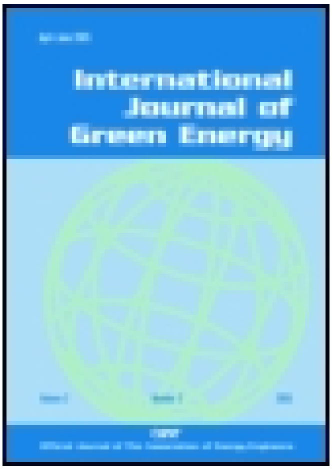

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Using CFD to Investigate Ventilation Characteristics of Domes as Wind-Inducing Devices in Buildings

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USING CFD TO INVESTIGATE VENTILATION CHARACTERISTICS OF DOMES AS WIND-INDUCING DEVICES IN BUILDINGS

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Many traditional architectural elements are still used in contemporary architecture. One way to give their existence more value is to use to serve design sustainability. Using CFD three-dimensional simulation, this paper investigates the effect of domed roofs on wind-induced natural ventilation performance, considering different building forms and areas, and different wind directions and velocities. Natural ventilation performance has been assessed in terms of airflow rate and internal airflow distribution. Results showed that domes improve ventilation performance in the upstream and central zones of the building, as suction forces acting over them induce more inflow rate through the building and attract some of the outflow to leave through dome openings instead of walls openings.

Keywords: ***Natural ventilation; CFD; Curved roofs; dome.***

INTRODUCTION

The dome is one of the oldest roofing forms in buildings. It has been used since the earliest times in many civilizations, including the Roman, Greek, and Byzantine, in addition to contemporary architecture. They have been considered efficient shapes to cover large spans. In some areas, this was possibly a result of the shortage of timber, which has been used to construct flat roofs (Bahadori & Haghighat, 1985). According to Statham (1927), a dome is "a built roof circular in plan and either semicircular or in some other arch shape in section". Domes are used in different shapes. The simplest one is the hemispherical dome. This may also be pointed at the top. Another shape is the onion one, where the dome body possesses a shape that has more than a half sphere. On the opposite, the saucer dome possesses a shape that has less than a half sphere.

Domed roofs help energy savings in cooling, since they have no corners where heat is likely to be trapped. This encourages the natural circulation of internal air. As mentioned by Yaghobi (1991), the dome shape has a larger wind shadow area when compared with flat roofs. This helps to limit heat transfer between hot outdoor air and the building envelope, and reduces heat gains in hot climates. This occurs due to the curvature of the roof, where wind passes over it with less resistance when pushed upward. Elseragy (2003) found that the use of hemispherical and pointed domes helps to reduce the received solar

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radiation in summer, compared to an equivalent flat roof, by about 70% and 50%, respectively, for hemispherical and pointed domes.

Concerning natural ventilation, Bahadori and Haghighat (1985) pointed out that domed roofs increase airflow rate due to wind effect in buildings when compared with flat roofs. This is independent of wind direction, due to the circular shape of the dome. This has been investigated using the network mathematical model for a room with four openings in its walls and one opening in the apex of its domed roof, where pressure coefficients for the domed roof were obtained from a previous wind tunnel study.

The use of domed roofs for natural ventilation is useful for both wind-induced and stack-induced natural ventilation strategies. This is, on one hand, because dome height encourages the vertical air movement by stack effect. On the other hand, domed roofs reformulate pressure zones around buildings, which encourages ventilation by suction. As a general observation, roofs of buildings are the elements that are subjected to the highest suction (Sachs, 1978). This high suction, which occurs in the separated flow region, has attracted the interest of researchers in many studies. The main advantage of the use of domed roofs for natural ventilation is that air velocity increases as wind passes over and around such spherical objects. This is true when air passes over a dome from any direction. This increase in air velocity occurs at the dome apex and around its drum, or base. This consequently increases airflow rates through the roof and improves internal airflow distribution, which is investigated in the following sections.

STUDY METHODOLOGY AND PARAMETERS

In order to establish a systematic and more comprehensive methodology, natural ventilation performance of the dome is investigated parametrically, which has been facilitated by the implementation of CFD code. The study programme has been designed to consider a variety of parameters examined in 72 cases. As these parameters are numerous, many of them have been assumed fixed, while others have been varied. These parameters can be divided into climatic and geometrical parameters.

For wind-driven ventilation, it is crucial to specify both wind speed and direction for the geographical site under investigation. This study aims to investigate the role of the dome in natural ventilation on a regional level, namely for the Middle East, where this architectural element is widely used for wind-induced natural ventilation. Regarding wind velocity, a survey of wind velocity records in many cities in the Middle East has led to choosing two wind velocities: 1 and 3 m/s, to represent relatively high and low velocities. Concerning wind direction, a theoretical range of 0°, 45°, and 90° wind directions has been chosen.

Two common plan shapes are examined: the square and the rectangular. Generally, and assuming the case of one-zone plan, cross ventilation is the most straightforward natural ventilation strategy (Smith, 2001). Thus, openings are provided in each wall of the building four walls in order to examine the effect of the different possible wind directions. Effective cross ventilation requires a shallow plan. A rule of thumb given by CIBSE (1997) indicated that cross ventilation is sufficient up to a building depth equal or less than five times its height. In fact, this rule of thumb cannot be taken as an absolute rule, as cross ventilation penetration into any space depends on wind speed and building shape as well. Therefore, modelled cases will include different depth values more and less than the value recommended by CIBSE.

In the case of square-plan configurations, building relative length and width have been varied to be: 3H, 4H, and then 5H, where H is the building height, which is confined to 5 m. This leads to plan areas of 225, 400, and 625 m^2 respectively. In the case of rectangular-plan configurations, relative building length and width have been recalculated to give an equivalent area of the relevant square case, given that building aspect ratio is confined to 1:1.5. Required airflow rate is assumed to be 8 l/s per person, as recommended by CIBSE (1988) for open-plan offices and other public building types. As a rule of thumb, the minimum porosity value required to implement cross ventilation is 5% (Smith, 2001). However, as the modelled building main volume is larger than the normal one, due to its height, in addition to the additional dome volume, porosity will be assumed to be 10% of the floor plan area.

The dome geometry used here is hemi-spherical, raised on a cylindrical base in which eight openings are placed to face the different possible wind directions. These openings are uniformly distributed with an increment of 45°. Bahadori and Haghighat (1985) have investigated the potential of the dome with an opening at its apex. However, this study examines openings at the dome nick or drum, which is also a common configuration in the contemporary architecture, and still not investigated in a detailed manner.

The examined dome is centred on the flat roof of the building main volume. The dome plan area is assumed 7.5% of the building floor area, which gives an acceptable architectural proportion of the tested model. Thus, three diameters of the dome will be tested: 4.6, 6.2, and 7.8 m. Porosity of the dome is assumed to be 13% of its plan area. Technically, this will allow the model construction to give eight dome openings. Each opening is facing a different wind direction, with an increment of 45°. Figure 1 illustrates the resulting building configurations, in addition to how dome openings are distributed. Thus, this study compares many buildings configurations, before and after utilising the dome for natural ventilation, considering:

- Square and rectangular forms, with different areas
- Normal and oblique wind directions
- Relatively low and high reference wind speeds

The different cases are designated with a letter ‘D’ to refer to the dome. This letter is associated with letter, ‘o’ to indicate that dome openings are opened, or letter, ‘c’ to indicate the opposite. letter ‘D’ is followed by letters ‘s’ or ‘r’, in order to indicate, respectively, the square or rectangular form of the plan, which has also a serial number from 1 to 3 to indicate its area, i.e., 225, 400, or 625 m^2, respectively. Two more numbers follow this symbol: the first one indicates wind angle: 0, 45, or 90, and the second one indicates reference wind speed: 1 or 3 m/s. For example, Do1-s1-0-1 indicates that the test is

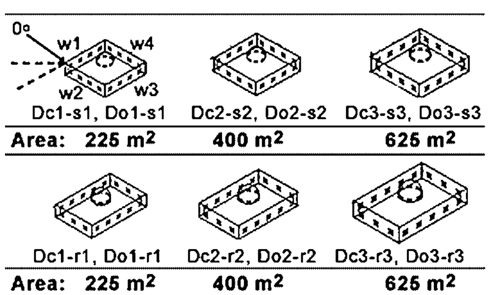


Figure 1 Different building configurations tested in this study, showing different cases codes, wind angles, and wall names.

targeting a building configuration with a plan area of 225 m^2 and opened dome apertures, exposed to a 0° wind incidence with a reference speed of 1 m/s.

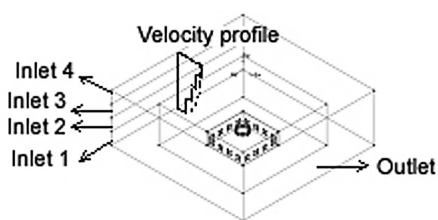
COMPUTER MODELLING CONSIDERATIONS

The implemented CFD code in this study has been validated in a separate study by the authors, where many cases with a variety in building geometries and wind directions have been considered (Asfour and Gadi, 2007). CFD model, using Fluent 5.5 software and the network mathematical model, have been compared. Both models have been used to estimate the wind-induced airflow rates in the different cases tested. Results obtained have supported the use of the proposed CFD code for wind-induced natural ventilation in buildings, as good agreement has been achieved. In a summary, the implemented CFD code used involves the use of three-dimensional modelling, Segregates Solver, the Standard k-$\in$ turbulence model, and 10^{-6} residual sum for convergence. Table 1 shows an illustration of the solution domain and boundary conditions used. Boundary conditions used are large and opposite velocity-inlet and outlet to simulate the wind and the ambient air. Wind blows over the building model, placed in the centre of the domain and penetrates its openings as a result of pressure difference across these openings. This is associated with many phenomena like airflow separation over the windward sharp edges of the building, air vortices, and reversed flows. As mentioned in the previous section, two reference wind velocities have been considered: 1 and 3 m/s. In order to consider wind velocity variation with height, it is important to define the wind velocity profile along the domain boundary, i.e., the large velocity inlet. This profile is defined by the following common equation (CIBSE, 1988), and assumes that the building is exposed to a wind speed that is modified by a city-like terrain:

$$V = V_r * cH^a \tag{1}$$

where V is wind speed at datum level (the sub-inlet here) (m/s), V_r is reference wind speed, H is the height above the ground, c is parameter relating wind speed to terrain nature (0.21 in the city terrain), and a is an exponent relating wind speed to the height above the ground (0.33 in the city terrain). This profile has been simulated using an

Table 1 Air velocities for different heights used in CFD modelling.



Height (m)	Vlocity inlet no.	Reference velocity, Vr	
		1 m/s	3 m/s
5	1	0.894	2.682
10	2	1.006	3.018
15	3	1.078	3.234
20	4	1.132	3.396

approximation method, with an acceptable level of accuracy, where the large velocity inlet has been divided into many sub-inlets. Then, air velocity magnitude has been defined for each sub-inlet according to equation 1, as shown in Table 1.

One of the main challenges in this study was to simulate the ambient air around the building and to create an appropriate mesh in terms of quality and resolution. To overcome these challenges, an extensive work has been carried out prior to the modelling study to demonstrate the different available options that lead the solution to converge. Minimum dimensions of the three-dimensional domain have been found to be 3.75 times the length of the longest side of the building. This is in the case of normal wind incidence. In the case of oblique wind incidence, this value should be increased up to 6 times the length of the longest side of the building. The height of the ambient air box is 4 times the building height, i.e., 20 m in all cases. The ambient air is divided into two zones in the case of 0° and 90° wind directions, and into 3 zones in the case of 45° wind direction. This is intended to allow for creating a hierarchy in mesh size, as shown in Figure 2.

Size and type of calculation mesh have been chosen to give an acceptable resolution within the available computer memory and speed. Concerning this study, the maximum possible mesh size is about ½ million cells. Thus, all cases should be managed to fall within this range. As openings along the building perimeter are not the same, symmetry boundary type cannot be a solution. Therefore, a hierarchy in mesh size has been created. Mesh type used is the tetrahedral one, which has been found to be appropriate for meshing curved geometries in a better quality, compared to the hexagonal mesh (Asfour and Gadi, 2007). However, this type gives a larger mesh size, nearly the double of the hex-map type, as its basic unit has less volume. This means that tetrahedral mesh with a size of 0.4 m is nearly equivalent in terms of resolution to a hex-map mesh with a size of 0.2 m. Extra care has been given to the mesh of building openings, where the airflow rate is recorded. Therefore, hex-map mesh has been used in building openings with a size of 0.2 m. It is worth mentioning here that file total size of the 72 cases involved in this modelling study is 6.4 GB.

In order to facilitate the analysis, different aspects of natural ventilation performance have been discussed separately, although it is believed that there is some interaction between them. Two main aspects of natural ventilation performance have been discussed here:

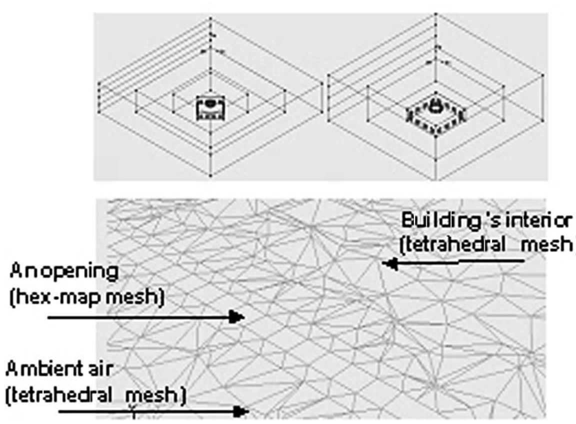


Figure 2 Method adopted of dividing the ambient air in the case of normal and oblique wind directions, with an illustration of mesh size hierarchy.

airflow rate and internal airflow distribution. Airflow rate has been recorded for every dome and wall opening. Inflow rate is indicated by a positive sign and vice versa. In the Fluent program, mass flow rate, presented in (kg/s), through any boundary, an opening for example, is computed by summing the dot product of air density times the velocity vector and the facet area of the opening (Fluent Inc., 1998). To obtain these parameters, Fluent 5.5 software solves the three basic conservation equations of mass, momentum and energy in an iterative manner. However, wind-induced ventilation is believed to be more effective in hot climates, when compared with a stack-induced one. This is because of the relatively lower difference between indoor and outdoor temperatures, which is the main factor affecting stack ventilation (Chow, 2004). Therefore, the energy option has been set off in this study.

This mass flow rate has been converted to volumetric flow rate in (l/s) to facilitate data processing, as mass flow rate usually possesses small value. Then, the resulting volumetric airflow rate has been divided by building area in order to establish the comparison between the different configurations tested in this study. It is important here to mention this study is not a design project. This means that the main concern here is to observe the effect of specific parameters on building natural ventilation performance, regardless of the actual obtained values. Summation of airflow rates through the different openings has been found to be zero in all cases. This shows the reliability of the results obtained according to the Law of Conservation of Mass.

AIRFLOW RATES THROUGH DOME OPENINGS

It has been found that ventilation performance varies for different building geometries and different wind speeds. However, the effect of these parameters was not as dramatic as the effect of wind angle. Therefore, the following analysis will be presented according to the different wind directions considered. The early findings of this study indicated that a dome with openings at its cylindrical base does not seem to work in cross ventilation mode as it may be presumed. Rather, it works in suction mode due to the suction forces acting around the dome. It has been observed that all dome openings, except the one that is normal to the wind, function as outlets. This is illustrated in Figure 3, which has been generated using the velocity vectors tool in the Fluent program.

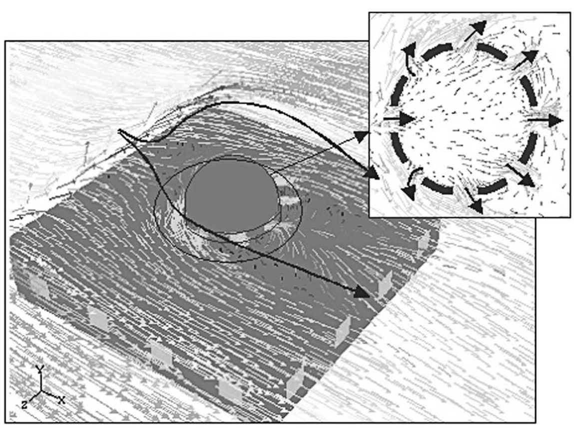


Figure 3 Airflow pattern over building roof, as illustrated by air velocity vectors (m/s), showing that dome openings function mainly in suction.

In the case of 0° wind direction, Figure 4 shows that outflow rate through the dome decreases as the building area, or depth, increases. This behaviour has a higher rate in the case of high wind speed. For example, in the case of square configurations and a 3 m/s wind speed, outflow rate drops from −10.66 to −7.1 (l/s)/m^2, with a difference of about 33%. This is explained by that any increase in plan area means that the distance between the dome body and the roof windward sharp edge, over which airflow separations occurs, also increases. Accordingly, this reduces the intensity of the negative pressure field surrounding the dome, which reduces its potential for suction.

This is also true for the rectangular cases. For example, in the case of 3 m/s wind speed, the dome has an average outflow rate range from −14.23 to −9.23 (l/s)/m^2, with a difference of about 35%. However, outflow rate recorded higher values in these cases. This is because the effect of airflow separation at a roof's sharp edge is stronger here. This is due to two reasons:

- The distance between the dome centre and the roof windward edge is shorter, compared to the square cases.
- Rectangular cases generally are characterised as elongated geometries. This means that airflow prefers to blow above the building instead of around it, following the less resistance. This increases the intensity of airflow separation and, therefore, the local suction forces around the dome.

Concerning inflow rate, Figure 5 shows that inflow rate through the dome inlet has recorded a low value in the square configurations at both reference wind velocities. This is due to the existence of a trapped air vortex in the corner between building flat roof and the

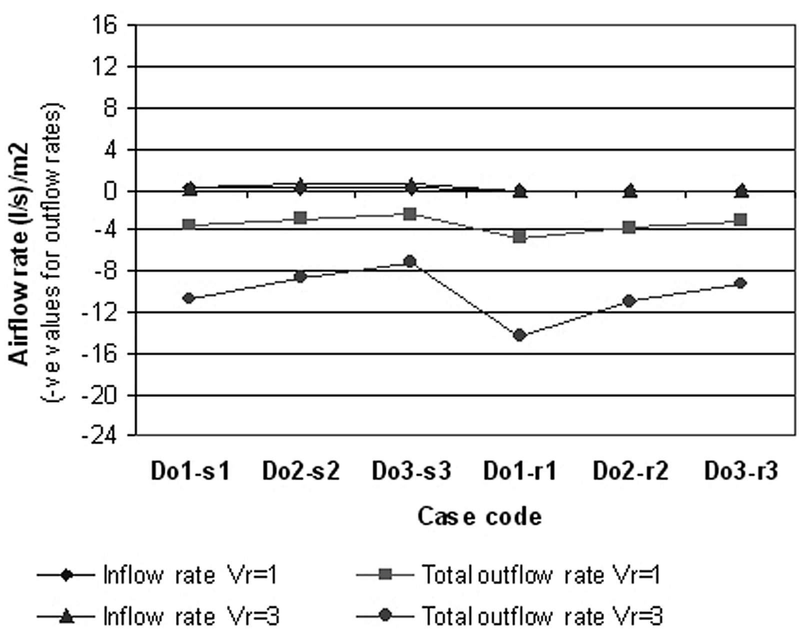


Figure 4 Airflow rates recorded through the dome in the different building configurations tested at 0° wind directions, and 1 and 3 m/s reference wind speeds.

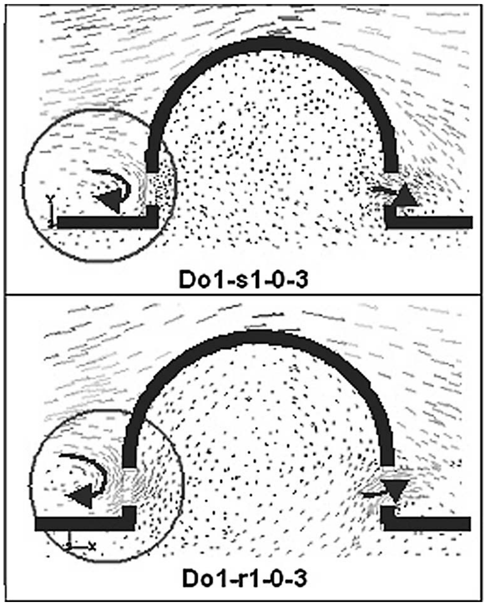


Figure 5 Velocity vectors for the indicated cases at 0° wind direction, showing a stronger air vortex before the dome inlet in cases that have smaller area.

dome cylindrical base, in which the dome inlet is located. In the case of shorter distance between the dome inlet and building windward edge, like rectangular cases, the observed rotating mass of air has more kinetic energy. This is why inflow rate in the rectangular cases is less than the square ones. In general, vortex existence in this case can be considered as an advantage because it increases the potential of the other dome openings for inducing ventilation by suction.

In the case of 45° wind direction, Figure 6 shows that outflow rates present the same behaviour observed in the case of 0° wind direction, i.e., it is inversely proportional to the area of the building. It has been explained in the previous wind direction section that the high value of outflow rate is caused by airflow separation over the windward sharp edge of the roof. This is also true here; given that airflow is generally attached on the two upstream building faces and then separates at the outer corners. According to Merony (1982), this forms a wide re-circulating wake region, which is associated with strong and persistent air vortices along the windward roof edges. This encourages air local suction through dome openings and increases outflow rates through the dome.

This airflow separation seems to have the same effect as the one observed in the normal wind direction in the case of rectangular building form, as outflow rate values are nearly the same for both wind velocities tested. However, outflow rate here has increased by about 30% in the square cases, which indicates more effect of airflow separation in this wind direction. Considering the net outflow rate, a dome's potential for inducing ventilation by suction in both square and rectangular cases has been negatively affected by the observed higher inflow rate, compared to the case of 0° wind direction. This higher inflow rate is because no frontal air vortices have been observed. Therefore, airflow moves freely to penetrate the inlet, as illustrated in Figure 7. This means that closing this inlet is expected to help increase the net outflow rate. This has been investigated for cases

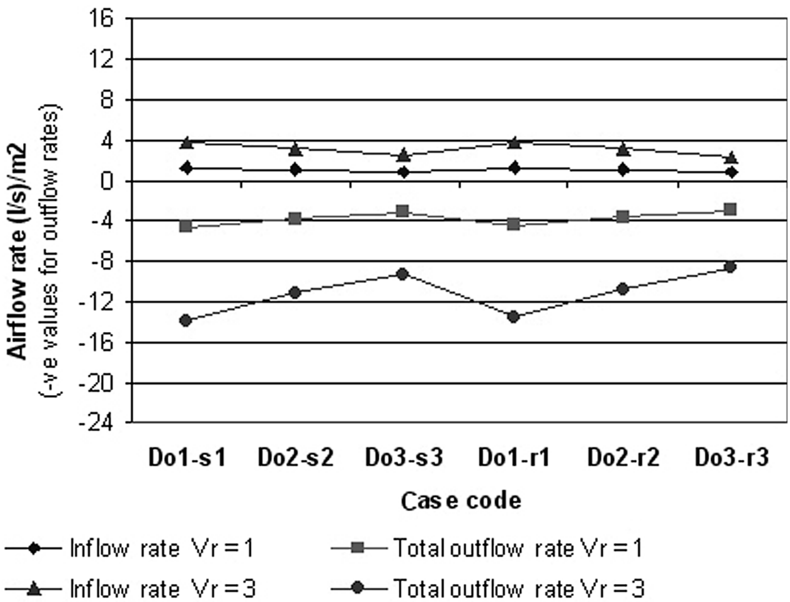


Figure 6 Airflow rates recorded through the dome in the different building configurations tested at 0° wind directions, and 1 and 3 m/s reference wind speeds.

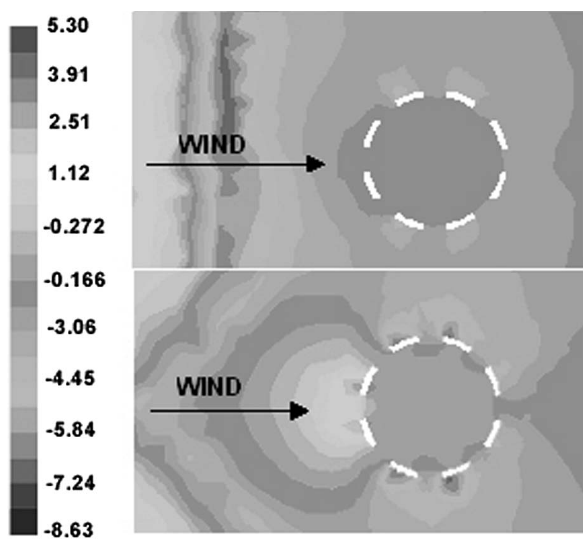


Figure 7 Contours of static pressure (Pa) at roof level showing that higher air pressure act on the dome inlet in the case of 45° wind direction (case: Do1-s1-45-3), compared to the case of 0° wind direction (case: Do1-s1-0-3).

Do2-s2–45–3 and Do2-r2–45–3. Results observed showed that the net outflow rate through the dome has increased by about 30% in both cases. Net outflow rate has increased from 8.2 to 10.6 (l/s) m^2 in the square case, and from 7.7 to 10.2 (l/s) m^2 in the rectangular case.

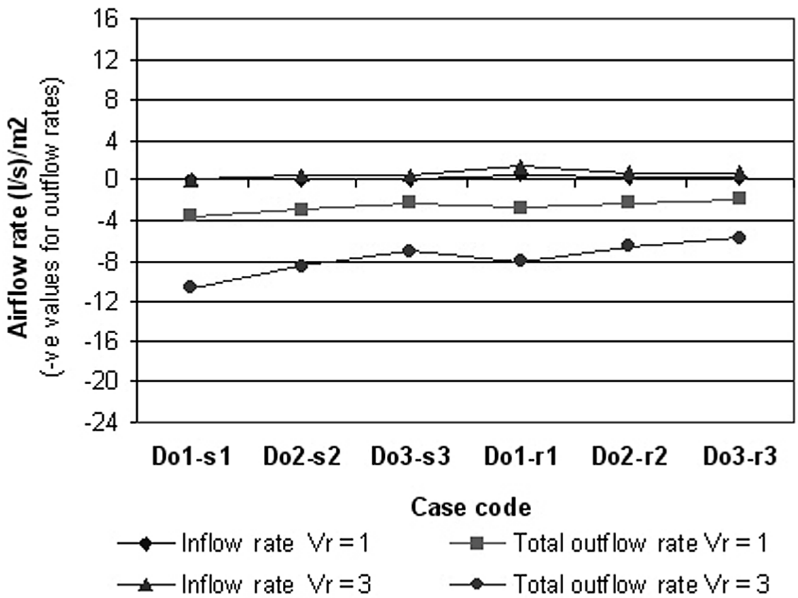


Figure 8 Airflow rates recorded through the dome in the different building configurations tested at 90° wind directions, and 1 and 3 m/s reference wind speeds.

In the case of 90° wind direction, outflow and inflow rate values in the square cases show the same behaviour presented and discussed in the case of normal wind direction. This is because square cases are symmetrical around both their axes.

Unlike the case of 0° wind direction, Figure 8 shows that the net outflow rate in the rectangular configurations presented fewer values compared to the square configurations (less by about 30%). This is due to the significant increase in building depth in this orientation. This causes airflow to lose more kinetic energy before it reaches the openings of the dome. This long distance results also in a positive airflow rate due to the absence of the air vortex that has been observed in the case of normal wind direction.

EFFECT OF DOME UTILISATION ON AIRFLOW RATE THROUGH WALL OPENINGS AND INTERNAL AIRFLOW DISTRIBUTION

Mass flow rate through every opening of the 16-wall openings in every case has been recorded, and then converted to volumetric flow rate for the plane unit area. It has been compared in the case of closed and opened dome apertures in order to demonstrate the effect of the dome. To observe and assess airflow distribution at the building interior, contours of air velocity magnitude, which is a main factor that affects thermal comfort, have been used. This technique in Fluent 5.5 software presents air velocity distribution across a defined plane and according to a defined velocity scale. The minimum is always 0 and the maximum has been unified for all cases possessing the same reference wind velocity.

To give this analysis ‘more value’, a numerical criterion has been adopted in order to calculate the plan area that have the same air velocity. Thus, area of every internal velocity zone has been estimated as a percentage of the total plan area using the AutoCAD program, where any velocity zone can be traced in order to calculate its area. Thus, internal air velocities recorded across building horizontal plane, at 1.7 m height, have been divided into four zones. The use of only four velocity zones has been found to be reasonable and practical. These zones are illustrated in Table 2 for both reference air velocities tested in this study.

Each zone is labelled by the same colour used in contours of velocity magnitudes. An example of these contours is given in Figure 9. As both low and high reference air velocities resulted in nearly the same airflow rate and distribution behaviours, the following results are applicable for both reference wind velocities tested here. This is supported by the fact that although air pressure is proportional to the square of the wind speed, its distribution does not change with speed for most sharp-edged buildings (Dalgliesh & Schriever, 1965).

In the case of 0° wind direction, Table 3 shows that some increase in inflow rate has been observed as a result of dome utilisation. This is due to the suction force acting on the dome. This is supported by the findings of Bahadori and Haghighat (1985) that the utilisation of domes for natural ventilation always increases inflow rates in buildings. Domes also attract some of the air that enters the building to leave through it instead of walls outlets, which are located in the literal building faces, w2 and w4, in addition to the leeward building face, w3. This resulted in a reduction in outflow rate. This reduction is in proportion with the suction forces acting on the dome, which are more when building area is less, as discussed in section (4). This redistribution of air results in a more active air movement in the central zone of the building.

One phenomenon that affects internal airflow distribution in this wind direction is the existence of the literal wall openings, especially in the square cases. This is because a large amount of airflow leaves the building directly through the literal openings, where the suction force is higher than the one acting on the leeward wall openings. This is assumed to reduce the quality of internal airflow distribution. To demonstrate this phenomenon, case D2-s2–0–3 has been modelled again, but with closed literal wall openings.

Results showed an improved internal airflow distribution. This is supported by a rule of thumb mentioned by Smith (2001) that outlets on opposite walls are more effective for cross ventilation than the adjacent wall. Also, reducing the number of outlets located at building walls has increased the importance of dome openings in suction. This is why outflow rate through the dome has increased from 8.0 to 15.0 (l/s) m^2, i.e., by about 85%. However, these literal openings will be kept in the rest of cases tested in this parametric study in order to consider their benefit in the oblique wind direction, as both windward faces of the building work in opposite cross ventilation mode with the other opposite two faces. On the other hand, using these openings is important for other environmental systems in such deep buildings, like day lighting.

Table 2 Different zones of internal air velocity.

Velocity zone	Internal velocity, Vi	
	Vr = 1 m/s	Vr = 3 m/s
A ■	0.0	0.0
B ■	0.07	0.2
C ■	0.14	0.4
D ■ & *above*	$0.14 < Vi < Vi_{max}$	$0.4 < Vi < Vi_{max}$

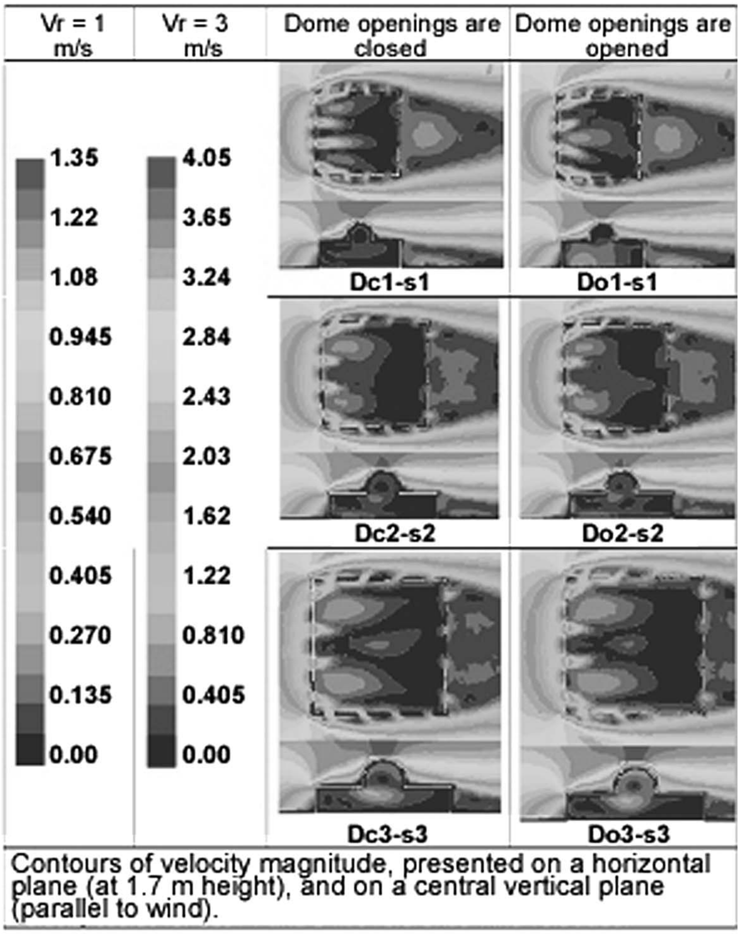


Figure 9 Comparison of internal airflow distribution, presented by velocity contours, before and after utilising dome openings in the square building form at 0° wind direction.

Another phenomenon that affects internal airflow distribution in this wind direction is that, and in some cases as illustrated in Figure 10, airflow penetrates the space diagonally. This results in a greater airflow movement in the higher level of building interior. It seems that there is a conflict between two forces in this regard:

- Suction forces acting on wall openings, which cause airflow to penetrate the space horizontally.
- Dragging forces due to airflow separation on the windward roof edge. This causes airflow to penetrate the space diagonally in the high level of the space and towards the opposite outlets. This results in a weak air movement in the downstream zone of the occupied level. Suction forces acting over the dome, in addition to the low height of the building, increase this effect.

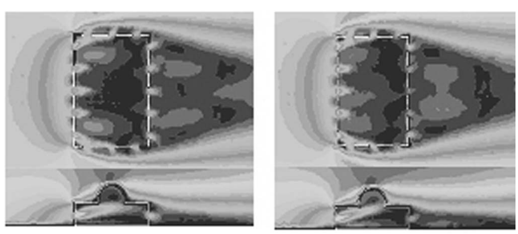
In the case of buildings having smaller depth, for example case Dc1-r1, air penetrating the space horizontally as a result of the suction forces acting on the leeward wall openings is more dominant than the dragging effect. This has resulted in a good internal airflow

Table 3 Assessment of airflow rate through wall openings and internal airflow distribution in the case of 0° wind direction and a 3 m/s reference wind speed, before and after the use of the dome.

Case	Airflow rate*					
	Inflow rate			Outflow rate		
	Before	After	Diff. (%)	Before	After	Diff. (%)
D1-s1	53.39	54.54	+2.2	−53.39	−44.01	−17.6
D2-s2	53.42	54.15	+ 1.4	−53.42	−46.16	−13.6
D3-s3	54.14	54.85	+1.3	−54.14	−48.22	−10.9
D1-r1	64.31	66.06	+2.7	−64.31	−51.83	−19.4
D2-r2	64.50	66.40	+3.0	−64.50	−55.56	−13.9
D3-r3	65.12	66.44	+2.0	−65.12	−57.21	−12.2
Velocity zone	Internal airflow distribution					
	Internal velocity, Vi (% of total plan area)					
	Dc1-s1	Do1-s1	Dc2-s2	Do2-s2	Dc3-s3	Do3-s3
A	30.9	26.4	37.0	31.2	33.1	34.7
B	30.3	38.1	28.8	37.8	28.5	26.3
C	15.3	15.5	15.9	14.1	17.5	16.7
D	23.5	20.0	18.3	16.9	20.9	22.3
Velocity zone	Internal velocity, Vi (% of total plan area)					
	Dc1-r1	Do1-r1	Dc2-r2	Do2-r2	Dc3-r3	Do3-r3
A	13.0	27.8	27.8	21.7	19.0	20.7
B	42.9	33.8	36.8	40.5	45.3	42.4
C	17.2	15.4	16.4	21	17.6	22.9
D	26.9	23.0	19.0	16.8	18.1	13.4

*All airflow rate values are in $(l/s)/m^2$ for Vr = 3 m/s.

**Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.



Dc2-r2-0-3   Do2-r2-0-3

Figure 10 Contours of air velocity magnitudes, showing the effect of dome utilisation on internal airflow direction, for the indicated cases (velocity scales are shown in Fig. 9).

distribution, which is characterised by a small still-air zone (only 13%). Utilising dome openings has caused air movement to become diagonal, and thus the area of the still-air zone has doubled in case Do1-r1. In the other two cases, i.e., Dc2-r2 and Dc3-r3, the building depth is higher. Thus, airflow penetrates the space diagonally, which reduced the quality of internal airflow distribution, compared to case Dc1-r1. Utilising the dome for natural ventilation has enhanced this diagonal air movement. The only difference is that airflow leaves through dome openings instead of wall openings. This is why internal air distribution has, positively or negatively, recorded slight changes.

In the square cases, the higher building depth has resulted in a diagonal air movement in all cases. Thus, a larger area of the still-air zone has been observed in the downstream zone, when dome openings are closed. This is about 30%. When dome openings are opened, air penetrates the space more deeply, since the dome helps to centralise airflow paths. This reduces the still-air zone by about 5% in the first two cases. Consequently, air velocity increases in zone B, i.e., 0.07m/s and 0.2m/s respectively, for the low and high wind velocities. However, a large area of still-air zones still observed, especially in the third case, which has the largest depth. One possible solution here is to propose an air provision system to the downstream zone of the building.

In the case of 45° wind direction, the natural ventilation system works in the cross-ventilation mode, where airflow entering and leaving the building does so from opposite openings. This means that the effect of the literal openings, as has been observed in the case of 0° wind direction, is no more valid here. The fact that two facades here are facing the wind did not result, however, in the gross inflow rate through these two facades to be twice the one observed in the case of normal wind incident. This is because the effective area of any opening oriented obliquely with respect to the wind is less. For example, the gross effective area of the four inlets is 10.24 m^2 in case Do1-s1–0–3. In the case Do1-s1–45–3, this gross area is 7.25 m^2.

Inflow rate through wall openings has significantly increased when dome apertures are opened. As explained in the case of 0° wind direction, this is because suction forces acting over the dome induce more air to enter the building. The higher gross area of inlets increases the potential of the dome for inducing inflow through these inlets. Suction forces acting over and around the dome also attract some of the air to leave through the dome instead of wall openings. This reduces outflow rates through wall openings, as can be observed in Table 4.

However, the reduction in outflow rates here is less than the case of 0° wind direction. This is due to the fewer number of outlets, which reduce the potential of the dome to attract some of the outflow that leaves through these outlets. In the case of closing the dome inlet, as explained in section (4), the role of the dome in suction has significantly increased.

Results observed showed that the net outflow rate through the dome has increased by about 25% in the tested square and rectangular cases. This, on one hand, has caused an additional increase in inflow rate by about 1.7% in the square case Do2-s2, and by about 1.2% in the rectangular case Do2-r2. On the other hand, it has caused an additional reduction in outflow rate by about 2.4% in the square case, and by about 3% in the rectangular case.

The above-mentioned opposite cross ventilation system has resulted in an improved internal airflow distribution, compared to the normal wind direction. This is characterised by a smaller area of the still-air zone, and higher air velocities in the other zones. In the square cases, dome utilisation in the first two cases has caused some increase in the area of the still-air zone and the area of the high velocity zone (zone D). In the third square case, which possesses the largest depth, the area of the still-air zone has increased in the downstream zone of the building. This is because part of the airflow leaves through dome openings instead of wall outlets.

Table 4 Assessment of airflow rate through wall openings and internal airflow distribution in the case of 45° wind direction and a 3 m/s reference wind speed, before and after the use of the dome.

Case	Airflow rate*					
	Inflow rate			Outflow rate		
	Before	After	Diff. (%)	Before	After	Diff. (%)
D1-s1	60.69	64.38	+ 6.1	–60.69	–54.41	–10.4
D2-s2	61.67	65.66	+ 6.5	–61.67	–57.49	–6.8
D3-s3	63.54	66.92	+ 5.3	–63.54	–60.09	–5.4
D1-r1	61.84	65.61	+ 6.1	–61.84	–55.89	–9.6
D2-r2	62.81	66.42	+ 5.8	–62.81	–58.70	–6.6
D3-r3	62.86	66.39	+ 5.6	–62.86	–60.09	–4.4
Velocity zone	Internal airflow distribution					
	Internal velocity, Vi (% of total plan area)					
	Dc1-s1	Do1-s1	Dc2-s2	Do2-s2	Dc3-s3	Do3-s3
A	17.5	18.7	11.2	13.3	2.8	7.4
B	34.5	30.8	52.9	45.5	49.9	44.8
C	16.6	16.9	18.7	16.8	26.7	27.8
D	31.4	33.6	17.2	24.4	20.6	20.0
Velocity zone	Internal velocity, Vi (% of total plan area)					
	Dc1-r1	Do1-r1	Dc2-r2	Do2-r2	Dc3-r3	Do3-r3
A	15.3	13.4	17.8	15.7	8.3	17.3
B	33.9	39.7	43.8	44.1	44.0	35.9
C	19.0	17.3	16.2	18.5	26.5	24.3
D	31.8	29.6	22.2	21.7	21.2	22.5

*All airflow rate values are in (l/s)/m^2 for Vr = 3 m/s.
**Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.

This is also true for the rectangular configurations, especially for the last case that has the largest depth. Generally, the resulting airflow distribution is unsymmetrical, as the still-air zone occurs in the downstream internal corner. This is because the pressure difference across the lower corner is higher due to wind deflection on buildings with windward facades.

In the case of 90° wind direction, as can be observed in Table 5, airflow rates and distribution in the square cases behave in the same way explained in the case of 0° wind direction. This is due to building symmetry. Regarding the rectangular cases, the reduction in outflow rates is generally higher. This is because some openings in the leeward wall, especially the middle ones, act as inlets. This is because suction forces acting on the long literal faces of the building drag airflow in the wake zone. The utilisation of the dome supports this dragging effect and causes the air to be reversed inside the building again. For example, average airflow rate through the leeward wall (w4) is positive in case Do1-r1.

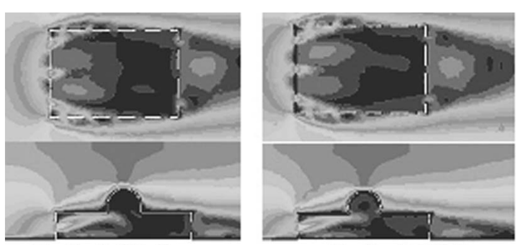
Figure 11 shows that the still-air zone area in the downstream wing of the rectangular cases is significantly higher due to the relatively large depth. When the dome

Table 5 Assessment of airflow rate through wall openings and internal airflow distribution in the case of 90° wind direction and a 3 m/s reference wind speed, before and after the use of the dome.

Case	Airflow rate*					
	Inflow rate			Outflow rate		
	Before	After	Diff. (%)	Before	After	Diff. (%)
D1-s1	53.39	54.54	+2.2	–53.39	–44.01	–17.6
D2-s2	53.42	54.15	+1.4	–53.42	–46.16	–13.6
D3-s3	54.14	54.85	+1.3	–54.14	–48.22	–10.9
D1-r1	39.17	39.31	+0.4	–39.17	–32.55	–16.9
D2-r2	39.76	40.03	+0.7	–39.76	–34.22	–13.9
D3-r3	40.36	40.39	+0.1	–40.36	–35.41	–12.3
Velocity zone	Internal airflow distribution**					
	Internal velocity, Vi (% of total plan area)					
	Dc1-s1	Do1-s1	Dc2-s2	Do2-s2	Dc3-s3	Do3-s3
A	30.9	26.4	37.0	31.2	33.1	34.7
B	30.3	38.1	28.8	37.8	28.5	26.3
C	15.3	15.5	15.9	14.1	17.5	16.7
D	23.5	20.0	18.3	16.9	20.9	22.3
Velocity zone	Internal velocity, Vi (% of total plan area)					
	Dc1-r1	Do1-r1	Dc2-r2	Do2-r2	Dc3-r3	Do3-r3
A	45.0	41.0	36.2	30.6	33.7	28.7
B	24.7	25.4	32.5	36.2	28.2	30.5
C	10.9	12.8	17.5	19.3	18.1	21.7
D	19.4	20.8	13.8	13.9	20.0	19.1

*All airflow rate values are in (l/s)/m^2 for Vr = 3 m/s.

**Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.



Dc2-r2-90-3 Do2-r2-90-3

Figure 11 Contours of air velocity magnitudes, showing the effect of dome utilisation on internal airflow distribution, for the indicated cases (velocity scales are shown in Fig. 9).

is utilised for natural ventilation, slight improvement has been observed. The still-air zone area has been reduced by about 5%, with a corresponding increase in other wind velocity zones. However, the still-air zone area in the leeward wing is still large (about 30% of the total area).

DESIGN GUIDELINES

The previous analysis leads to the following general design guidelines:

- In the case of 0° wind direction, the use of a dome with a rectangular building form is more efficient than an equivalent square one. This is more pronounced in small building areas due to the shorter distance between the dome and the roof windward sharp edge, over which airflow separation occurs.
- In the case of a 45° wind direction, the use of a dome with either a square or rectangular plan from has the same advantage. This is because the net outflow rate observed is nearly the same for both building forms. However, a dome here has more potential for inducing ventilation by suction, namely when its inlet is closed.
- In the case of 90° wind direction, the use of a dome with a square building from is more efficient than an equivalent rectangular one, especially for small building areas. This is due to the large depth of the rectangular building form in this orientation, which reduces suction forces acting over the dome.
- Reducing inflow rate through the dome is a desired feature, because it increases dome potential for air suction.
- Reducing wall-opening areas for the advantage of the dome is expected to improve the performance of the proposed system in terms of airflow rate and internal airflow distribution at users' level in the building. This is typically the situation when a building is wind-sheltered.

CONCLUSION

The aim of this study was to investigate the effect of dome employment for natural ventilation on the performance of wind-induced ventilation in the modelled building prototypes. This has been presented in terms of airflow rate and internal airflow distribution. More than 70 cases have been modelled using Fluent 5.5 software, considering different climatic and geometrical parameters.

Concerning ventilation performance of the dome, it has been found that a dome with openings at its base works mainly in suction, as at least 87.5% of its opening area serve as air outlets. This suction increases as the distance between the dome and the roof's windward sharp edge(s) decreases, i.e., when building area is smaller. In the case of 0° and 90° wind directions, inflow rate through the dome is low due to the generated air vortex before it. This has been found to be useful for increasing dome potential for suction. In the case of 45° wind direction, inflow rate is higher due to the absence of this air vortex. Thus, closing the dome inlet has been found to cause a significant improvement in its performance (about 25% in the configuration tested).

Regarding airflow rate through building walls, dome openings always induce more inflow rate through a building's windward face, especially in the case of an oblique wind direction (about 6%). This is in inverse proportion with building area. On the other hand, dome utilisation always reduces outflow rate through wallsopenings, as it attracts some air to leave through it, especially in the case of 0° and 90° wind directions (about −14%). This is also in inverse proportion with building area. The above-mentioned two observations have generally improved internal airflow distribution in the upstream and central zones of the building. However, this has not guaranteed the same improvement in the downstream zone. This is because air is attracted to leave the building directly through the dome before it penetrates the downstream zone of the building.

Thus, domes can be integrated with an air supply system in order to encourage air movement in the building, especially in its downstream wing.

REFERENCES

Asfour, O., Gadi, M. (2007). A Comparison between CFD and Network Models for Predicting Wind-Driven Ventilation in Buildings. *Building and Environment* doi:10.1016/j.buildenv.2006.11.021

Bahadori, M., Haghighat, F. (1985). Passive cooling in hot arid regions in developing countries by employing domed roofs and reducing the temperature of internal spaces. *Building and Environment* 20(2): 103–113.

Chow, W.K. (2004). Wind-induced indoor-air flow in a high-rise building adjacent to a vertical wall. *Applied Energy* 77: 225–234.

CIBSE. (1988). *CIBSE Guide*. Vol. A. 5th ed. London: CIBSE.

CIBSE. (1997). *Natural ventilation in non-domestic buildings*. London: CIBSE.

Dalgliesh, W.A., Schriever, W.R. (1965). *Wind Pressures and Suctions on Roofs* [online]. Available at National Research Council Canada website: <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd068_e.html> [11 Oct. 2005].

Elseragy, A.A. (2003). *Architectural and solar potential of curved and flat roofs in hot arid regions*. PhD thesis, University of Nottingham.

Fluent Inc. (1998). *Fluent 5.5 program help menu*. www.fluent.com

Meroney, R.N. (1982). Turbulent diffusion near buildings. In: Plate, E. Ed. *Engineering meteorology: Studies in wind engineering and industrial aerodynamics* (pp. 481–525). Oxford: Elsevier Scientific Publishing.

Sachs, P. (1978). *Wind forces in engineering*. 2nd Ed. Oxford: Pergamon.

Smith, P.F. (2001). *Architecture in a Climate of Change*. Oxford: Architectural Press.

Statham, H.H. (1927). *A short critical history of Architecture*. London: Batsford Ltd.

Yaghobi, M.A. (1991). Air Flow Patterns Around Domed Roof Buildings. *Renewable Energy* 1(3/4): 345–350.