

## BUILDING HEIGHT AND URBAN CONFIGURATION EFFECTS ON WIND FLOW ABOVE A BARREL VAULTED ROOF

Dr Islam Abohela, Dr Neveen Hamza, and Dr Steven Dudek  
School of Architecture, Planning and Landscape  
Newcastle University, UK

### ABSTRACT

This paper presents a numerical (CFD) analysis of wind flow above a barrel vaulted building placed within two different urban setting (urban canyon and a staggered configuration). The building height is changed to identify the effect of the building height and the surrounding urban configuration on the wind velocity above the barrel-vaulted roof. Results show that with the increase in building height the wind velocity increases and accordingly the energy yield of a roof mounted wind turbine increases. When the building is higher than its surroundings, the urban canyon introduces more acceleration above the investigated roof than the staggered configuration. However, when the building is lower than or the same height as the surrounding urban configuration, the staggered urban configuration introduces more acceleration above the investigated roof than the urban canyon configuration.

### INTRODUCTION

Abohela *et al.* (2011) using Computational Fluid Dynamics CFD conducted research to identify the optimum roof shape for roof mounting wind turbines. Six roof shapes were compared namely; flat, domed, gabled, pyramidal, barrel-vaulted and wedged roofs. It was concluded that the barrel-vaulted roof is the optimum roof shape for roof mounting wind turbines in terms of accelerating wind above the roof. Other investigated factors included the wind direction; it was proven that with the change in wind direction the accelerating effect of the roof shape changes, accordingly the optimum roof mounting location for the wind turbine above each of the investigated roof shapes.

Simulation results indicate that the barrel vaulted roof shape is the optimum roof shape for roof mounting wind turbine under a wind direction parallel to the roof profile ( $0^0$ ). Both the barrel vault and the  $0^0$  wind direction were chosen for investigating other variables affecting wind flow above the roof. The other variables are the building height and the surrounding urban configuration. In this paper, wind flow around a 12m and 24m barrel vaulted buildings are investigated and compared to a 6m high base case to identify the effect of varying the height of the building on the turbulence intensity

and the streamwise velocity above the barrel vaulted roof and its effect on specifying the mounting location of the wind turbine.

### SIMULATION MODEL

CFD simulations are embedded with errors and uncertainties. Thus, for running consistent CFD simulations, literature on best practice guidelines for using CFD is reviewed and used as a starting point for simulations in this paper. The simulation conditions used in this paper were extracted from Blocken *et al.* (2011), Franke *et al.* (2004), Chen and Zhai (2004), Wit (2004) and Sørensen and Nielsen (2003). According to these publications, the minimum requirements for carrying out a consistent CFD simulation needs to adopt:

- Second order Schemes or above for solving the algebraic equations.
- The scaled residuals should be in the range of  $10^{-4}$  to  $10^{-6}$ .
- Multi-block structured meshes are preferable and carrying out sensitivity analysis with three levels of refinements where the ratio of cells for two consecutive grids should be at least 3.4.
- Mesh cells to be equidistant while refining the mesh in areas of complex flow phenomena.
- If cells are stretched, a ratio not exceeding 1.3 between two consecutive cells should be maintained.
- For flows around isolated buildings, the realizable  $k-\epsilon$  turbulence model is preferred.
- Accuracy of the studied buildings should include details of dimension equal to or more than 1m.
- If H is the height of the highest building the lateral dimension =  $2H + \text{Building width}$ , Flow direction dimension =  $20H + \text{Building dimension in flow direction}$  and Vertical Direction =  $6H$  while maintaining a blockage ratio below 3%.
- For the boundary conditions, the bottom would be a non-slip wall with standard wall functions, top and side would be symmetry,

outflow would be pressure outlet and inflow would be a log law atmospheric boundary layer profile which should be maintained throughout the length of the domain when it is empty.

- Horizontal homogeneity of ABL profile throughout the computational domain.

All ten points were considered for running the simulations and horizontal homogeneity was achieved for the atmospheric boundary layer profile. For validating the use of CFD and achieving a homogenous boundary layer, simulation results were compared to published in-situ measurements, wind tunnels tests and validated CFD simulations results for the flow problem of wind round a surface mounted cube in a turbulent channel flow (Abohela et al., 2011).

The realizable  $k-\epsilon$  turbulence model was used for the closure of the transport equations. The SIMPLE algorithm scheme was used for the pressure-velocity coupling. Pressure interpolation is second order and second-order discretisation schemes were used for both the convection and the viscous terms of the governing equations. The solution was initialised by the values of the inlet boundary conditions. The chosen convergence criterion was specified so that the residuals decrease to  $10^{-6}$  for all the equations.

For the computational mesh, a mesh independence study was carried out to determine the dependence of the flow field on the refinement of the mesh. The base case has resolution of 0.3m around the cube. Two other meshes were used. The first mesh had a resolution of 0.2m around the cube and 0.8m throughout the rest of the computational domain. The second mesh had a resolution of 0.1m around the cube and 0.8m throughout the rest of the computational domain. The three meshes were compared to each other; qualitatively the main flow features for the 0.3m mesh are the same as in the 0.2m and the 0.1m mesh. The same agreement was noticed for the pressure coefficients plot along the streamwise centreline along the windward facade, roof and leeward facade of the cube. Insignificant discrepancies on top of the cube were noticed in the pressure coefficients plot. Thus, it can be concluded that the 0.3m mesh is sufficient for running a mesh independent simulation.

## RESULTS ANALYSIS

This investigation has proven that both, the building height and the surrounding urban configuration, affect wind flow above the roof of a building. In the following sections, the effect of both variables will be discussed through analysing the streamwise velocity pathlines, turbulence intensity and streamwise velocity above the investigated roof cases. Visualizing the flow pattern around the investigated cases help determine recirculation areas, stagnation points, flow separation and reattachment. This gives a qualitative assessment of the potential

places above the roof where a wind turbine can be mounted.

However, in order to determine the exact location for mounting a wind turbine, both the turbulence intensity and wind speed should be determined quantitatively. A rule of thumb is to avoid locations of high turbulence intensity and low wind speed. In order to study wind flow characteristics, streamwise velocity pathlines were plotted along the vertical central plan passing through the building, turbulence intensity and streamwise velocity were plotted for 15 different locations above the roof (Figure 1) starting at 6m height up to 15m height. To be able to identify the accelerating effect, all plotted values were normalized against the values at the same locations in an empty domain.

### The height variable

In the 12m barrel vaulted building case domain dimensions of 315 x 132 x 72m are used to simulate wind flow around the studied case which resulted in a blockage ratio of 0.3% which is less than the maximum recommended blockage ratio. In the 24m barrel vaulted building case a domain with dimensions 504 x 264 x 144m is used to simulate wind flow around the studied case which resulted in a blockage ratio of 0.1% which is also less than the maximum recommended blockage ratio of 3%. The flow variables are measured from directly above the roof to a distance of 9m (the vertical distance where the building has an effect on the wind flow field above it).

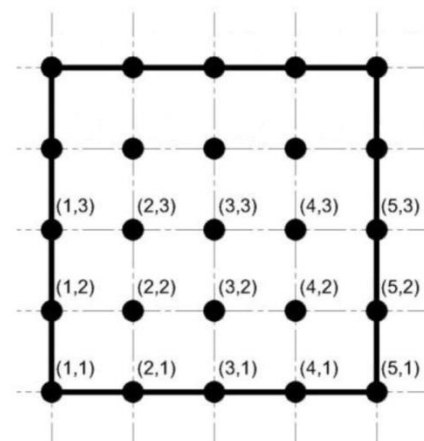


Figure 1 Locations of measurement points superimposed on the roof plan

Figure 2 shows the streamwise velocity pathlines for the three cases, where the main flow features are similar to each other and the 6m vaulted roof case. The flow was attached to the roofs surfaces and only separated at the leeward direction of the building, the stagnation point was formed at the same location at a height of  $2/3$  of the building height in all cases and the standing vortex in front of the windward facade was formed at the same location for all three cases. As for the vortex leeward the building, both the 6m case and the 12m exhibit the same pattern except for the reattachment length which is larger for the 12m

case than the 6m case which suggests that there is a relation between the building height and the reattachment length leeward the building. For the 12m case the leeward vortex was formed at the same location with respect to the building roof, however the recirculation area did not reach the ground as it interfered with another backflow area which was formed near the ground due to the pressure difference between the leeward and the windward areas of the building. However, it can be argued that this behaviour did not affect the flow pattern on top of the roof.

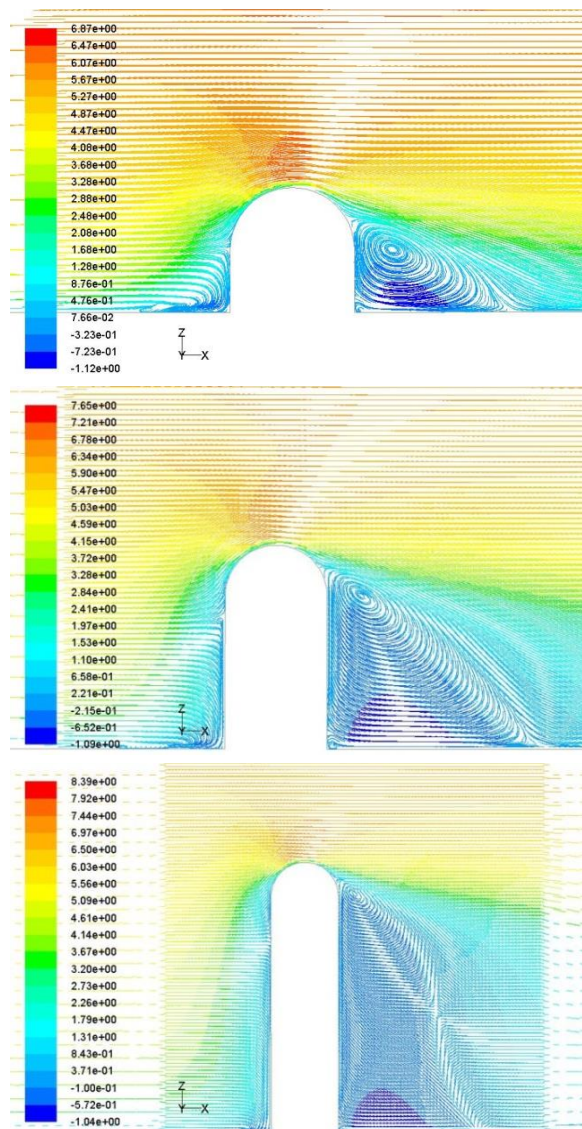


Figure 2 Streamline velocity pathlines along the central vertical axis for the 6m (top) 12 m (middle) and the 24 m vaulted buildings (bottom).

Plotting both the turbulence intensities and the streamwise velocities along the 15 measurements points for the 12m and 24m barrel vaulted buildings, it was noticed that the same flow patterns were consistent among both cases since the maximum turbulence intensity occurred at the same location of V2-3 (between the roof windward edged and the middle of the roof) and the maximum streamwise velocity occurred at the same location of V3-3

(midpoint of the barrel vaulted roof). However, when comparing the values at both locations for the three cases, Figure 3 shows that there was an increase in the turbulence intensity with the increase in the height of the building which suggests that there is a relationship between the building height and the turbulence intensity. This observation was confirmed by Jha (2010) who noted that turbulence within the built environment is highly dependent on buildings heights; the higher the building height the more turbulence will be generated.

Other variables might affect the location of the maximum recorded turbulence intensity such as the width and the length of the roof. It should be noted that the recommendations from the Encraft Warwick Wind Trials Project (Encraft, 2009) and the WINEUR (2007) report relates the position of maximum turbulence areas with the building height (30% and 35% - 50% of the building height respectively). However, both projects depended on in-situ measurements for assessing wind resources at locations of urban wind turbines, but, there was no clear information about how the turbulence data was collected, especially when the anemometers used are conventional cub anemometers known for their limitations in capturing turbulence; ultrasonic anemometers are required for registering turbulence. Thus, research is needed in this area to identify whether or not this relationship exists. In light of the obtained results in this work, building height affects the value of turbulence above the roof while it does not affect the location where the turbulence occurs.

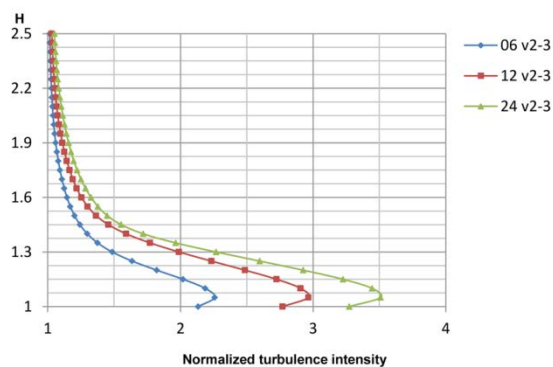


Figure 3 Comparison between the maximum recorded turbulence intensities at location v2-3 for the 3 heights

As for the streamwise velocity, Figure 4 shows that the accelerating effect of the building was consistent among the three cases above the height of 1.2H where the acceleration increased with the increase in height, but from the highest point of the roof to that height the same pattern applied to the 12m and the 24m cases but for the 6m case the pattern was different, which suggests that the ground roughness had an effect on the streamwise velocity. The used roughness length in all three cases was equal to 0.03m which corresponds to nearly flat or gently undulating countryside.

Although this is considered low roughness, Figure 4 shows that it had an effect on the accelerating effect above the 6m barrel vaulted building and this effect decreased with the increase of the building height. For all three cases, the maximum streamwise velocity occurred at the same location (V3-3: roof midpoint at height 1.3H (where H is equal to 6m; height of the 6m case)), the 6m case registered a maximum streamwise velocity of 1.16U, the 12m case registered 1.17U, as for the 24m case, it registered 1.17U. The increase in the energy yield is calculated based on the cube relationship between the wind velocity and the energy yield of a wind turbine, which is governed by the equation:  $P = 1/2 C_p \rho A V^3$  where  $P$  is the power output,  $C_p$  is the power coefficient of the turbine,  $\rho$  is the air density,  $A$  is the turbine's swept area and  $V$  is the wind velocity. Thus, it can be argued that a roof mounted wind turbine on top of higher buildings will be introduced to more wind acceleration and accordingly would capture more power from the wind provided that all other conditions such as turbulence remain constant.

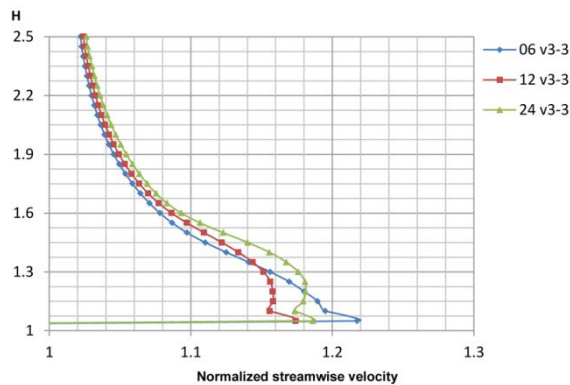


Figure 4 Comparison between the maximum recorded velocities at location v3-3 for the 3 heights

These results were in accordance with those from Reiter (2010) who found that the accelerating effect above the building is highly dependent on the building height and independent of building length. Several simulations were carried out with different buildings heights and constant length and width and it was noticed that the acceleration effect increases with the increase in the building height. Other simulations were carried out varying building's length and fixing building height and the results were not changing. Thus, it was confirmed that building height is a key parameter influencing the accelerating effect around a single building: the higher the building, the more the accelerating effect.

### Surrounding urban configuration

In this section, two urban configurations are used to examine their effect on the energy yield and positioning of a roof mounted wind turbine. These

configurations are a street canyon urban configuration and a staggered urban configuration whose buildings heights are 6m and the spacing between the buildings are 6m in all directions (Figure 5). The barrel vaulted roof case with wind direction parallel to the roof profile was chosen as the study case in this section since it has proven to be the optimum roof shape for mounting wind turbines.

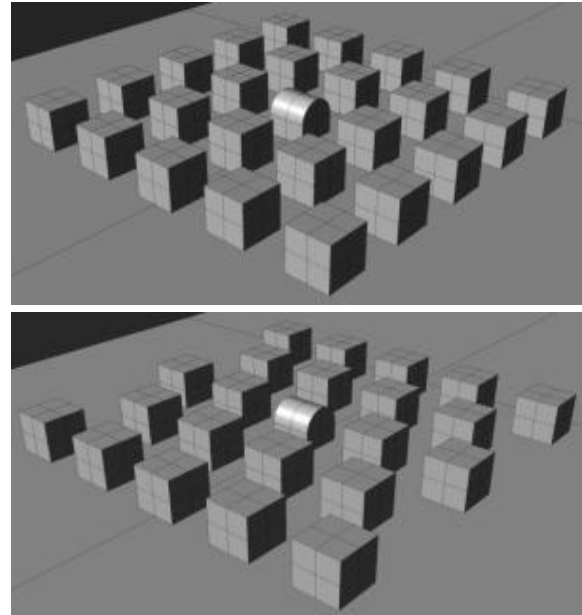


Figure 5 The two urban configurations modelled, top: the street canyon and bottom the staggered street, both show the barrelled vaulted building in the centre at a height of 6 metres.

As seen in the previous section the height of the building had an effect on wind flow above the investigated roof, thus four different heights were chosen for the barrel vaulted building to be placed within the proposed urban configurations. For the first case, the building height is less than the surrounding urban context (4.5m), the second case the building height is the same as the surrounding urban context (6m), the third and the fourth cases the buildings heights are higher than the surrounding urban context (12m and 24m respectively).

In constructing the computational domain, the same distance between the extents of the studied urban configuration and the front, the side and top boundaries is equal to five times the height of the highest building and a distance from the leeward building in the urban configuration which is 15 times the height of the tallest building. The obtained blockage ratios for the 24m, 12m, 6m, 4.5m cases are 0.7%, 1.7%, 4.3% and 4.3% respectively. Since the blockage ratios for the 4.5m and 6m cases exceeded 3%, the domain size of the 24m case was used for all the cases to maintain a blockage ratio less than 3%.

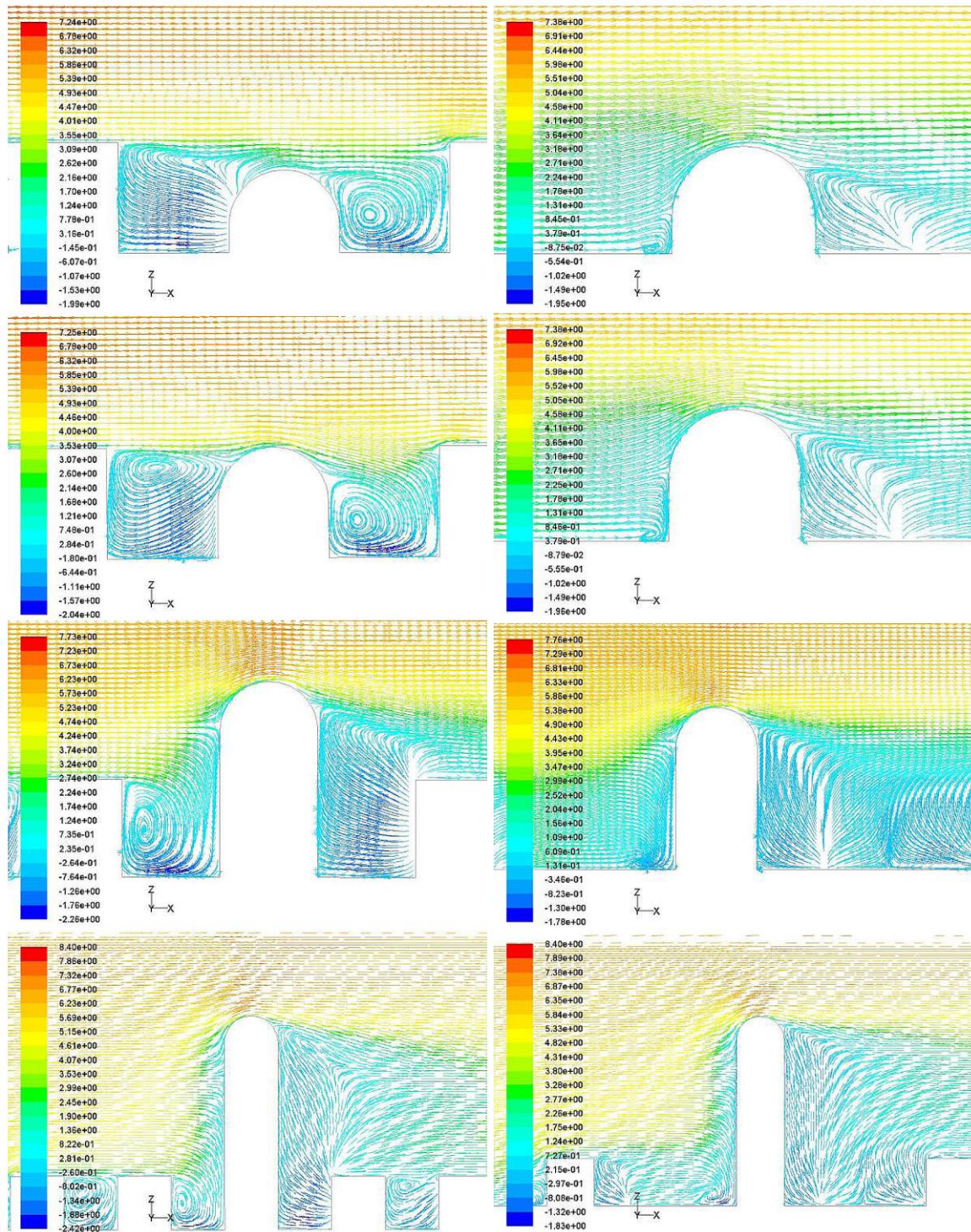


Figure 6 Streamwise velocity pathlines along the vertical central plan passing through the 4.5m, 6m, 12m and 24m (up to down) vaulted building in an urban canyon configuration (left) and a staggered urban configuration (right).

The mesh is the same as in the 6m barrel vault case; 1.2 m spacing in the x, y and z directions away from the urban configuration and 0.3 m spacing in the x, y and z directions close to the urban configuration. However, for the 24 m cases the mesh away from the urban configuration has a resolution of 2.4 m in the x, y and z directions and the same resolution of 0.3m close to the urban configuration. This is due to the limited computational power which did not enable having a finer mesh away from the urban

configuration. In order to assess the effect of coarsening the mesh away from the studied urban configuration, the mesh for the 6m vaulted building within a street canyon urban configuration was coarsened to reach 2.4m, the simulation was run, the results were compared to the fine mesh and no differences were observed. Thus, the results for the coarsened mesh away from the urban configuration in the 24m barrel vaulted building within different urban configurations were accepted.

The results from these last series of simulations need to be split into two groups to be understood, the first group is where the modelled building is below or equal to its surroundings' height and the second group where the modelled building is higher than its surroundings. In the first group, the surface roughness dominates the airflow, whilst in the second group the roughness effect is less marked. Figure 6 shows the streamwise velocity pathlines for all eight investigated cases. For the 4.5m case, the turbulence intensity diminishes above 1.6H, and the maximum normalised streamwise velocities reach a maximum at 2.5H. At this height the staggered configuration has a normalised streamwise velocity (compared to an empty domain) of 1.09, whilst the canyon configuration value is 1.07. When the barrel vault is at the same height as its surroundings, the roughness of the surroundings increases the turbulence and pushes the position of the maximum normalised streamwise velocity to 2.5H. The values and order were identical to the 4.5m case.

As the barrel vaulted building rises above the surroundings (the second group) the roughness effects diminish, resulting in the turbulence intensity and normalised streamwise velocity profiles corresponding to the isolated building case. For both building heights and urban configurations, the turbulence intensity becomes less significant above 1.3H, following the performance of the isolated building. For the 12m high case the canyon and staggered configuration have a normalised streamwise velocities of 1.13 and 1.1 respectively at 1.3H. And the 24m height case has normalised streamwise velocities of 1.15 and 1.13 for the canyon and staggered configurations respectively. A reversal of the situation found in first group in that the canyon configuration has less impact on velocity than the staggered configuration, but for both cases the normalised streamwise velocities were less than the isolated building case.

Comparing the results for each building height for the isolated building case, the building placed within an urban canyon configuration and the building placed within a staggered urban configuration, the effect of the urban configuration on the streamwise velocity above the vaulted roof can be identified. Figure 7 shows the normalised streamwise velocities at the locations of maximum recorded streamwise velocity for both the urban canyon case and the staggered urban case for the 4.5m vaulted building. It is noticed that the increase in streamwise velocity is very low in both cases compared to the isolated 6m vaulted building which means that both staggered and urban configurations reduced the accelerating effect of the vaulted roof shape. The maximum streamwise velocity for both cases were recorded at the same location (V3-3) which might be attributed to the symmetry of both configurations and not necessarily due to the roof effect of the vault since the locations of maximum recorded turbulence intensities were different for both cases.

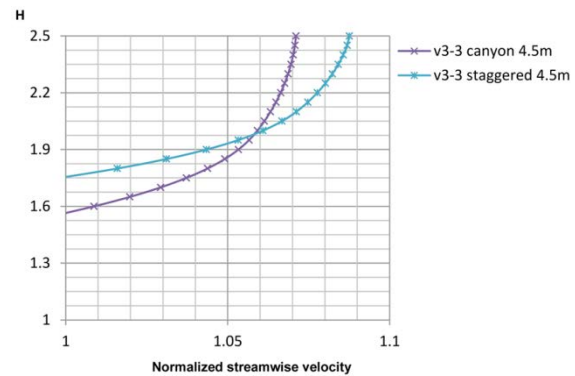


Figure 7 Maximum normalized streamwise velocity above the 4.5 vaulted building within an urban canyon configuration and a staggered urban configuration

For the 6m vaulted building case, Figure 8 shows a comparison between the three cases; the isolated building case, the building within an urban canyon configuration and the building within a staggered urban configuration. All maximum streamwise velocities occurred at the same location (V3-3). However, the three patterns were different from each other; both the urban canyon and the staggered urban configurations were similar to the previous two cases of the 4.5m. The pattern of the isolated 6m building case is different from both cases, indicating a higher streamwise velocity than in all cases of examined urban configurations which suggests that the placement of the building within an urban configuration would have an effect on the streamwise velocity above the roof.

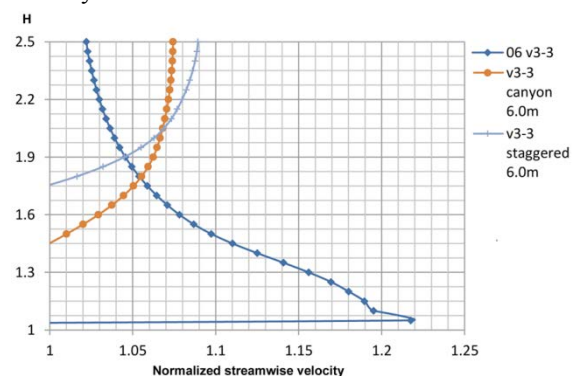


Figure 8 Maximum normalized streamwise velocity above the 6m vaulted building for the isolated building, within an urban canyon configuration and a staggered urban configuration

In the region where it was proposed to mount a wind turbine above an isolated roof (at height 1.3H), it is noticed that the isolated building would introduce more acceleration to the wind than a building placed within an urban context. This area where an isolated building is more preferable than a building within an urban context extends 1.8H when compared to the urban canyon configuration and to 1.9H when compared to the staggered urban configuration, after these heights respectively the roof mounted wind

turbine will benefit from more acceleration on top of a vaulted building within urban context. This can be attributed to the decrease in the roof effect with height above the roof of the isolated building and the larger effect of the urban configuration due to its larger surface area.

For the 12m cases, Figure 9 shows that all three cases benefited from the accelerating effect of the vaulted roof shape. Above the area of maximum turbulence intensities (1.0H to 1.3H), the isolated building recorded the maximum increase in streamwise velocity than the vaulted building within urban canyon configuration and then the vaulted building within staggered urban configuration.

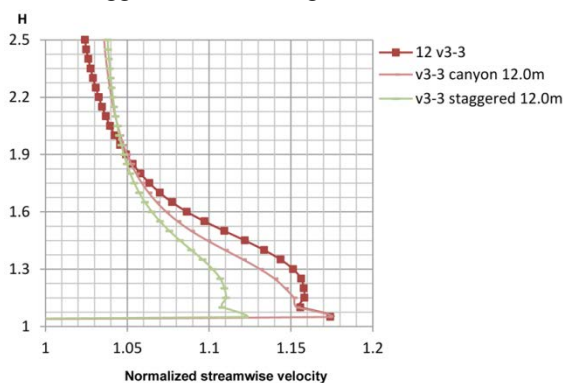


Figure 9 Maximum normalized streamwise velocity above the 12m vaulted building for the isolated building, within an urban canyon configuration and a staggered urban configuration

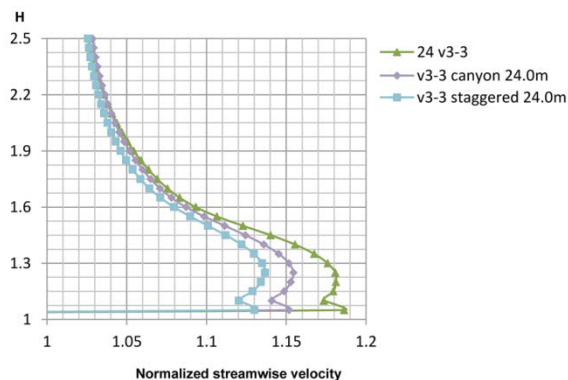


Figure 10 Maximum normalized streamwise velocity above the 24m vaulted building for the isolated building, within an urban canyon configuration and a staggered urban configuration

The location of the maximum increase in streamwise velocities is the same for all cases but the values are slightly different when compared to the overall acceleration. This means that the surrounding urban configuration still had an effect on the extent of acceleration above a 12m vaulted roof placed within different urban configurations. However, this effect is small when compared to the previous two cases. For the 24m cases, Figure 10 shows that the three curves had the same pattern and the maximum recorded values were recorded at the same location (V3-3). However, there were small differences

between the values recorded for the three cases. Above the area of maximum turbulence intensity (TI) (1.3H), the isolated building recorded a maximum of 1.18U then the building within an urban canyon configuration recorded 1.15U and then the building within the staggered urban configuration recorded 1.13U.

## CONCLUSION

It can be argued that a roof mounted wind turbine has higher potentials if mounted on top of higher buildings than low-rise buildings. However, it should be noted that a wind turbine mounted on top of higher buildings would also be subjected to higher levels of turbulence which should be kept in mind when choosing a specific wind turbine model as it should be able to withstand the higher levels of turbulence.

When studying the effect of the surrounding urban configuration (urban canyon and staggered configurations) on wind flow above the barrel vaulted roof subjected to a  $0^{\circ}$  wind direction having different heights, it was noticed that the closer the building height to its surrounding, the more disturbance the flow will be subjected to and the taller the building than the surrounding urban configuration, the less the effect on the flow around and above the building. This is attributed to the surrounding terrain roughness. In the case of the isolated building, the roughness length was equal to 0.03 which corresponds to nearly flat or gently undulating countryside as for the other cases where the barrel vaulted building was placed within urban context, the roughness corresponds to that of domestic housing areas which affected the wind flow above the investigated cases.

When comparing the flow patterns of the urban canyon configuration to the staggered configuration, it was noticed that the staggered configuration had less effect on the flow patterns around the investigated buildings than the urban canyon configuration. This can be attributed to the larger distance in front of the studied building in the staggered configuration than the urban canyon configuration which gives the flow a chance to develop and exhibits similar features to those of the isolated buildings cases.

Thus, for roof mounting a wind turbine within an urban configuration, it is recommended that the building should be higher than the surrounding buildings. For specifying the optimum location for mounting the wind turbine, both the turbulence intensity and the streamwise velocity should be assessed above the roof placed within the urban setting.

CFD results indicate that the turbulence intensity for the barrel vaulted roofed building is affected by the building's height whether isolated or within different urban configurations. However, the presence of the building within an urban configuration will not necessarily contribute to increasing the turbulence

intensity above its roof as the flow is complicated and other factors such as the roof shape, the urban configuration, building geometry and any other elements within the urban context might affect the flow. As seen in the case of the 12m barrel vaulted building within both urban configurations, the isolated building case registered higher turbulence above the roof (2.98TI) than the building placed within different urban configurations (2.72TI for both urban configurations). In addition, it was noticed that with the increase in the height of the building whether isolated or placed within an urban area, the turbulence intensity increased which indicates the presence of a relationship between the building height and the turbulence it causes above its roof.

Figure 11 shows a comparison between the increase in the streamwise velocity at the proposed wind turbine optimum mounting location for all investigated barrel vaulted roof cases under  $0^{\circ}$  wind direction. It is noticed that at the proposed optimum mounting location of a wind turbine above the investigated cases, the isolated building would introduce more acceleration to the wind than a building placed within an urban context. Comparing the cases of different barrel vaulted buildings with different heights within different urban configurations, the decrease in the difference between the recorded values is related to the increase in the height of the studied building. This suggests that with the increase in height, the effect of the surrounding urban context diminishes and other variables such as the roof shape and the height of the building affect the flow above the building roof.

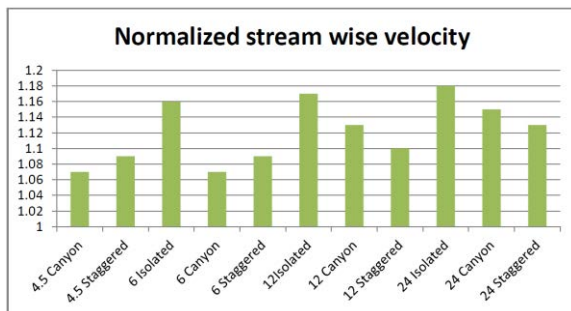


Figure 11 Comparison between the increase in the streamwise velocity for the investigated cases

It is noticed that when the building is higher than its surroundings the urban canyon introduces more acceleration above the investigated roof than the staggered configuration. However, when the building is lower than or the same height as the surrounding urban configuration, the staggered urban configuration introduces more acceleration above the investigated roof than the urban canyon configuration. The difference in patterns between the two cases might be attributed to the effect of ground roughness on wind flow above the investigated cases and how the CFD code solves the flow near to the ground. Thus, more research is required to

investigate the reason behind this change in pattern and whether it is related to the effect of the geometry of the urban setting or it is related to the way in which the CFD code solves the flow at lower altitudes.

## REFERENCES

- Abohela, I., Hamza, N. and Dudek, S. (2011) 'Effect of Roof Shape on the Energy Yield and Positioning of Roof Mounted Wind Turbines', *Building Simulation 2011 (BS2011)*. Sydney, Australia. pp. 1203-1210.
- Blocken, B., Stathopoulos, T., Carmeliet, J. and Hensen, J.L.M. (2011) 'Application of computational fluid dynamics in building performance simulation for the outdoor environment: an overview', *Journal of Building Performance Simulation*, 4(2), pp. 157-184.
- Chen, Q. and Zhai, Z. (2004) 'The use of Computational Fluid Dynamics tools for indoor environmental design', in Malkawi, A.M. and Augenbroe, G. (eds.) *Advanced Building Simulation*. Oxfordshire: Spon Press.
- Encraft (2009) *Encraft Warwick Wind Trials Project*. Available at: <http://www.warwickwindtrials.org.uk/resources/Warwick+Wind+Trials+Final+Report+.pdf> (Accessed: 06 February 2013).
- Franke, J., Hirsch, C., Jensen, A.G., Kliis, H.W., Schatzmann, M., Westbury, P.S., Miles, S.D., Wlisse, J.A. and Wright, N.G. (2004) *Recommendations of the COST action C14 on the use of CFD in predicting pedestrian wind environment*.
- Jha, A.R. (2010) *Wind Turbine Technology*. Hoboken: CRC Press.
- Sørensen, D.N. and Nielsen, P.V. (2003) 'Quality control of computational fluid dynamics in indoor environments', *Indoor Air*, 13(1), pp. 2-17.
- WINEUR (2007) *Wind Energy Integration in the Urban Environment: Report on Resource Assessment (5.1)*. [Online]. Available at: [http://www.iee-library.eu/images/all\\_ieelibrary\\_docs/514%20wineur.pdf](http://www.iee-library.eu/images/all_ieelibrary_docs/514%20wineur.pdf) (Accessed: 06 February 2013).
- Wit, S.D. (2004) 'Uncertainty in building simulation', in Malkawi, A.M. and Augenbroe, G. (eds.) *Advanced Building Simulation*. Oxfordshire: Spon Press, pp. 25-59.