CFD SIMULATION FOR WIND COMFORT AND SAFETY IN URBAN AREA: A CASE STUDY OF COVENTRY UNIVERSITY CENTRAL CAMPUS

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Abstract: This study is based on a series of computational fluid dynamics (CFD) simulations to evaluate wind conditions at pedestrian level around the Hub, a newly built structure, part of Coventry University campus. The aim was to provide more insight in the pedestrian living conditions around the Hub and at the same time, study the influence of the building shapes on wind distribution. Detailed aerodynamic information can be obtained using CFD, which offers considerable advantages compared to wind tunnel testing. It was also meant to advice the University’s Estates Department of the possibility of wind nuisance around the central campus area. The simulation was performed for different wind speeds and directions. The velocity field was computed using the finite volume method. Wind comfort and wind safety are assessed and potential design improvements are evaluated. The predicted results showed that the distribution of the velocity field varied and had different characteristics with different wind directions. The results showed that the wind speed amplification factors in diverging passages were generally larger than in converging passages. By using CFD in this manner it is anticipated that these types of advanced performance-based studies will be a useful tool and an essential aid for urban designers and environmental planners.

Keywords: CFD, pedestrian wind comfort, built environment, modelling

1 INTRODUCTION

Pedestrian-level wind (micro)-conditions is one of the first microclimatic issues to be considered in modern city planning and building design (Wu and Kriksic 2012). The construction of a new building alters the microclimate in its vicinity; hence wind comfort and safety for pedestrians become important requirements in urban planning and design. Today, some city authorities request studies of pedestrian wind comfort and safety for new buildings and new urban developments.

High-rise buildings are particularly influential to wind effects. Therefore, information about wind flow patterns around buildings can be important to architects and urban planners. As a result of the public’s growing awareness of the latest scientific and engineering achievements, contemporary architects, designers and engineers should pay more attention in creating more comfortable and functional buildings and their surroundings.

In particular, near and around high-rise buildings, high wind velocities are often introduced at pedestrian level that can be experienced as uncomfortable, or sometimes even dangerous. Traditionally, wind flow at pedestrian level can be simulated in boundary-layer wind tunnels. However, with the advent of computational power and the introduction of numerical methods like the
Finite Element Analysis, it is possible to accurately simulate the same conditions in a virtual environment using advanced modelling techniques like the Computational Fluid Dynamics (CFD). The latter can provide significant cost benefits for assessing and optimising engineering design solutions related to environmental concerns.

CFD allows the investigator to analyze the full domain of the model, provides a complete picture of the problem and presents the results in an easy-to-understand graphical way, as opposed to relying on expensive and time consuming collection of several dozens of discrete points, as it is usually the case with physical wind tunnel modelling. CFD modelling has been used by enviro-metrics to assess comfort levels with respect to wind climate, based on evaluating the wind flow fields around buildings, as well as the associated outdoor thermal comfort, air ventilation, snow accumulation, rain infiltration and other microclimatic conditions (Stathopoulos and Baskaran 1996).

Over the last two decades, along with the perfection of the CFD method, many researchers have concentrated on the numerical simulations of air flow past a single building. Their studies revealed some complicated flow phenomena, such as separation, vortex shedding, recirculation and reattachment and predicted some accurate numerical results (Paterson et al 1986, Murakmi 1998, Bosch and Rodi 1998).

Pedestrian-level winds can be described quite adequately in terms of mean velocities in the presence and absence of a new building within a specific urban environment. Although it can be argued that pedestrians are mostly affected by gust effects and mean wind speeds may not be sufficient to cause results for concern, the fact remains that several major cities planners require only the fulfillment of certain mean (sustainable) speeds with a specified probability of exceedance (Stathopoulos 2006). The process of comparison between computational and experimental results has already been challenged and appears problematic on its own. For instance, is it more meaningful to carry out point-by-point comparisons or does it make more sense to examine pedestrian-level wind speeds affecting a particular zone or area of influence for a specific activity within the urban environment?

2 CLIMATE-RESPONSIVE DESIGN STRATEGIES

Outdoor human comfort in an urban climate may be affected by a wide range of parameters, including wind speed, air temperature, relative humidity, solar radiation, air quality, human activity, clothing level, age, etc. Several criteria have been developed by the wind engineering community for evaluating only the wind-induced mechanical forces on the human body and the resulting pedestrian comfort and safety. There are significant differences among the criteria used by various countries and research institutions to establish threshold values for tolerable and unacceptable wind conditions even if a single parameter, such as the wind speed, is used as a criterion. These differences range from the speed averaging period (mean or gust) and its probability of exceedance (frequency of occurrence) to the evaluation of its magnitude (experimental or computational) (Blocken et al 2012, Chronis et al 2012, Mochida and Lun 2008, Blocken and Persoon 2009, Tominaga et al 2008, Yoshie et al 2007).

The presence of tall buildings influences wind speeds at low level in their immediate surroundings. The effects on the local microclimate may be favourable or unfavourable depending on the building shape, size, orientation and interaction with neighbouring buildings or obstacles. The faster winds at high level may be deflected down to ground level by tall buildings causing unpleasant and even dangerous conditions for pedestrians. Wind may be channelled around buildings, between buildings or along avenues causing accelerated wind speeds at pedestrian level and giving rise to pedestrian discomfort. On the opposite end, suitably arranged tall buildings may provide sheltered areas for pedestrians, although this can lead to accumulation of traffic fumes and/or other pollutants, if there is insufficient air circulation (wind speeds) (Tan et al 2007, Stathopoulos et al 2004, Mohamed 2009).
2.1 Typical Locations of Strong Wind in Built up Areas

When a gust of wind strikes a tall building surface it tends to deflect towards the ground causing high speed winds on the windward side, as well as near the corners of the buildings at street/pedestrian level. Based on strong wind, occurrences at pedestrian areas often occur at the three regions shown in Figure 1 and are associated with the three types of flow (Emil et al 1996): Type I: Vortex flow between buildings, near ground level (region A), Type II: Descending air flows passing around leeward building corners (region B), Type III: Air flows passing through openings (passages) at ground level connecting the windward and leeward sides of buildings (region C).

Figure 1: Regions of high surface wind speeds around a tall building

2.2 Pedestrian Comfort

Pedestrian comfort criteria are based on mechanical wind effects without consideration of other meteorological conditions (temperature, relative humidity). These criteria provide an assessment of comfort, assuming that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes and their corresponding gust wind and speed ranges are used to assess pedestrian comfort. More specifically, the comfort classes, associated wind speed ranges and limiting criteria are summarized in Table 1 based on information from Shane (2011).

<table>
<thead>
<tr>
<th>Comfort Classes</th>
<th>Description</th>
<th>Location types (Examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting</td>
<td>Occurrence: &gt; 70% of the time. Acceptable for sedentary activities, including sitting.</td>
<td>Outdoor Cafés, Patios, Terraces Beaches, Gardens, Fountains, Monuments.</td>
</tr>
<tr>
<td>Standing</td>
<td>Occurrence: &gt; 80% of the time. Acceptable for standing, strolling, etc.</td>
<td>Building Entrances, Exits Children’s Play Areas</td>
</tr>
<tr>
<td>Walking</td>
<td>Occurrence: &gt; 80% of the time. Acceptable for walking, or rigorous activities</td>
<td>Public/private Sidewalks Pathways. Public / Private Vehicular Drop-Off Zones</td>
</tr>
<tr>
<td>Uncomfortable</td>
<td>Occurrence: &gt; 20% of the time. Unacceptable for walking</td>
<td></td>
</tr>
<tr>
<td>Dangerous</td>
<td>Occurrence: &gt; 0.01% of the time. Dangerous to walk</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Desirable pedestrian wind comfort classes for various location types
2.4 Aim and main objectives of the current study

The aim of this study is to provide a qualitative assessment of the student and pedestrian comfort and safety due to the likely wind conditions formulating around the main Coventry University campus and especially around the newly constructed Hub. The main objectives were set as follows:

- To investigate the typical wind patterns around the Hub and the resulting wind environment at pedestrian level and to detect the so called ‘critical areas’ and classify them according to Table 1.
- To identify the origin (source) of possible causes of undesirable wind conditions.
- In essence, to assess and quantify the wind generated around the campus and specifically near and around the Hub and to advice on the effect this predicted wind may have on the neighbourhood.
- To generalise the findings by analysing, commenting and, if appropriate, revise certain wind comfort criteria to suit the requirements for busy city life and business usage.

3 MODEL DEVELOPMENT

Coventry University has changed dramatically in the last few years. Among several new buildings, The Hub distinguishes as it creates an architectural as well as an environmental impact to the City of Coventry. The particular building claims very high standards such as low carbon footprint, low energy consumption (first class insulation), flexibility in its use, functionality (minimum number of columns), etc. However, none has considered the effect this building has or has-not on their occupants, such, as students and other pedestrians outside and around it. Hence, the relation between wind effects, wind comfort, wind danger and wind (local) climate may be of interest.

Using the Fluent Code (FLUENT 2007), the wind generated around the campus and specifically near and around The Hub will be assessed and quantified. The typical wind flow pattern around the aforementioned building and the related wind environment at pedestrian level will be investigated and discussed. Useful comments will be drawn on the effect this predicted wind may have on the neighbourhood.

The CFD simulations were performed using the commercial CFD code Fluent and the 3D steady RANS equations. Closure was provided by the realisable $(k-\varepsilon)$ turbulence model (Shin et al 1995) The choice of this turbulence model was based on recommendations by (Franke et al 2004) and on earlier successful validation studies for pedestrian-level wind conditions(Blocken and Persoon 2009) and (Blocken et al 2004). Pressure velocity coupling was taken care off by the SIMPLE algorithm (Lanunder and Spalding 1974). Second order discretisation schemes were used for both the convection terms and viscous terms of the governing equations. Simulations were performed for four wind directions (0°, 90°, 180°, and 270°). The latter were deemed to be sufficient to cover the most onerous conditions. The iterations were terminated when the scaled residuals showed very little further reduction with increasing number of iterations. The following minimum values were reached: For x, y, z-velocity components: $10^{-8}$. For $(k-\varepsilon)$: $10^{-7}$. For continuity: $10^{-6}$

Various articles recommend the following generalised boundary conditions for the simulation limits (Franke et al 2004) and (Blocken et al 2004):

- Symmetries on the edges and the upper surface of the volume.
- Pressure-outlet for the boundary leaving the simulation volume.
- Variation of the wind speed profile with height, at the air entrance of the simulation field.
- Adoption of the wall function model for the treatment of cells near solid walls.

For treatment of areas close to “wall” surfaces such as ground or building facades, there are two calculation models in FLUENT. Considering the complexity of our simulations, the criterion for the choice of the “wall function” model was based on the coarse mesh implementation, as opposed to that of the “two-layer approach”, hence, economising on the resources available in Fluent. Essentially, for studies related to wind comfort at pedestrian level, it is appropriate to use smooth surfaces for ground and buildings (zero height of roughness). the total number of grid elements used in simulation 355187.
3.1 Boundary Conditions
The approaching wind was created from a power-law model to approximate the mean velocity profile:

\[ U = U_g \left( \frac{Z}{Z_g} \right)^\alpha \]  

(1)

Where; \( U \) = mean wind speed, \( U_g \) = gradient wind speed, \( Z \) = high above ground, \( Z_g \) = depth of the boundary layer (gradient height, \( Z_g = 40 \) m), and \( \alpha \) (alpha) = power law exponent. The exponent \( \alpha \) varies according to the type of terrain; \( \alpha = 0.14, 0.25 \) and \( 0.33 \) for open country, suburban and urban exposures respectively. All calculations in this article were based on the value of \( \alpha = 0.14 \). (Aynsley et al 2002) and (Jianming et al 1999). The variation of the inlet velocity at inlet is shown in Figure 2.

Figure 2: Inlet mean wind speed profiles in the CFD simulation

Since the \( k-\epsilon \) model was used, the values of \( k-\epsilon \) were required to account for the turbulence in the approaching wind. The turbulent kinetic energy \( k \) can be calculated if the turbulence intensity at a given height is known, , the turbulence intensity of the inlet velocity profile is assumed to follow the Gaussian distribution with a standard deviation of 0.15.

\[ k = C_k \cdot \left( \frac{u^*}{\nu} \right)^3 \]  

(2)

The other important value required is the dissipation rate \( \epsilon \); which can be obtained from the assumption that the wind is neutrally stratified and homogeneous in the surface layer, where the rate of energy production is approximately equal to its dissipation rate, therefore

\[ \epsilon = \frac{\rho_0 u^*}{\kappa} \left( \frac{u^*}{\nu} \right)^5 \]  

(3)

Where \( k \) is the von Kármán constant (\( k = 0.41 \)) and \( u^* \) is the friction velocity. The \( u^* \) was calculated from

\[ u^* = \frac{\sqrt{k \nu}}{\kappa} \]  

(4)

Since \( k \) had been obtained from Eq. (2). The value of \( u^* \) determined by (4). The boundary conditions applied in the computing domain are summarized as Table 2.

3.2 Local meteorological data for Coventry
The average annual local atmospheric wind conditions for Coventry are shown in the wind-rose plotted in Figure 3, This is based on historical Meteorological Office data taken from Coventry (Coleshill) and measured over a 7 years period. It is obvious that southerly winds dominate throughout the year, with easterly winds being particularly infrequent (Cameron 2005).
4 CASE STUDY

The area under study is shown on the Coventry University campus. Figure 4(a and b), depicts the top and iso-views with overall dimensions of the main building (Hub B1, B2) and the building height of 20 m.

5 VELOCITY DISTRIBUTION FOR WIND FLOW AROUND BUILDINGS

The velocity stream lines around the building were studied using the CFD method. The results were presented for the mean wind speed, \( V_{\text{mean}} \), at a pedestrian height of 1.5 m from ground level. The basic results from the CFD simulations for the proposed new building are presented in Figures 5(A, B, C and D). These figures show plan views of head level velocity streamlines for prevailing wind speed 6 m/s.

5.1 North direction

Figure (5A), northerly wind direction, shows wind velocity above the prevailing wind speed especially between the two main blocks. This creates an extended shelter zone behind the buildings but also creates problems because pedestrian wind discomfort arises underneath the main building (Hub). The wind flow pattern at pedestrian level between the two buildings is shown quite complex with recirculation areas behind the buildings and large velocity gradients near the main building, B1 (see Figure 4d). In addition, the leeward side of the building, shows the formation of eddy flow (eddy...
currents developing), at the point where the two air streams meet, following earlier splitting at the windward side. This eddy flow is closer to the short side of the building.

![Figure 4 (a): A view of the pedestrian area between the Hub and James Starley building](image)

(b): Main dimensions of the buildings considered

### 5.2 East direction

In the case of East wind direction Figure (5B), near the entrances to the buildings, the wind speed increases owing to the narrow pass between buildings B1 & B3 (Bernoulli’s Principle). The most notable point to observe is the presence of local wind velocity above the prevailing wind speeds (indicated by the yellow lines) near all corners and between building blocks. The distribution of velocity around the building proves that the air also splits at the windward side and meets at the leeward side of building B3. The maximum velocity is present at the front corner of building B3 and at pedestrian level.

### 5.3 West direction

When the wind is blowing from West Figure (5C), the velocity streamlines build up in the area surrounded by buildings B1 & B2 and the most affected zones are the corners of the upstream in building B1. At the student pedestrian, the wind speed accelerates by 40% higher than wind velocity can occur compared to the reference wind speed at the pedestrian height.

### 5.4 South direction

For Southerly winds Figure (5D), the most affected zones are the area surrounding buildings B1 and B2 due to the Venturi effect leading to wind speed accelerated by 40%. Also, at the building coroners, the wind speed exceed by 50-60% those at reference wind speed.

### 6 ASSESSMENT OF WIND COMFORT AND SAFETY

In order to evaluate the wind comfort in pedestrian, Figure 6 shows CFD results at selected points between buildings B1 and B3 (labelled as: 1, 2 and 3), at pedestrian level. It demonstrates that the peak ‘pedestrian’ wind speeds are higher when the wind direction is from North, South and East, rather than West. This is because building B3 acts as an obstacle to westerly currents.

Also, when the wind direction is from the North or South, it is clear that wind speeds at point 2, in the middle and near the end of pedestrian path, are greater than that at point 1, for all wind speed values.
Figure 5: Wind stream-line at pedestrian level (1.5 m above the ground) of the area surrounding the Hub, (A) North direction, (B) East direction, (C) West direction and (D) South direction

Figure 6: Wind rose diagram for mean wind speed at pedestrian level; points 1,2 and 3
Yet, when the wind blows from East, point 3 has the lower peak value because of the location of building 2.

It is apparent that the identification of origin causing undesirable wind comfort depends on the building design. So, optimisation of wind comfort to suit the requirements for city life and commercial usage can be important.

In general, solving a wind nuisance problem after the design has been finalized can be difficult, expensive and not very effective. Hence, wind environmental conditions should be taken into account during the design stage. Combining architectural design with considerations for acceptable wind climate is often difficult. After reading the report produced from this study the University’s Estates Department took the results under consideration. It was decided to introduce vegetation with plants and trees in an effort to ‘break’ the wind and decrease the velocity at key areas specified in the study (Figure 7).

Figure 7: Area between the Hub and James Starley (building B3) before and during vegetation works

7 CONCLUSION

In general, when two or more buildings are constructed in proximity, the fluid flow surrounding the buildings may be significantly deformed and of a much complex nature than usually acknowledged. Knowing the strong dependence of comfort on velocity and turbulence it is of practical interest to study these flow features associated with certain building arrangements, typical of urban areas and hence to assess the comfort conditions on the neighbour pedestrian circulations.

This paper has presented a CFD simulation for the evaluation of pedestrian wind comfort and safety in urban areas, the use of CFD in assessing and optimising engineering design solutions related to environmental concerns has been demonstrated through several case studies.

Results from the simulations presented in this paper show that FLUENT is a good tool for evaluating critical effects of wind around buildings from the viewpoint of pedestrians comfort. In addition, helping us to quantify wind discomfort levels.

The idea of studying wind comfort and safety in urban area incorporate the aim of raising attention to available methods and tools that facilitate planning with health and comfort in mind. Urban planning decisions including landscape transformation, rejuvenation—all determine the thermal and aerodynamic conditions, the bioclimatic load users will be exposed to. Therefore the involvement of all relevant disciplines in the design process, cooperation and communication between various professionals (architecture, planning, climatology and biometeorology) is therefore of paramount importance.

REFERENCES


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