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Static split duct roof ventilators

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Split-duct roof ventilators or windcatchers are used to provide both supply and extract ventilation to the spaces which they serve. However, buildings are often erected in conditions where there is no prevailing wind direction. An investigation into four and six segment windcatchers to determine their relative performances under different wind conditions was undertaken usind scale models in a wind tunnel. Conclusions indicate that six segment windcatchers have a more predictable, reliable performance in uncertain or variablewind conditions. However, a four segment windcatcher that is orientated 45 degrees to the prevailing wind will generate the highest pressure differences and consequently the highest duct speeds in an installation. Further work on strategies for windless conditions are summarized, and scope for further research is indicated.

On utilise des ventilateurs de toit à fentes ou des capteurs de vent dans le but à la fois d'alimenter et d'évacuer l'air des locaux pour lesquels ils sont prévus. Cependant, les bâtiments sont souvent érigés dans des conditions où il n'y a aucune direction de vent dominante. Des recherches ont été menées en soufflerie sur des capteurs de vent à quatre et à six segments afin de déterminer leur fonctionnement relatif dans des conditions de vent différentes en se servant de maquettes en soufflerie. Les conclusions indiquent que les capteurs de vent à six segments ont des performances plus prévisibles et fiables dans des conditions de vent incertaines ou variables. Cependant, les ventilateurs à quatre segments orientés à 45 degrés par rapport au vent dominant, produiront la différence de pression la plus haute et par conséquent les vitesses de transmission les plus élevées dans une installation.

Keywords: natural ventilation, ventilators, ducts, wind, alternative technology

Introduction

There is increasing interest in providing natural ventilation in buildings. This has arisen out of a concern to reduce building energy consumption by avoiding the use of fans and air conditioning in the summer months. Natural ventilation is also perceived to be healthier than air conditioning.

Diurnal cooling using natural ventilation has been extensively studied. High rates of airflow at night are required. Typical examples are given in CIBSE Applications Manual AM10 (1997). A recent example is the highly successful BRE environment building (Watford, UK), engineered by Max Fordham and Partners.

It is usually possible to ensure natural ventilation through windows and vents in buildings by exploiting the pressure differences created by the wind and the pressure differences created when internal and external air temperatures are different. It should be noted that while the former can be substantial, the latter are relatively slight and depend on the height of a column of warm air relative to an equivalent column of external cool air.

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Means of calculating driving pressures are given in the CIBSE Applications Manual. More complex calculations are given by Etheridge and Sandberg (1996). Many buildings that are ventilated in this way have been modelled and tested using CFD programmes prior to construction.

Internal spaces which are designed to be ventilated using pressure differences created by the differences in air temperatures must be provided with inlets at low level. Windows or vents must be provided at all levels to buildings ventilated by wind induced pressure differentials.

Top down ventilation

There are cases when it is inadvisable or impossible to ventilate through the building facade. In urban areas, buildings face onto roads and carparks which generate gaseous, particulate and noise pollution. Opening low level vents can also present a security risk. Some building types are best organized with deep plans where spaces are remote from external walls. There are good reasons for taking air in and out of buildings from the top. There are historical precedents as to how to do this, the best known are Middle Eastern and Indian windcatchers. The traditional windcatcher is often represented as a scoop facing a prevailing wind to discharge air down into a building through a large masonry duct (Beasley and Harverson, 1982). This type of windcatcher is shown in Fig. 1. The device is unidirectional and can provide a form of wind assisted displacement ventilation when the wind is blowing from the design direction.

It can be argued that detailed meteorological data is available for most sites and that this will give wind speed and direction. This information is of substantial value. Nevertheless the wind blows, in most places, from directions other than the prevailing direction for a significant amount of time. This problem is compounded in urban areas by inadvertent climactic modification which can give local airflows which are significantly different from prevailing directions and are dependant on surrounding buildings which may be erected or demolished (Oke, 1978).

The fixed scoop windcatcher will fail when the wind blows from a direction other than the design

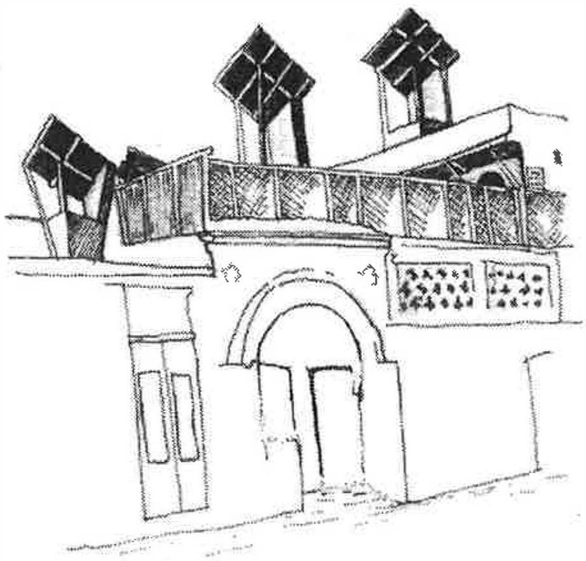

Fig. 1. A traditional middle eastern windcatcher (after Beazley and Harverson).

range unless the air entry point in the space that is served is at sufficiently high level for the buoyancy drive to overcome adverse wind conditions. If this is the case it is possible to envisage that a column of warm air will form in the flue and that the airflow will reverse.

Other traditional and modern types of windcatcher, shown in Fig. 2, supply and extract air through the same fitting. It is a bluff body placed in the airstream. A pressure difference is induced between the windward and leeward faces in all wind directions. The device contains a four way split duct. Air enters the building on the windward side of the device and exits on the leeward side. The direction of the airflow in an individual duct under this type of windcatcher varies – it is entirely dependant on the direction of the wind. Inlets and outlets are ceiling mounted and, as a result, true displacement ventilation does not occur – see Fig. 3. Investigations by the Building Research Establishment (1999) have demonstrated that this type of ventilation device is effective in inducing acceptable ventilation rates throughout a space.

Because the devices which are commercially available split the intake into four quadrants, they present very different intake conditions depending on the wind direction. There are historical precedents for split duct windcatchers in Iran, in the form of large masonry towers (see Fig. 4). These

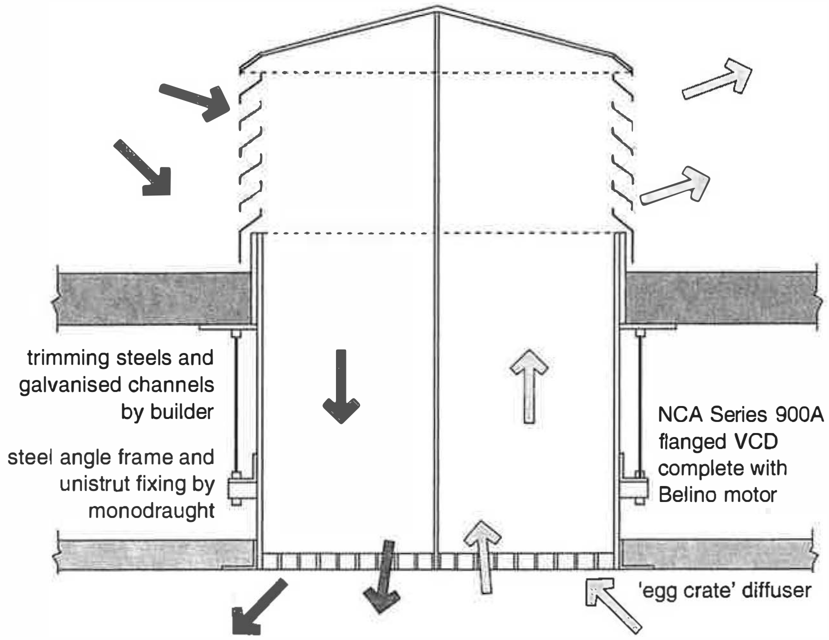

Fig. 2. A recent proprietary windcatching device..

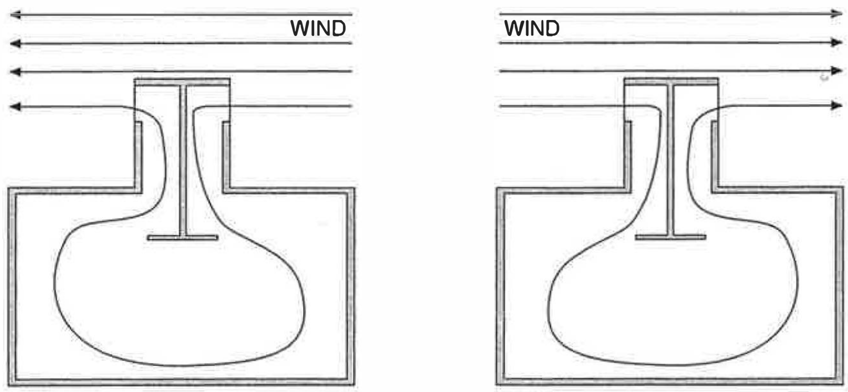

Fig. 3. A windcatcher inducing airflows in a space.

are not necessarily four way, many other forms were used (see Fig. 5). It seems likely that there were good functional reasons for this. Multi-faceted windcatchers with more than four faces are likely to have more consistent intake characteristics.

The paper describes a series of experiments which establish the different pressure and flow characteristics of a four way and a six way split duct windcatcher. Calculations based on the experiments can be used to predict the performance of these devices in different external airflow conditions with different levels of resistance below them. The main experiments have measured the static pressure difference between the relevant wind-catcher duct and the external atmosphere for different controlled flow rates either in or out. These results may be combined with estimates of the resistance to the ventilation flow through any proposed building beneath the windcatcher to give a prediction of flow rate. The last experiment measured flow rate from inlet to outlet of the model windcatcher under conditions approximating a windcatcher with a high level of reistance in the rest of the circuit. But in general the experiments were not set up to simulate the resistance of the flow through the building. These experiments are similar to other model experiments carried out previously to determine the effectiveness of unidirectional ventilators (McCarthy, 1996; Dunster and Pringle, 1997).

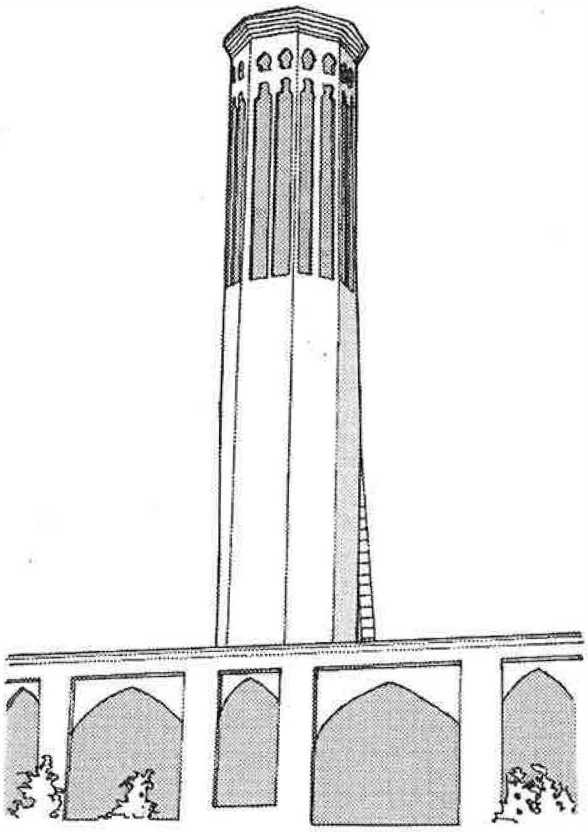

Fig. 4. Historical precedent for split duct windcatcher in Iran, in the forum of a large masonry tower (after Beazley and Harveson).

Experimental work

At full scale a windcatcher in the form of ventilation duct inlet and outlet sited in the same structure is often placed on the roof of the building it serves and is exposed to an incident shear flow. The onset flow is a combination of the incident atmospheric boundary layer (ABL), the wakes of neighbouring upstream buildings and the influence of the building itself on which it is sited. Thus the onset velocity $U_{\infty}(z)$ is a function of z the height above some datum. Because of the large range of building geometries on which a windcatcher may be placed it is not possible to formulate a generic study to incorporate all cases. Data for reference velocities at given sites are normally defined at a known height h, $V = U_{\infty}(h)$, where h is usually 10 m above ground level. It is also difficult to carry out ventilation flow studies at the very small scales (of order 1/200) usually required to simulate an ABL in a wind-tunnel. In the present tests, in order to avoid these issues of ABL simulation and building interactions the measurements were conducted in a uniform incident flow in a wind tunnel (i.e. incident wind shear was not modelled in the tests) with the model windcatcher mounted on a plane wall. Application of the results to a real situation must therefore take account of the actual onset flow at

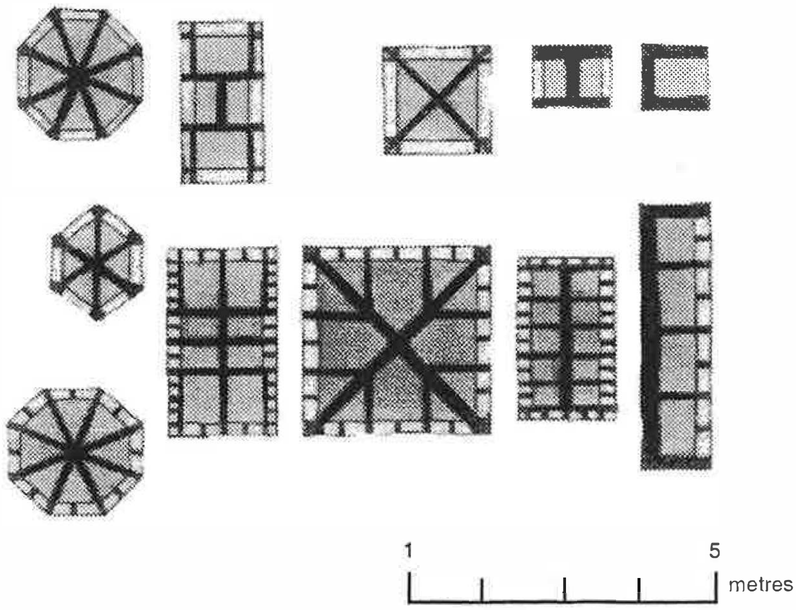

Fig. 5. Historical precedents for multi-way ducts in Iran (after Beazley and Harveson).

the proposed windcatcher site on the proposed building. This could be obtained reasonably accurately by standard wind-tunnel tests of the building, without representation of the ventilator system, and its environment at small scale with ABL simulation.

The experiments were carried out in a wind tunnel of the Department of Aeronautics at Imperial College on model wind catchers. The wind tunnel had a cross-section of 1.0 m × 0.6 m. The wind catchers were respectively a square planform tower of 0.2 m side and a hexagonal tower of the same cross-sectional area. The two windcatcher models are shown in Fig. 6. They may be considered to be models of the order of 1/10 scale to full size. The square planform wind catcher tower is sub-divided into four square ducts and the hexagonal one into six triangular ducts. The ducts communicate with a plenum chamber beneath each tower and the duct dividers which are surmounted by a plane roof may be moved up or down in the towers in order to change the heights of the apertures of the inlets and outlets at the tops of the towers.

Between the ducts and the plenum chamber are circular orifices in the base plate so that the duct flow rates can be measured from the pressure differences across them. The orifices are a large proportion of the area of the duct which they terminate in each case in order to minimize the pressure losses. Static pressure tappings are fitted to the side walls of two of the ducts and to the side walls of the plenum chambers, giving in all cases a representative mean pressure

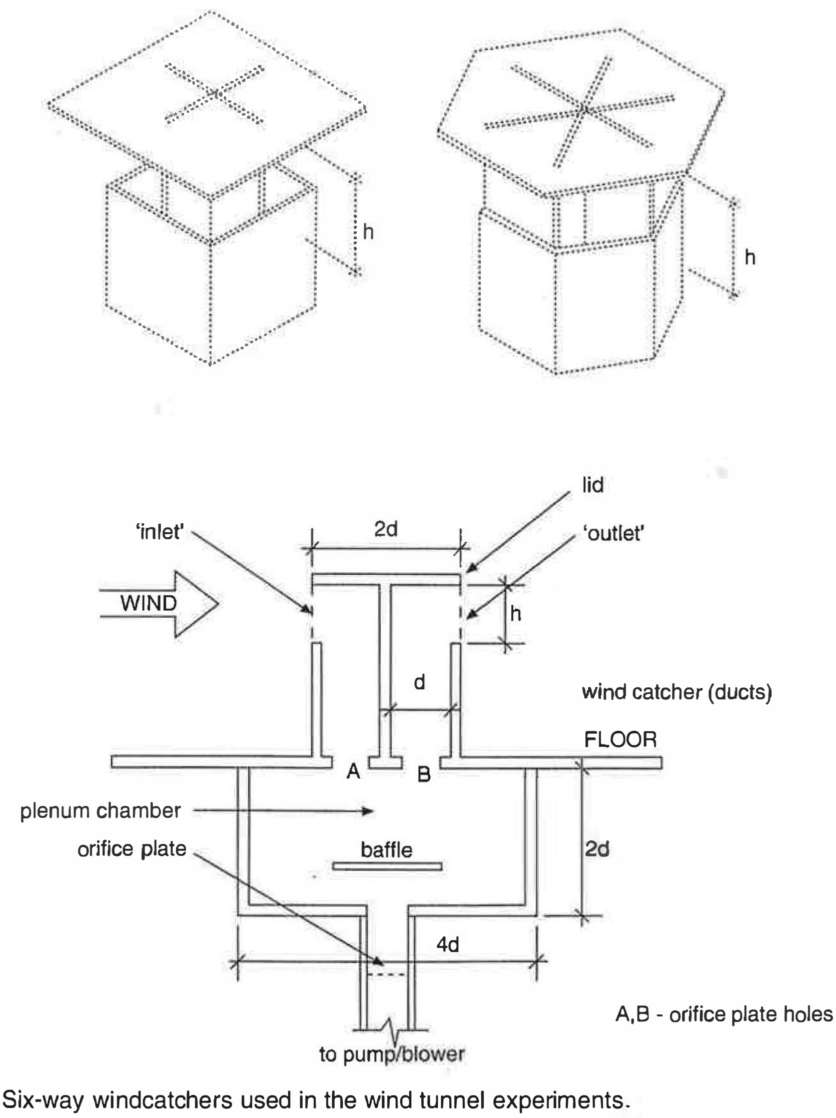

Fig. 6. Four and Six-way windcatchers used in the wind tunnel experiments.

reading for the component in which they are located. The windcatcher models were fixed to a false floor in the wind tunnel which minimized the thickness of incident boundary layer. This floor is the datum level in the wind-tunnel tests. If it is considered to represent a simplified building roof allowance must be made for local flow gradient and possible separations. Since the incident flow was uniform in these tests, the only significance of the datum level is that it defines the vertical dimension of the windcatcher tower.

Three types of experiment were conducted for each windcatcher. In order to obtain measurements of pressure drop for a range of flow rates the first two experiments were artificially controlled tests, carried out using a configuration which allowed the flow rate to be set independently of the external wind. The windcatchers were tested in turn standing on the false floor beneath which was the plenum chamber such that the windcatcher could be tested in any orientation to the incident flow. This plenum chamber was in turn attached to a controllable suction or blowing pump via a 3 cm pipe fitted with an orifice plate with pressure tappings on either side. This measured the total flow rate being extracted or supplied to the plenum. In addition the orifice plate in the base of each of the separate internal vertical ducts formed by the flow divider in the wind-catcher tower allowed the flow rate through that duct to be measured separately.

In the first experiment the under-floor device was switched to provide suction. All the orifice plates at the bottom of the ducts which indicated pressure below the free stream ambient (typically these were the more downstream ducts) which would therefore operate as outlets, were sealed so that the suction pipe took flow from the inlet ducts only, at a controlled set rate measured by the orifice plate in the pipe. The square tower was then tested for three orientations:

- With a face of the tower normal to the incident wind (two inlet ducts)
- At 22.5° from this (two inlet ducts)
- At 45° i.e. with a diagonal of the tower aligned with the wind (one inlet duct)

Similarly the hexagonal tower was tested:

- Face normal (one inlet duct)
- At 15° from this (two inlet ducts)
- At 30°, i.e. duct divider aligned with the wind (two inlet ducts)

In each case the duct inlet pressure difference from ambient was measured for two different heights of aperture to the ducts. This is taken as the vertical dimension of the exposed faces of the flow divider from the tops of the duct side walls to the flow divider roof or lid. In the first case, labelled (1), this facing inlet/outlet area had a height h equal to one internal square duct width d and in the second case (2) equal to twice it (i.e. $h = 2d$). Tests were carried out for three ratios of non-dimensionalzed duct flow rate to wind speed with the wind-catcher operating as a controlled inlet device alone.

In the second experiment the under-floor device was reconnected as a blower and the connections were made to the (more downstream) outlet ducts while the upstream, inlet ducts were sealed. The outlet duct pressure difference from ambient for the same combination of cases, as above, was measured with the wind-catcher operating as a controlled outlet device. The number of ducts operating as outlets was in each case equal to the total number of ducts in the device (4 or 6) minus the number already established as operating as inlets for that particular wind direction.

After these initial experiments a final experiment was conducted with a direct flow through the wind catcher approximating the situation that would occur in normal operation. The under-floor blower was disconnected altogether and the plenum orifice to it sealed. The externally driven wind then flowed into the plenum chamber via the inlet ducts, through it and out again via the outlet ducts so that the model wind-catcher operated as a complete inlet-outlet device ventilating the plenum chamber and simulating the full scale device. However in the model case the flow had to overcome a rather larger than representative resistance due to the presence of the internal orifice plates which were present in the circuit in order to measure flow rates. In this case both inlet and outlet duct pressures were measured together with the pressure differences across the internal orifice plates which provided flow rate values.

Results and discussion

The results of these three experiments are presented in Figs 7 to 10 and the performance of the combined device in Table 1. It should be noted that the nondimensionalized values of velocity in the duct (V_{duct}/U_∞) in column 6 are related to the values of nondimensional flow rate ($Q/\Sigma A_{tot}.\ U_\infty$) by the ratio of the total area of all the ducts together (ΣA_{tot}) to the cross-sectional area of the

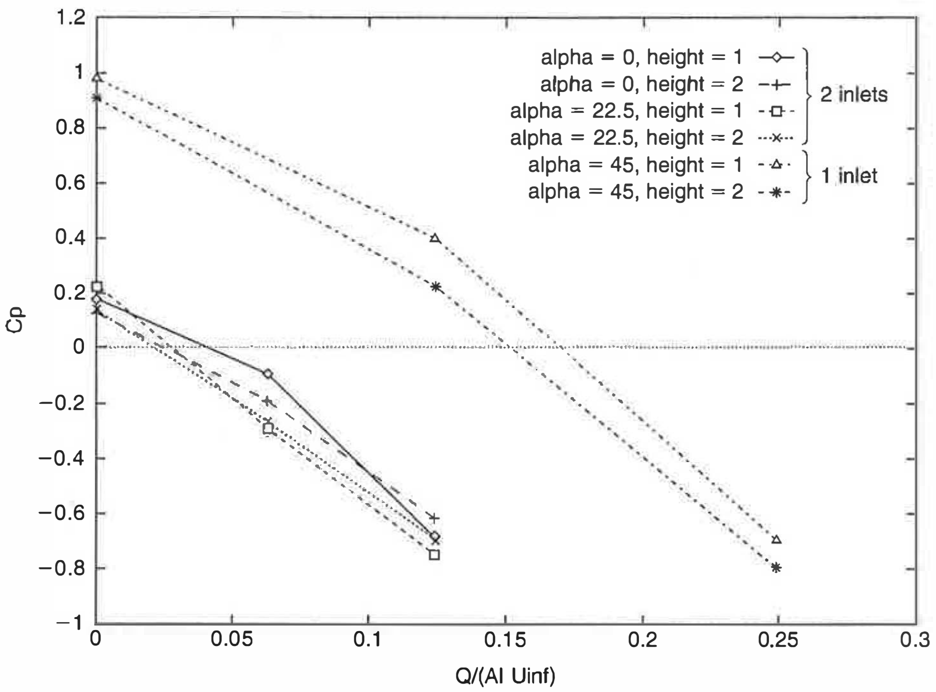

Fig. 7. Square section inflow test (expt 1).

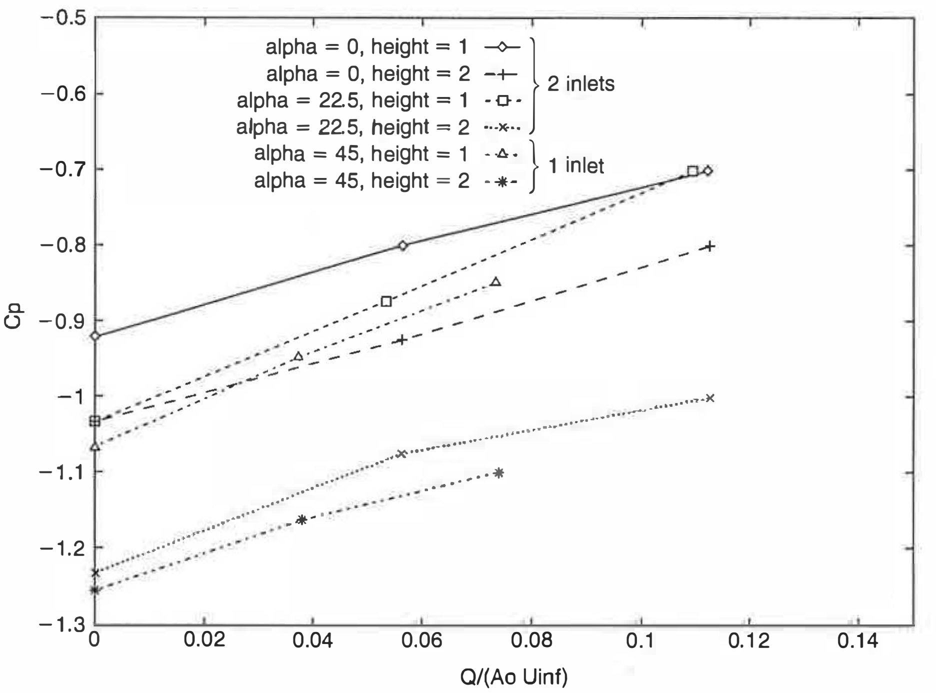

Fig. 8. Square section outflow test (expt 2).

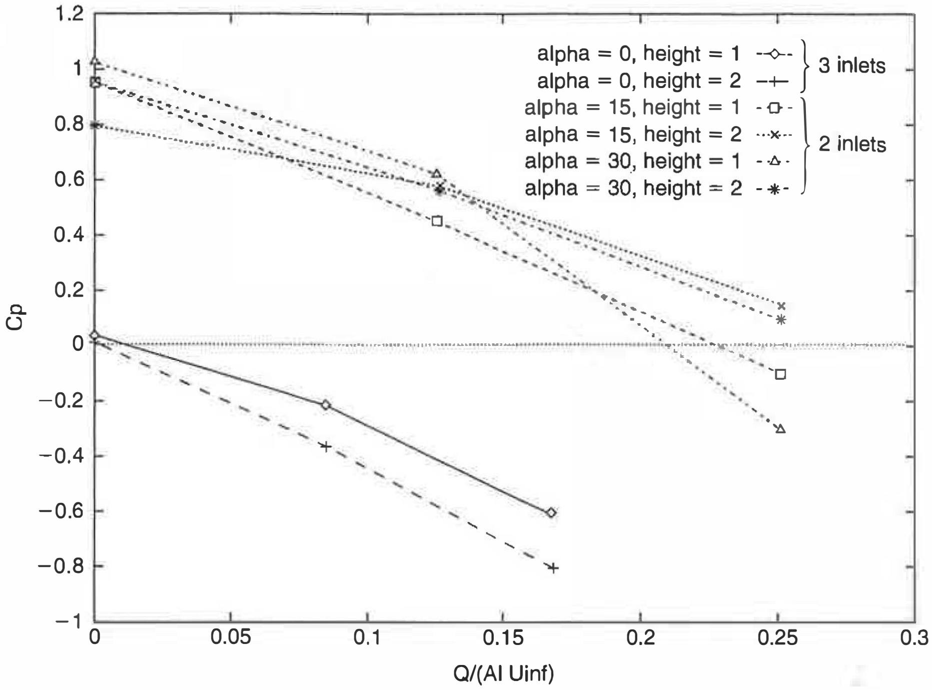

Fig. 9. Hexagonal section inflow test (Expt 1).

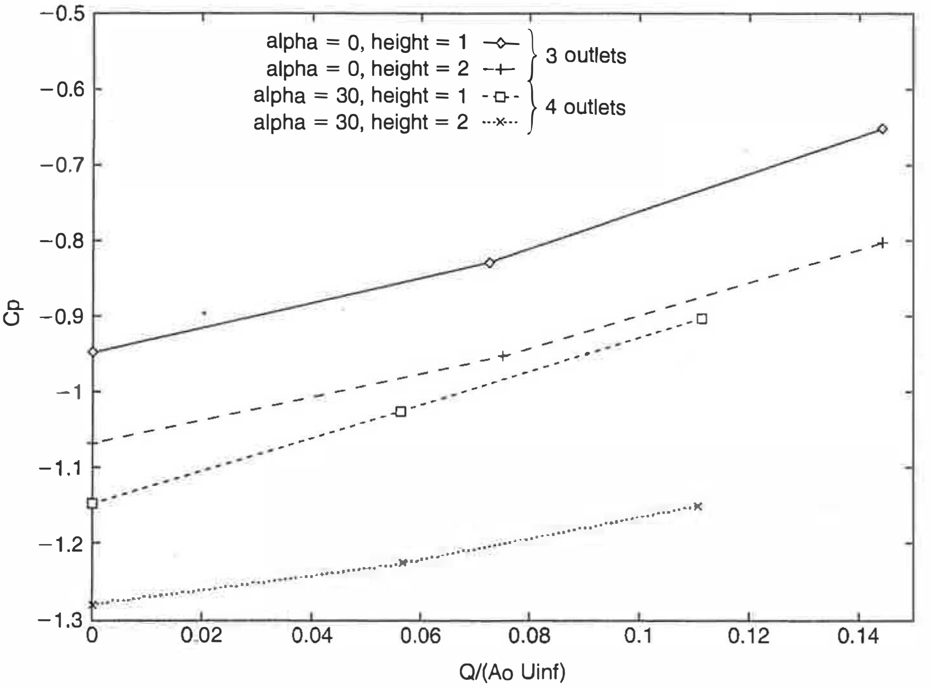

Fig. 10. Hexagonal section outflow test (Expt 2).

operating ducts for either inlet or outlet as appropriate. The pressure differences are expressed as pressure coefficients:

$$C_{\triangle p} = (p_1 - p_0)/1/2\rho V^2$$

versus the non-dimensionalized flow rates:

$$Q/V\sum A$$

where:

p_1 = static pressure in duct

Table 1. Combined device performance: intake and exhaust operating

Section	Height (h/d) configuration	Alpha (degrees)	No. of inlets operating	Flow rate Q/Atot.U∞	Vduct/U∞
Square	1	0	2	0.0447	0.089
	2	0	2	0.0525	0.105
	1	22.5	2	0.0531	0.106
	2	22.5	2	0.062	0.125
	1	45	1	0.062	0.250
	2	45	1	0.0662	0.265
Hexagon	1	0	3	0.0603	0.121
	2	0	3	0.0624	0.125
	1	15	2	0.0623	0.1873
	2	15	2	0.0689	0.207
	1	30	2	0.0709	0.213
	2	30	2	0.0709	0.213

p_0 = ambient static pressure in incident wind (except that in the third experiment p_1 is inlet duct pressure and p_0 outlet duct pressure.)

ρ = density of air

V = reference wind speed

Q = flow rate in duct

A = cross-sectional area of one internal duct

d = width of internal square duct

$\sum A$ = cross-sectional area of all operating ducts (expt. 1 or 2)

U_∞ = incident stream velocity

h = reference height from ground level, vertical dimension of wind-catcher opening from top of duct side wall to lid

z = height above ground datum

Subscripts: *tot* = sum of total duct area of wind-catcher, *duct* designates as appropriate either an inlet or an outlet duct.

Therefore $V = U_\infty$ and $C_{\Delta p} = (p_1 - p_0)/1/2\rho U_\infty^2$

As stated above the results for the third of the three experiments were obtained for flow through the model wind catcher opposed by the resistance of the orifice plate in the circuit. Because this is a significantly high resistance compared with the actual resistance likely to be in a typical ventilation circuit driven by a wind catcher ventilating, for example, a large atrium below it, the results for this case, in Table 1, have been adjusted to what would be predicted for zero resistance in the internal circuit. Columns 5 and 6 show these results further *corrected* assuming losses in the system equal to the dynamic head of the flow such as might occur if the inlet duct were exhausting abruptly into a large plenum (atrium).

The results as a whole show that as expected there is a drop in performance through the windcatcher (i.e. the driving pressure available from the wind catcher) as the flow rate through the windcatcher increases. This may be explained by the fact that on the upstream side the maximum available pressure is the stagnation pressure of the flow acting near the centre of the inlet, which only occurs for zero flow rate. As the flow rate into the device increases so this pressure rapidly falls below this maximum. Negative pressure coefficients occur due to the influence of the (inlet) ducts on either side where the pressure is very low and are sustained by the suction which controls the flow in this experiment. On the downstream outlet side the pressure (in the base region of the body) rises with the exhaust flow rate into the base region. This phenomenon is well known from studies of the effect of base bleed behind bluff bodies (Bearman, 1996). Comparison of the results for inlet flows and for outlet flows in isolation (Figs 7–10) show that they are consistent with the results for the overall inlet-outlet flow (Table 1).

The hexagonal tower shows a somewhat more uniform variation of performance with changing orientation compared with the square tower.

These wind tunnel tests were carried out in a uniform approach flow rather than in a simulated atmospheric boundary layer (ABL). In addition to reasons of simplicity and the large range of possible building interference mentioned above, it also avoids the problem that the zero datum of the incident wind profile to be simulated may not be ground level in a built-up area and depends on the type of site. Application of the results must take account of this either, as discussed, by incorporating results of wind-tunnel tests of the building and its neighbourhood in a simulated ABL or by more approximate estimates of the local flow around and over the building.

The wind tunnel results described here are at small scale and the Reynolds number is typically 5 to 10 times smaller than that which would occur at full scale. However because the major losses in the windcatchers themselves, i.e. the part surveyed as distinct from the internal ventilation ducts which may be long, are dominated by losses due to separations from sharp edges which are practically Reynolds number independent it is expected that the results may be applied at full scale without any large correction. If wind-tunnel ABL simulations are used the incident wind at the reference height may be set from the wind statistics for the site, all other velocities being directly proportional. Otherwise estimates may be based on a standard power law profile for the ground condition type. Using this approach to provide an estimated or measured value of onset wind velocity for V in the above data together with the area of the full scale duct enables the driving pressure to be evaluated as a function of ventilation flow rate or vice versa from the Figs (7–10 for the inlet or outlet performances alone). Relating these driving pressures to the resistance of the internal ducting and flow circuits through the building which are not estimated or measured in the present work because of the wide range of possible values, enables the ventilation flow rate to be predicted. The final set of measurements, Table 1, gives a result for a complete device connecting inlet to outlet via a fairly high resistance circuit (due to the orifice plates), but corrected for the effects of the high resistance.

The tests also do not include effects of turbulence which of course is considerable in the wind. Small scale turbulence has an effect on the sizes of separation regions and hence affects losses for this type of flow, but probably not strongly. In addition effects of wind veering externally and inertia internally may be significant.

Conclusions

Buildings are often erected in conditions where the prevailing wind direction cannot be relied on or where there is no predictable prevailing wind direction when high ventilation rates are required (for example, in summer). It is critical that a natural ventilation system will perform well for all wind conditions. These results indicate that it is possibly best to use a six way split duct configuration to meet this objective.

However, in known wind conditions the four way split duct oriented at 45 degrees to the prevailing wind direction will generate the highest pressure difference between intake and outlet and consequently the highest duct speeds in an installation.

These results also indicate that the duct speeds generated in four or six way split duct devices of this nature are considerably less than the wind speed (varying from approximately 12% to 20% of the speed in the case of the six way devices).

In most installations the design wind speed (U_∞) will not exceed 4 m/sec and may well be half this in sheltered conditions. The performance of the windcatcher is marginally improved by increasing duct intake and extract areas. Design intake velocities can be very low, probably in the order of 0.5 m/sec–1.0 m/sec and dampers will probably be installed to ensure that these velocities will not be exceeded in conditions of high wind.

Reference to traditional modes of construction must be made with caution. However, this study demonstrates that useful lessons can be drawn from them. A further lesson from the windcatchers of Iran could be their often considerable height. There is a well known correlation between wind speed and height, especially in highly profiled terrain or in urban areas. It may be that the increased duct resistance of a high tower is more than offset by the available windspeed at the top.

Windcatchers can be beautiful objects. They are feasible additions to buildings, contain no external moving parts and are, consequently, inherently durable. Architects and their clients currently specify proprietary four way split duct windcatchers and the improved performance of six way split duct ventilators is an obvious advantage.

A major disadvantage of this type of ventilator is its performance when there is no wind. In these conditions ventilation must be achieved using stack (gravity) effects – and traditional building types are shown serving spaces with ventilation openings at low level which can achieve this. On urban sites an unpolluted off street or courtyard is required.

The direction of airflows in the ducts under a split duct windcatcher depends on the wind direction. It is, consequently, very difficult to serve more that one space on one level using typical windcatcher systems. It is, however, possible to 'rectify' the airflow under a windcatcher terminal using sets of dampers and a device which infers duct airflow directions from wind direction. In this case more than one space can be served and displacement ventilation can occur in windless conditions.

Both of these issues are discussed in more detail in Bartlett Research Paper No. 11 'Top down ventilation and cooling in urban areas' (Gage, 1999). Further work is required to examine how optimum performance can be achieved.

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