VENTILATION TECHNOLOGIES IN URBAN AREAS

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WIND DRIVEN VENTILATION IN COURTYARD AND ATRIUM BUILDINGS IN URBAN AREAS

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SYNOPSIS

A wind tunnel study was carried out to investigate the airflow through courtyard and atrium building models. Ventilation strategies resulting from the use of different atrium roof pressure regimes (positive pressure and suction) were examined and compared with the performance of the open courtyard. The model buildings were monitored both in isolation and in idealised urban environments of varying group layout densities. The effect of wind direction was also observed. The results from the study suggest that the open courtyard in an urban environment had a poor ventilation performance whilst an atrium roof with many openings operating under a negative (suction) pressure regime was the most effective. Changing the wind direction from perpendicular to the building façades to a 45° incidence angle had the effect of making the differences in the observed flows between all the models much smaller.

INTRODUCTION

The use of natural ventilation in non-domestic buildings is now seen as a sustainable approach to providing acceptable internal environments for building users. There has been much recent work in the UK [1] and Europe [2] to develop a better understanding of natural ventilation and to produce relevant design tools for engineers and architects. One building type that has been considered to offer great potential for natural ventilation is the atrium. It is has proved such a popular form since its 'reinvention' in 1967 with the construction of the Hyatt Regency Hotel in Atlanta that it is now unusual to find a new commercial building that does *not* contain some form of atrium.

The atrium building utilises both stack and wind forces to generate air flows through the room spaces adjoining the atrium well. In summer the stack force can be dominant and the atrium well acts as a chimney to vent warm air out of rooftop openings. For other times of the year wind forces may create pressure gradients between the outer façades of the building and the inner façades facing the atrium well. A complex mix of parameters will determine the magnitude of the wind-induced airflows. These include the magnitude and distribution of the pressure coefficients around and inside the atrium building, the leakage characteristics of the façades, the shape of the roof over the atrium well and the sheltering effects of surrounding buildings. For atrium buildings sited within a congested urban area the sheltering effect may be so great that external wind-induced pressures on the building's walls will be very small. Under these circumstances the atrium roof can be the key element for generating sufficiently strong positive or negative pressure gradients to induce satisfactory natural ventilation flows. The influence that atrium roof form, wind direction and surrounding buildings have on air flow through atria is the subject of this study, which was conducted using building models in a wind tunnel.

BACKGROUND

The use of roof elements to enhance the ventilation of buildings in built-up areas is not new. Wind towers and wind catchers have been prevalent in the Middle East and North Africa for hundreds of years, and have formed a key component of the indigenous architecture of those regions. Figure 1 shows traditional wind towers from Iran [3].

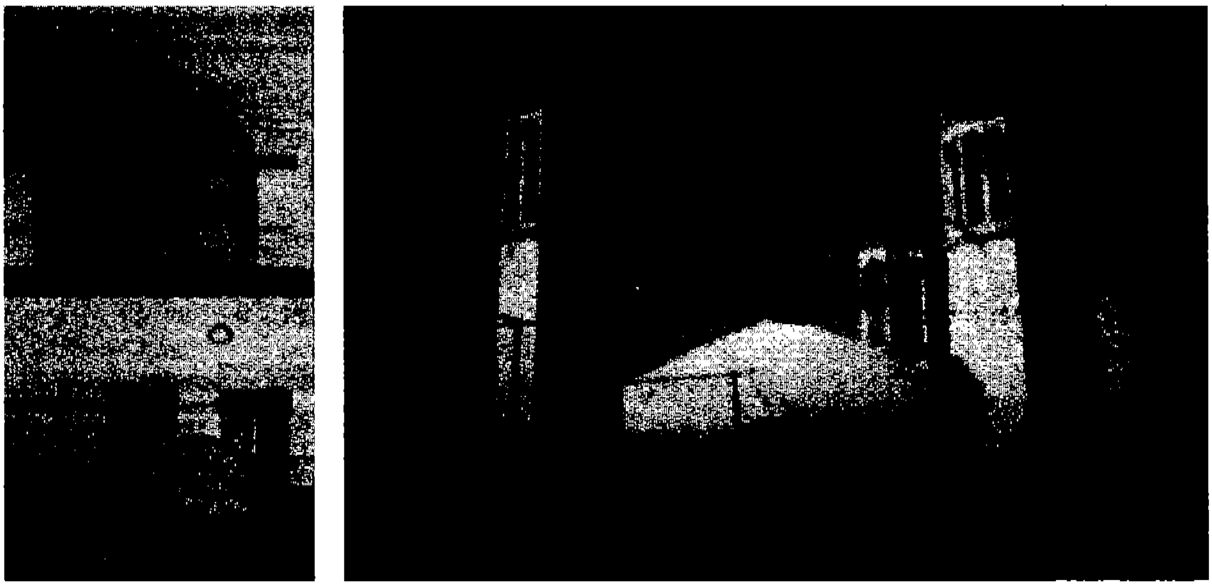

Fig.1 Wind towers of Iran (from [3])

Vents incorporated into the roof ridge and eaves provide a more integrated solution. Baumann et al [4] used a wind tunnel to investigate a 'jack roof' configuration for densely packed housing in hot humid climates, with vents placed in the sides of an elevated roof ridge. The jack roof was found to be effective in inducing internal air movement. A study by Riskowski et al [5] of the airflow performance of a range of commercial and fabricated ridge vents provided quantitative data for a range of wind speeds and directions.

The shape of the roof can also have a major role in inducing internal air movement. Kindangen et al [6] performed a CFD analysis of ten roof configurations to study their impact on airflow velocities and distributions. For the isolated, cross-ventilated dwelling modelled the shape of the roof did have an effect on the airflow patterns, and, in particular, air velocities. Wind direction, roof overhangs and roof heights were also important influences on airflow. Some studies of ventilation in atrium buildings have been carried out, mainly as either wind tunnel or CFD [7]. Most such studies have tended to investigate either isolated building models or have been trying to apply the results to a particular actual full-scale building. Little work has been done on a parametric analysis of the interactions between several factors, such as roof shape, atrium ventilation mode, wind direction and surrounding buildings. Such a parametric analysis would help identify the best combination of design parameters to maximise the benefits of wind-driven natural ventilation in atria. The experimental details of just such a parametric study are given below.

EXPERIMENTAL PROCEDURE

In order to evaluate the wind-driven natural ventilation in courtyards and atria in an urban setting a range of model buildings were constructed, instrumented and then positioned in a boundary layer wind tunnel.

Building models

The models represented four storey courtyard and atrium buildings at a scale of 1:100. The models measured externally 339 x 339 x 130mm high. The central courtyard / atrium was square in plan with the sides being equal to the height of the building (i.e. 130 x 130 x 130mm). The model walls representing room depth were 104mm deep. Monopitch roofs were placed over the courtyard opening to produce a range of ventilation strategies. Each roof was 52mm high, giving a roof pitch of just under 22°. The models were constructed from Perspex and consisted of rectangular building block modules that could be fixed together to create a range of model types. Together with the courtyard (model A0), four atrium roof ventilation strategies were to be investigated:

a)	closed roof	[model A1]
b)	suction	[models A4 and A5]
c)	positive pressure	[model A6]
d)	near atmospheric	[model A7].

These strategies, which were all achievable with the monopitch roofs, are shown schematically in Fig. 2.

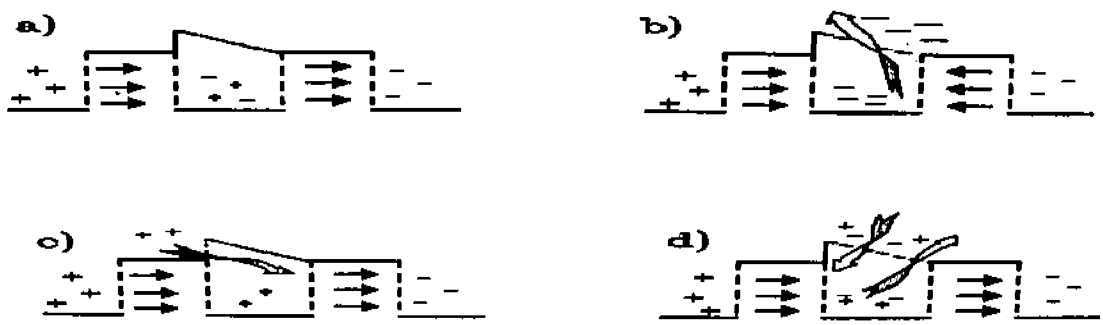

Figure 2 Atrium roof strategies for wind-driven ventilation

The models' walls and roofs were perforated with 10mm diameter holes to simulate building leakiness. The porosity of the walls (hole area to total façade area) was 11.4%. The porosities of the monopitch roofs (relative to the total façade area) were 0% for the closed roof (model A1), 11.4% and 30.4% for models A4 and A5 respectively, 11.4% for model A6 and 30.4% for model A7. Airflow rates through the models were measured directly with a specially made orifice plate device that was incorporated into one of the modular Perspex building block modules. The device was a square edge plate of 17mm diameter inserted between two short brass pipes of 25mm diameter, and fitted with two corner pressure tappings. The pressure drop across the tappings was measured using a digital manometer. The orifice plate was calibrated, in its Perspex container, against a precision commercially available flowmeter with an accuracy traceable to national standards. The dynamic pressure in the tunnel at gradient boundary height, together with the internal pressure in the atrium well at mid height, were also recorded. The flows through each model were monitored on each floor and on each façade of the model at two locations positioned centrally. The error in flow observations was estimated at approximately ±10%, reflecting the fluctuations of the manometer signals. The measurement arrangement is shown schematically in Figure 3 and the actual orifice plate located in an atrium model is shown in Figure 4.

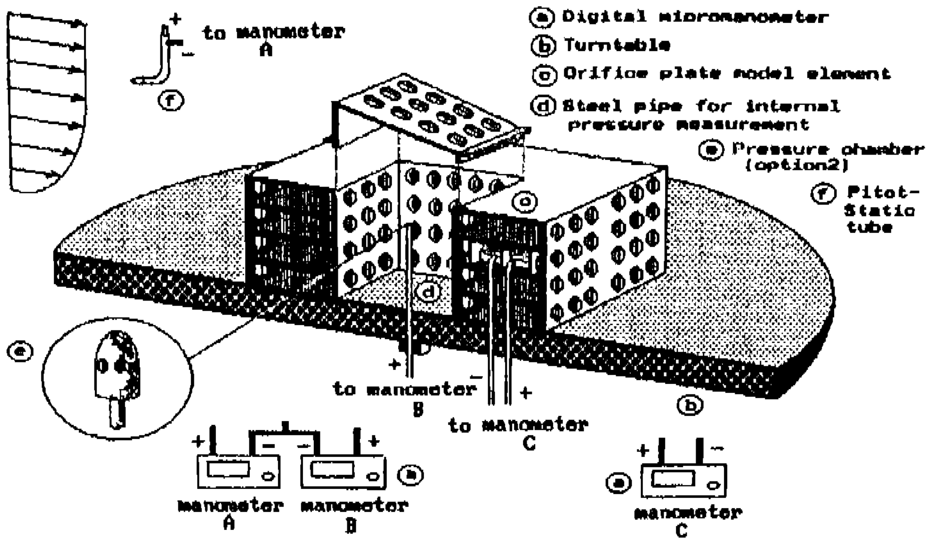

Figure 3 Schematic of measurement arrangement

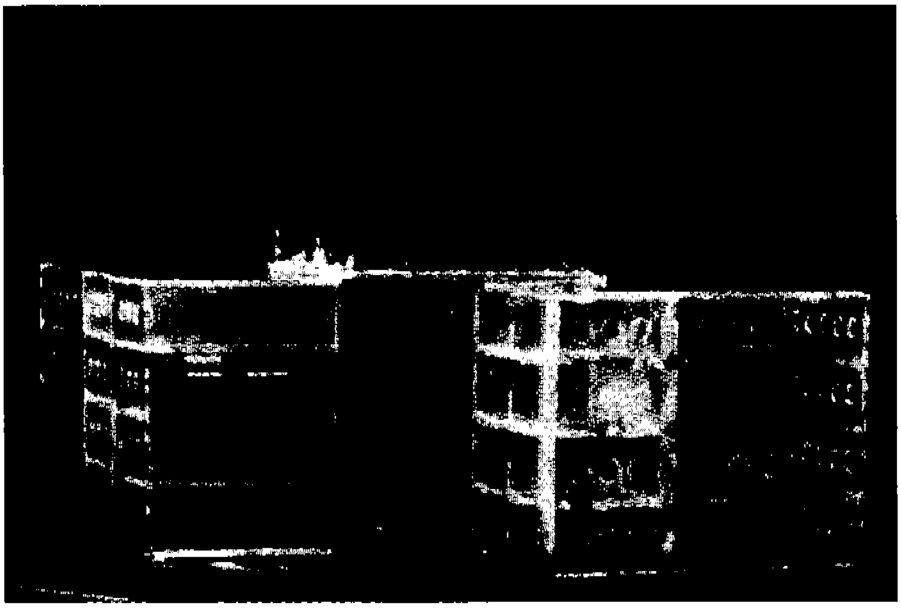

Figure 4 Orifice plate located in building model

The wind tunnel

The instrumented model was placed at the centre of a 1.1m diameter turntable in an atmospheric boundary layer wind tunnel. The turntable allowed two wind directions (0° and 45°) to be investigated. The tunnel had a working length of 7.2m with a cross-section measuring 1.2 x 1.2m, and a maximum gradient speed of 25 ms^{-1}. A series of spires, castellated fence and roughness elements in the wind tunnel generated a suburban type velocity profile at the turntable with a gradient height of 800mm and a power-law exponent of 0.245. The urban environment around the model was simulated by surrounding the model with rectangular wooden blocks of the same dimensions as the model, where the height of each block, H, was the same as the eaves height of the atrium and courtyard models. The blocks were arranged in either a uniform or staggered (checkerboard) arrangement. The wall-to-wall spacing between the blocks, Sc, was set at 1.5 and 2.3 times the building height H. The lateral spacing, L, was set to 0.5Sc for the staggered arrangement and to Sc for the in-line layout. These arrangements gave group layout densities of 0.28 and 0.40 for the uniform layout and 0.48 and 0.60 for the staggered layout. Group layout density is defined as the ratio of building plan area to building site area. A set of measurements was also made on all the models in isolation with no surrounding buildings.

The blocks were laid out to a fetch radius of 15H (three rows of blocks upstream and three rows downstream) as test results showed no change in measured airflows above this fetch value. The blockage in the tunnel was up to 8% at normal wind incidence (0°) and up to 11% for the 45° wind incidence direction. Although these values are a little high it was decided to apply no corrections to the results.

Each model was secured to the wind tunnel turntable and the required layout put in position. The tunnel was run for one hour to allow flow and temperature conditions to stabilise. The wind tunnel was run at its maximum gradient speed of 25 ms^{-1}, which corresponded to a speed at model eaves height of 16.4 ms^{-1}. These high speeds were used to ensure the highest Reynolds numbers possible. Each measurement consisted of logging the pressure drop across the orifice plate whilst simultaneously recording the dynamic pressure in the tunnel at the gradient height of 800mm with a pitot-static tube. The results were expressed as a non-dimensional flow coefficient CQl:

$$CQl = Q / (A \times V_{800}) \qquad (1)$$

where Q is the flow through the orifice plate, A is the area of the openings in the model room block and V_{800} is the reference gradient wind speed. In other words, CQl represents the ratio of the velocity at an opening in the model to the gradient velocity. CQt was used to represent the average of all the CQl values measured on each model.

RESULTS AND DISCUSSION

The results of the experiments will be discussed in terms of the average model flow coefficient CQt and the minimum value of CQl observed in each model for the two wind directions.

At 0° wind angle

Among the structures tested, the courtyard model A0 had the poorest ventilation performance. For any of the urban layouts the CQt values were typically between 0.065 and 0.071, compared to a value of 0.126 for the courtyard in isolation. The minimum CQl was very low, being measured at one location at 0.02.

The closed roof atrium model A1 showed a slightly improved performance over the courtyard, with CQt values from 0.062 to 0.093 in the urban layouts (compared to 0.147 for the isolated case), and a minimum CQl of 0.04. However, the distribution of the flows within the closed model was uneven, with weak ventilation flows identified on the leeward side of the atrium. This suggested that improved ventilation could be achieved by encouraging flows to enter via the roof.

Atrium models A6 (with a porosity of 11.4%) and A7 (with a porosity of 30.4%) operated under positive and near atmospheric roof pressure regimes respectively and demonstrated better air flow characteristics than the previous models. Model A6 had CQt values from 0.086 to 0.119 (0.179 in isolation), whilst model A7 had CQt scores from 0.070 to 0.126 (0.162 in isolation). Minimum flow values for both models were raised to around 0.06.

Atrium models A4 and A5 both operated under a roof suction regime, with A4 having a porosity of 11.4% and A5 a porosity of 30.4%. This roof suction mode was in conflict with the negative pressure forces that were generated on the leeward walls of the model. As a consequence the CQt values for the low porosity roof A4 displayed little or no improvement over the other models, with a range of 0.083 to 0.088. The much greater roof porosity of model A5 created larger roof suction flows and removed the problem of the negative leeward wall pressures. CQt values were now found to be from 0.131 to 0.139, with a minimum CQl never falling below 0.10. It was observed that some of the CQt values were slightly higher for model A5 in an urban layout than when in isolation. This is thought to indicate that the negative leeward wall pressures may have been reduced in magnitude as the group layout closed up.

At 45° wind angle

Two major changes were observed when the wind direction was altered to 45°. Firstly, most of the CQt values for the models increased –that is, the ventilation performance of the models improved. Secondly, the range of CQt values between the different atrium and courtyard models for a given group density became much narrower, being typically within ±10% of the mean value for all models. The average CQt values were approximately 0.15 at a group density of 0.28, 0.12 at 0.40 and 0.48 densities and 0.09 at 0.60. The high porosity suction roof of model A5 still performed slightly better than the other arrangements, but the magnitude of the improvement was only significant for the highest group density value. The detailed results from the experiments are presented in Table 1, where the change in the CQt values produced by the sheltering effects of the urban layout are quantified. Figure 5 also includes the minimum values of CQl observed on each model.

Table 1 Average flow coefficients CQt for uniform (U) and staggered (S) group layout densities (D) and wind directions 0° and 45°

	CQt		CQt		CQt		CQt		CQt	
	Isolation		**U, D = 0.28**		**U, D = 0.40**		**S, D = 0.48**		**S, D = 0.60**	
Model	**0°**	**45°**	**0°**	**45°**	**0°**	**45°**	**0°**	**45°**	**0°**	**45°**
Courtyard A0	0.126	0.179	0.074	0.144	0.071	0.118	0.065	0.126	0.057	0.084
Closed roof A1, 0%	0.147	0.188	0.093	0.153	0.086	0.124	0.080	0.119	0.062	0.091
Suction roof A4, 11.4%	0.140	0.166	0.085	0.145	0.087	0.114	0.088	0.122	0.083	0.095
Suction roof A5, 30.4%	0.135	0.159	0.134	0.137	0.136	0.127	0.139	0.135	0.131	0.124
Positive roof A6, 11.4%	0.179	0.189	0.108	0.159	0.119	0.127	0.086	0.117	0.098	0.094
At. pres. roof A7, 30.4%	0.162	0.162	0.126	0.126	0.100	0.100	0.104	0.104	0.070	0.070

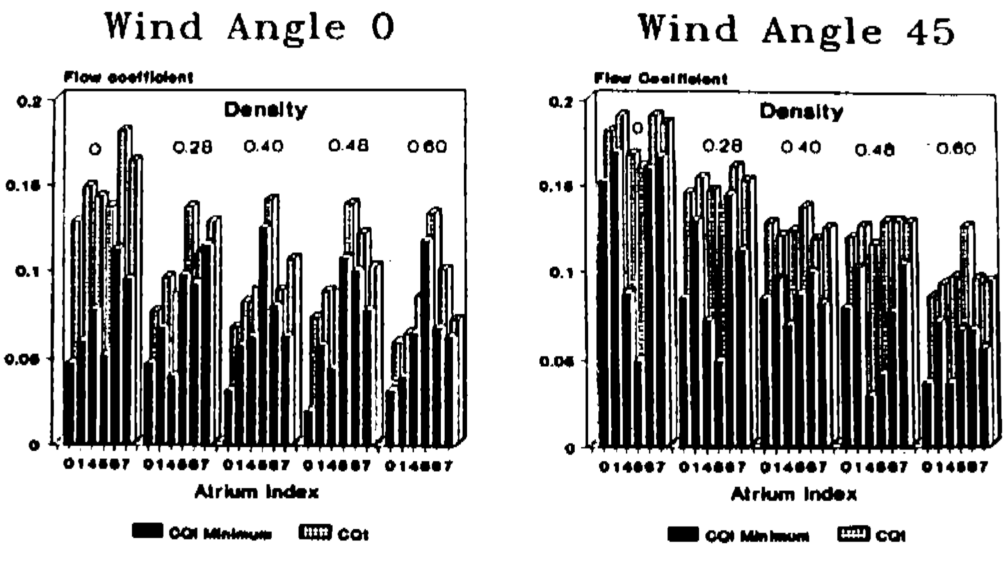

Figure 5 CQt and minimum CQl values (0 density is models in isolation)

CONCLUSION

This study has investigated the ventilation performance of courtyards and atrium buildings in isolation and in urban group layouts. An open courtyard in urban areas was found to have a weak ventilation performance, particularly when the courtyard was perpendicular to the oncoming wind. Covering the courtyard with a porous roof to form an atrium enables the large pressure fields on the roof to provide stronger ventilation pressure differentials. Roofs positioned to experience positive or near atmospheric pressure conditions performed less well than roofs exposed to negative pressure forces (suction) when winds are perpendicular to the buildings. At an oblique wind direction (45°) most of the atrium roofs performed to a similar standard. There are two major problems with using atrium roofs as ventilation devices in urban areas. Firstly, to use the weaker positive pressures requires large surface areas of roof and / or a great number of openings. Secondly, for the suction roofs the negative pressures on the leeward side of the building counteract the negative pressures on the roof. More efficient ventilation roof design may involve exploiting Venturi effects or vortex generation at roof leading edges where accelerated flows could be utilised.

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