triple vent model (TV) only. To facilitate investigations into the affect of various wind directions, four wind incidences were investigated, as shown in Fig. 2.

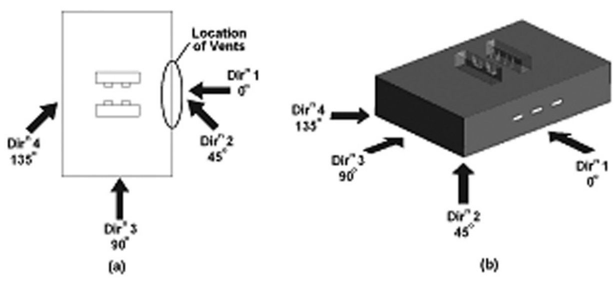

Figure 2.: A plan view (a) and isometric view (b) of the generic building model and the four wind directions investigated in this study.

The selection of the mesh parameters was based upon model dimensions and computing resources, limiting each model to approximately 1.5M elements. As a result, the internal mesh was restricted to approximately 0.5M elements based on an internal grid sensitivity study with the external mesh containing approximately 1.0M elements. Structured hexahedral meshing was used for the internal portion of the model as it has been shown to outperform unstructured tetrahedral meshing when modelling internal airflow in NV buildings. Unstructured tetrahedral meshing was used to model the external portion of the building model. A domain size of 18Lx13Wx5H, with 6L upstream of the building was utilised to ensure a domain independent solution.

4. RESULTS

4.1 External Wind Speed

Increasing the external wind speed resulted in a clear increase in the ACH rate for the atrium space for all models investigated. An approximately linear relationship between the ACH rate and the external wind speed was observed, irrespective of the number of vents included in the model or the external wind direction. This may be seen in Figure 3, which shows the predicted ACH values for several wind directions using the three vent building model (TV, Fig. 1b). The extent of the influence of external velocity on the ACH rate was found to be highly dependent on wind direction. For the triple vent model, an increase in external wind speed from 3.0 to 7.0 m.s^{-1} resulted in an increase in the ACH rate of 7.4, 4.4, 1.3 and 1.7 respectively for the four wind directions 0^o, 45^o, 90^o and 135^o. Figure 4 illustrates the case for the double vent model (DV, Fig. 1c), an increase in external wind speed from 3.0 to 7.0 m.s^{-1} resulted in an increase in the ACH rate of 5.3, 3.0, 1.2 and 1.7 respectively for the four wind directions 0^o, 45^o, 90^o and 135^o. Increasing the external wind speed was found to result in similar increases in ACH rate for wind directions of 90^o and 135^o, for both the triple (TV) and double vent (DV) models. This, however, was not the case for the single vent model (Model SV), where increases in the external wind speed were found to produce significantly different ACH rates for the 90 (SV90) and 135 (SV135) directions. This may be seen in Figure 5, a plot of the predicted ACH rate for several wind directions using the single vent model (Model SV, Fig. 1d). The reason for this variation between Models SV90 and SV135, which is not apparent between Models TV90 and TV135 and Models DV90 and DV135, is due to the greater proportion of air entering into the atrium through the rooftop windows in Models SV90 and SV135. As only one side vent is included in the single vent models, once the wind direction moves beyond 90^o towards 135^o, the proportion of air entering into the atrium space through the rooftop windows increases.

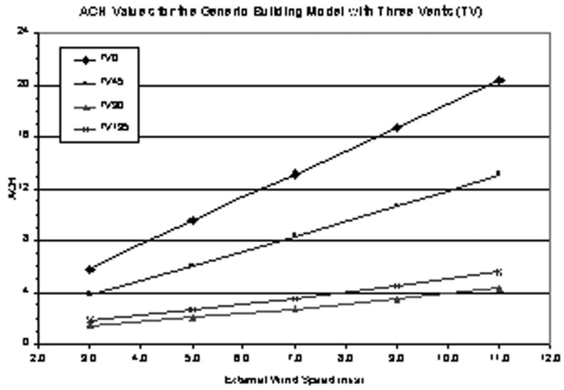

Figure 3: Predicted ACH values based on the entire building volume, as a function of external wind speed, for all wind directions and the model (TV) containing three vents.

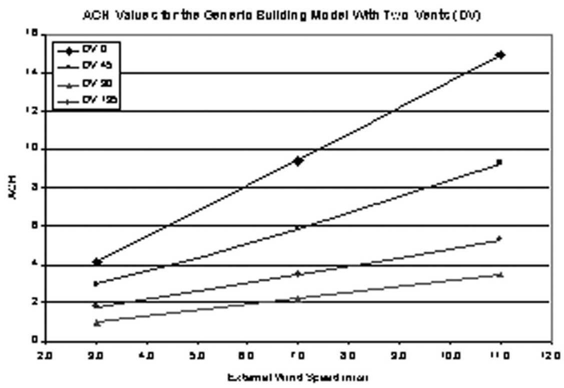

Figure 4: Predicted ACH rate as a function of external wind speed, for all wind directions and the two vent model (DV).

4.2 External Wind Direction

The external wind direction was found to have a significant affect on the ACH rate. The extent of this affect was found to be dependent on both wind direction and the number of vents used in the model. The ACH rates were found to decrease rapidly once the wind direction moves from 0^o to 90^o (as defined in Fig. 2). Between 90^o and 135^o, the ACH rates increase as the direction approaches 135^o. This was the case for all wind speeds and is irrespective of the number of side vents used in the model. The relationship between ACH and wind direction over the range of 0^o to 135^o is non-linear for all models. However, the relationship between 0^o and 90^o may be reasonably approximated by a linear function. This may be seen in Figure 6, a plot ACH rate against external wind direction. For an external wind speed of 5.0 m.s^{-1}, airflow in through the windows accounts for only 6.3% of the total airflow into the building when the wind direction is 90^o. In comparison, when the wind direction is 135^o airflow in through the windows accounts for 56.3%. Similar airflow values were found for all model configurations and external wind speeds.

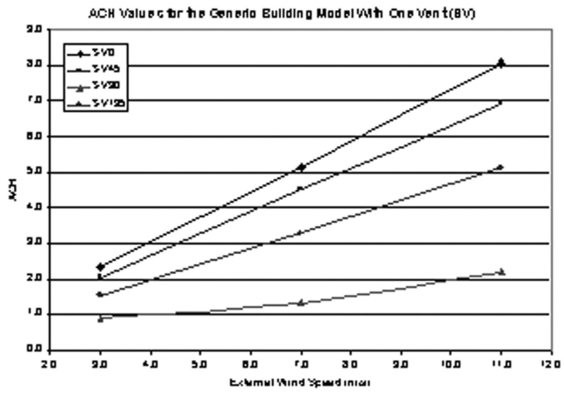

Figure 5: Predicted ACH rates as a function of external wind speed, for all wind directions and the single vent model (SV).

The double vent model (Model DV) produced similar trends to those of the triple vent model (TV) with ACH rates decreasing almost linearly with wind direction between 0° and 90°. Examining Figure 7, the ACH rate for the double vent model (DV) are observed to decrease by between 3.1 and 11.5 ACH between 0° and 90°, for wind speeds between 3.0 and 11.0 m.s^{-1}. This is equivalent to decreases in ACH of approximately 77%. As the wind direction moves past 90° and towards 135°, the ACH rate is observed to increase for all three external wind speeds by between 0.8 and 1.8 ACH, equivalent to increases of between 78% and 52%. This increase in ACH rate is due to a significant rise in the airflow entering the atrium space through the rooftop windows due to the direction of the approaching wind. For the triple vent model (Model TV) with an external wind speed of 5.0 m.s^{-1}, airflow in through the windows accounts for only 6.3% of the total airflow into the building when the wind direction is 90°. In comparison, when the wind direction is 135° airflow through the windows accounts for 56.3%. Similar airflow values were found for all model configurations and external wind speeds.

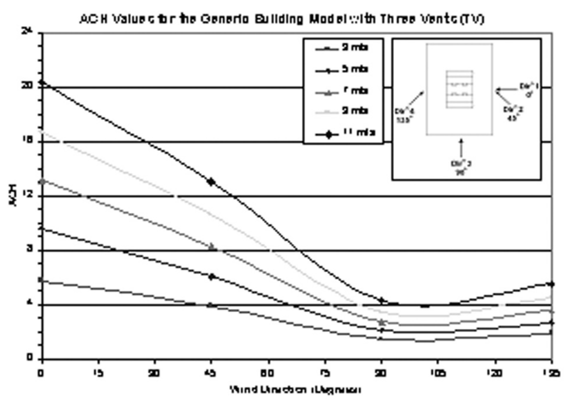

Figure 6: Predicted ACH rate plotted against wind direction for the triple vent model (TV).

The results for the single side vent model (Model SV, Fig. 1d) are shown in Figure 8, where considerable non-linearity is observed between ACH and wind direction over the entire wind direction range. Relatively small decreases in ACH rates of 0.3 ACH (a 13% decrease) and 1.1 ACH (a 14.5% decrease) are observed for external wind speeds between 3.0 and 11.0 m.s^{-1} respectively when wind direction changes from 0° to 45°. A more considerable decrease is observed from 45° to 90° where the ACH rate was found to decrease by 1.2 ACH and 4.7 ACH for external wind speeds between 3.0 m.s^{-1} and 11.0 m.s^{-1} respectively. This is equivalent to a decrease in ACH of between 56% and 68%. As with the double (DV) and triple (TV) vent models once the wind direction moves past 90°, the ACH rate increases rapidly for the single vent model (SV).

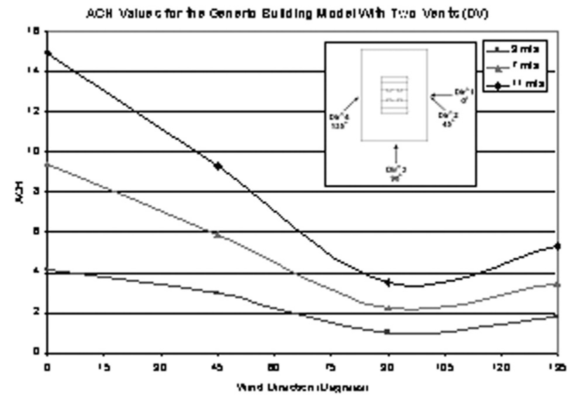

Figure 7: Predicted ACH rate plotted against wind direction for the double vent model (DV).

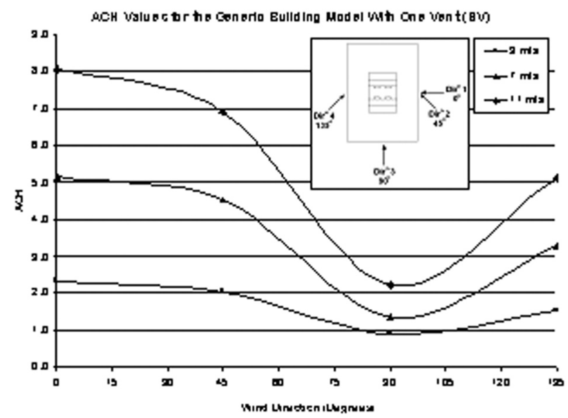

Figure 8: Predicted ACH rate plotted against wind direction for the single vent model (SV).

5. CONCLUSIONS

External wind speed was found to have an appromimately linear relationship with ACH rate for all wind directions irrespective of the number of side vents included in the model. The ratio of the ACH rate at 3.0 m.s^{-1} to those at

7.0 and 11.0 m.s^{-1}, was found to be similar for all wind directions and models (SV, DV and TV). This indicates that external wind direction has little effect on the extent of the change in ACH rate caused by an increase in external wind speed. The average ratio of the ACH rate at 3.0 m.s^{-1} to those at 7.0 and 11.0 m.s^{-1} for all models and wind directions was found to be approximately 2.1 and 3.2 ACH respectively. The external wind direction, relative to the generic building, was found to significantly affect the ACH rate. The relationship between wind direction and ACH rate for the three (TV) and two vent (DV) models was found to be almost linear for wind directions between 0^o and 90^o, whilst the single vent model (SV) exhibited a non-linear relationship for the same wind direction range. The difference in trends between the single vent model and those of the double and triple vent models was a result of the positioning of the single vent relative to the airflow pattern established around the building. With the ACH rate having decreased as the wind direction moved from 0^o to 90^o for all three models, the ACH rate was then observed to increase once the wind direction went beyond 90^o for all three models. This increase in ACH rate with external wind direction was caused by increased airflow entering into the building through the rooftop vents. The ratio of the ACH value for a wind direction of 90^o to that for a wind direction of 45^o was found to be 2.93, 2.74 and 2.93 for the single (SV), double (DV) and triple (TV) vent models respectively, when averaged across all wind speeds. This means that a change in wind direction from 90^o to 45^o caused the ACH rate to almost triple depending on the number of vents included in the model. In comparison, a change in wind direction from 90^o to 135^o caused the ACH rate to as much as double, depending on the number of vents included in the model. More generally, the significant variations in atrium ACH with external wind direction illustrates the importance of considering wind direction when designing for adequate ventilation in NV buildings.

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