Title	Sustainable Design using Computational Fluid Dynamics in the Built Environment-A Case Study
Authors(s)	Keenahan, Jennifer, Mac Réamoinn, Réamonn, Paduano, Cristina
Publication date	2017-02-19
Publication information	Keenahan, Jennifer, Réamonn Mac Réamoinn, and Cristina Paduano. “Sustainable Design Using Computational Fluid Dynamics in the Built Environment-A Case Study.” Kansas University of Technology, February 19, 2017. https://doi.org/10.5755/j01.sace.19.2.17991.
Publisher	Kansas University of Technology
Item record/more information	http://hdl.handle.net/10197/10277
Publisher's version (DOI)	10.5755/j01.sace.19.2.17991

JSACE 2/19

Sustainable Design using Computational Fluid Dynamics in the Built Environment – A Case Study

Received
2017/04/19

Accepted after revision
2017/05/30

Sustainable Design using Computational Fluid Dynamics in the Built Environment – A Case Study

Jennifer Keenahan*

Arup, 50 Ringsend Road, Ringsend, Dublin 4, Ireland and University College Dublin
Newstead, Belfield, Dublin 4

Reamonn MacReamoinn, Cristina Paduano

Arup, 50 Ringsend Road, Ringsend, Dublin 4, Ireland

*Corresponding author: **jennifer.keenahan@ucd.ie**

http://dx.doi.org/10.5755/j01.sace.19.2.17991

In recent years, end users have become more concerned with the human experience and the personal comfort of the individual is becoming more important in the design of the built environment. Computational Fluid Dynamics (CFD) is a tool that permits assessment of personal comfort. CFD is a stream of fluid mechanics that utilises numerical methods to analyse and solve problems involving fluid flows. While research applications of CFD are developing, as is the use of CFD in the aerospace and Formula1 industries, the use of CFD in Civil Engineering applications is currently at the cutting edge. This paper will investigate the use of computational fluid dynamics as a complementary approach to wind tunnel testing for pedestrian comfort. The results showcased here were determined through a consultancy project by the team at Arup, Dublin. On determining potential wind problems, mitigation measures were proposed and tested in CFD to prove that the mitigation measures were effective. These proposed changes were incorporated into the final design and as a result planning permission was awarded for the development. This work is exemplar of how, from the very conception of the project design, new technological advances lead to a better built and sustainable environment for all.

Keywords: Built Environment, CFD, Pedestrian Comfort, Wind, Wind Tunnel Test.

Introduction

The design of urban environments ought to focus on the effects of the design on the outdoor built environment, in addition to focusing on the envelope of the building and on the quality of the indoor environment. To date, the outdoor built environment has received relatively little attention by designers, particularly with respect to wind. The negative effects of windy environments were first discussed by Wise (1970) who noted the presence of vacant shops where shoppers were discouraged due to the windy environment. Separately, Lawson and Penwarden (1975) noted the deaths of two elderly ladies who were victims of windy gusts near a high-rise building. It is evident that the risks and consequences of unfavorable wind environments for pedestrians cannot be overstated.

The main source of pedestrian discomfort is related to the force of the wind felt on their body and their clothing as additional effort is required to negotiate the wind. The Beaufort scale was the first empirical measure that related wind speed to observed conditions, it has been presented and incorporated in wind comfort studies by (Penwardon, 1973 and Soligo et al., 1998). Other authors (Penwardon et al., 1975 and Murakami and Deguchi, 1981) propose threshold wind ve-

Journal of Sustainable
Architecture and Civil Engineering
Vol. 2 / No. 19 / 2017
pp. 92-103
DOI 10.5755/j01.sace.19.2.17991

locities for pedestrian wind comfort. More detailed comfort criteria reflecting individual opinions on acceptable frequencies of occurrence of various wind speeds have been proposed in Isyumov & Davenport (1976), Apperly and Vickery (1974) and Melbourne and Joubert (1971). Later, grades of comfort are introduced related to the probability that a threshold wind speed may be exceeded (Willemsen and Wisse, 2007).

The Lawson Comfort Criteria (Lawson and Penwarden, 1975; Lawson, 2001) quantifies an individual's annoyance with the wind. It enables the level of pedestrian discomfort to be evaluated based on pedestrian activity, wind speed and frequency of occurrence. A wind is *acceptable* if it goes unnoticed, *unpleasant* if it is noticed but it does not prevent the area from being used for its designated purpose, and *annoying* when it is of sufficient strength and frequency to prevent the area being used for its designated purpose. Certain building configurations may give rise to intense local wind flows. Buildings that stand taller than their neighbors collect the wind over much of their height and direct it towards the ground. Intuitively, given that wind speed increases with height, the taller the building, the faster the wind speeds delivered to ground level (Lawson, 2001). The funneling of wind through narrow gaps between buildings can also cause unpleasant wind environments.

To move towards a long-term sustainable built environment that is useable by pedestrians, it is necessary to determine the risk and occurrence of possible zones of unacceptably high pedestrian discomfort. It is crucially important that appropriate design decisions are made to eliminate such zones. While the challenge of wind-induced discomfort of pedestrians is not new, more modern types of buildings and open space configurations have evolved to create potentially even windier environments. Typically, such configurations involve tall buildings rising well above the surrounding built environment and adjacent to open spaces such as plazas and malls (Simiu, 1996).

There are many design considerations that architects, engineers and planners take into account to mitigate windy conditions in the built environment. The orientation of commercial and residential buildings, the selection of the type of balcony (winter-garden or re-entrant balcony) relative to the direction of the prevailing winds and the inclusion of wind canopies and shelters are some examples that markedly improve the wind environment for the end users and pedestrians.

Urban authorities and councils are beginning to recognize the importance of pedestrian wind comfort and wind safety. The Dutch Wind Nuisance Standard NEN 8100 (NEN, 2006), to the best knowledge of the authors, is the first standard in the world to account for pedestrian wind comfort in the built environment. It is noteworthy that the standard unambiguously permits the designer to choose between wind tunnel experimentation and CFD modelling to assess the wind environment (Blocken et al. 2012).

Flachsbart (1932), concluded that simulations of the behavior of wind around buildings should be conducted in wind tunnels. Wind tunnel testing is now a long-established approach and the knowledge and experience gained over the years has established wind tunnel testing as the traditional method for conducting wind analysis. However, wind tunnel testing is not without its short-comings. For instance;

- Wind tunnels requires physical equipment to collect the data. As a result, it is only possible to monitor the flow field at a limited number of locations and it is difficult to measure the pressure field and velocity field at the same time. Furthermore, the presence of the measuring device can often disrupt the flow.
- For a truly representative model, the Reynolds number should be similar for the model as for the prototype. However, the reduced scale models used in the analysis of tall or long-span structures would require impossible air flow velocities though the tunnel to ensure Reynolds number consistency.
- Time and effort is required to develop a scale model for the wind tunnel test, this renders them unsuitable to the earlier stages of the design process when the design is in greater flux.
- Wind tunnel estimates from different wind tunnels can vary widely.

With the advent of computational power and the capability of numerical methods like Finite Element Analysis, it is now possible to accurately simulate wind flow conditions in a virtual environment. Computational Fluid Dynamics (CFD) is an advanced modelling technique that establishes a basis to solve problems of fluid flow. CFD solves partial differential equations in continuum mechanics using numerical techniques. The equations governing fluid motion are based on the fundamental physical principles of the conservation of mass, momentum and energy. CFD discretizes the overall problem into many small volumes that can be solved more easily (Ferziger, 2002). Combining the solutions from these small volumes permits the generation of a complete solution.

CFD has been successfully applied in many areas of fluid mechanics including, heat and mass transfer (Lien, 2012), chemical reaction and combustion (Senveli, 2014), aerodynamics of cars and aircrafts, and pumps and turbines. Applications of CFD to the built environment include wind modelling and the dynamics response of structures (Montazeri, 2013) ventilation (Meroney, 2009) fire, smoke flow and visibility (Senveli, 2014) dispersion of pollutants and effluent (Prasad, 2013) and heat transfer in buildings (Kobayashi, 2003). Traditionally, the interaction of these phenomena has been carried out experimentally, using scaled models and short calculations.

Computational Wind Engineering (CWE) is a branch of CFD concerned with the behavior of wind. Similar to wind tunnel tests, it can be used to understand the interaction of wind flow through an urban environment and the effect of a proposed development on the local wind microclimate.

In CFD the problem is expressed as a mathematical model and is solved iteratively using numerical methods this gives abundant benefits over the physical wind tunnel, including:

- The entire flow field is solved simultaneously in CFD and therefore, it is possible to collect results from anywhere within the computational domain without influencing accuracy.
- The scale of the model is irrelevant in CFD modelling as the computational domain can be set to any scale. As a result, CFD does not suffer from any issues with Reynolds number violation.
- Generally, CFD software packages interface easily with computer aided-design (CAD) packages. Should changes in design be necessary, it is relatively easy to adjust a CFD model due to these new design specifications and therefore, CFD is better integrated into iterative design processes.

However, CFD is not without its disadvantages. For instance, it is difficult to model free stream turbulence in CFD and it can be challenging to accurately model flow separation and free shear layers. If it is possible to verify and validate a CFD model using wind tunnel testing as a benchmark, there is potential to examine a greater variety of flow configurations due to greater flexibility of CFD. Lastly, to capture wind flow phenomena in sufficient detail, large finite volume models are necessary requiring significant processing power. These large models generate a great amount of data, which in turn needs to be stored and analyzed.

There have been a few studies that use CFD in the built environment. He and Song, (1999) used a LES simulation CFD model based on the weakly compressible flow equations to simulate pedestrian fields around an urban area. Three case studies are presented showing differing wind effects. CFD is not however used as a design tool to modify proposed buildings nor is a wind tunnel test used to validate the results. A comparison of numerical results is presented with the classic wind tunnel tests on different buildings.

Janssen, Blocken and Hooff (2013) compared different wind comfort criteria based on a case study of Eindhoven University, Netherlands. Validation was possible using real-world measurements from the university, taken over a two-hour span. There was no modification proposed during a design process. In (Blocken Janssen and Hooff, 2012) a framework is presented for the integration of the existing best practice guidelines into wind comfort and wind safety studies performed with CFD. The same Eindhoven University case study and validation is used to build the framework. Fadl and Karadelis (2013) undertook CFD simulation for wind comfort and safety at Coventry University, in the UK. No validation tests were conducted and no changes to the design were needed.

This paper proposes a world first, to validate CFD against wind tunnel tests for the same building while also proposing a change in design to alleviate pedestrian discomfort. The results showcased here were determined through a consultancy project by the team at Arup, Dublin. On determining potential wind problems, mitigation measures were proposed and tested in CFD to prove that the mitigation measures work. These proposed changes were incorporated into the final design and as a result planning permission was awarded for the development. This work is exemplar of how, from the very conception of the project design, new technological advances lead to a better built and sustainable environment for all.

Methodology

The proposed development at the Dublin docklands consists of the construction of an office building ranging in height from 8 to 17 storeys, herein referred to as the Dublin Docklands tall building. The construction of new buildings and the alteration of the existing landscape may alter the flow of the wind in the surrounding area (Penwarden, 1973). It was found that the proposed development can generate a wind environment at ground level that is discomforting or even possibly dangerous to pedestrians, these metrics were determined in accordance with the Lawson Comfort Criteria (Lawson, 2001) previously discussed. This case study was first modelled in a wind tunnel test, where the potential for pedestrian discomfort was identified. Arup undertook the wind modelling of the entire built landscape using CFD to first validate and prove that the augmentation to the design taking into account these findings. The wind tunnel test and the CFD model are discussed in this section. An assessment of the microclimate was also undertaken to test the CFD model in historic wind conditions.

Wind Tunnel Test

The objective of a wind tunnel test is to produce estimates of wind effects with specified mean recurrence intervals. Wind tunnel tests measure aerodynamic or aero-elastic data associated with wind-structure interaction, i.e. aerodynamic pressures, the dynamic or aero-elastic response and wind speeds affecting pedestrian spaces. The object or model under investigation is placed in the centre of the wind tunnel, sufficiently downstream to facilitate the development of the velocity profile, and sufficiently upstream to capture the wake of the flow. Air at a given velocity is blown down the tunnel using a fan. Small blocks or spike are used upstream of the model under investigation to simulate turbulence in the flow. Sensors are distributed on the surface of the scale model placed in locations of interest.

A boundary layer wind tunnel study of the proposed development at the Dublin Docklands tall building was previously conducted by another company at a local wind tunnel facility to assess the impact of the proposed development on the wind microclimate. The study examined the wind microclimate of the Dublin Docklands in its existing configuration and the proposed development.

CFD Modelling Methodology

Modelling in CFD comprises three main stages: pre-processing, simulation and post-processing. Pre-processing involves the construction of the geometric model for the flow domain of interest, and the subsequent division of this domain into small control volumes (cells), a process often called ‘meshing’. The flow field and the equations of motion are discretized, and the resulting system of algebraic equations is solved to give values at each node. Once the model and the mesh have been created, appropriate initial conditions and boundary conditions are applied.

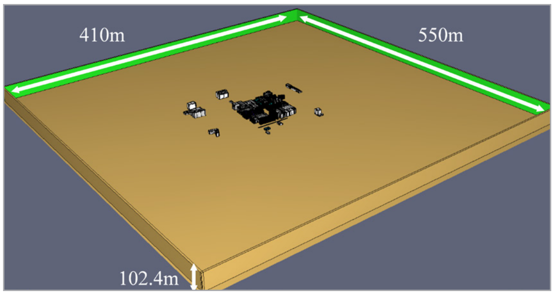
The Navier-Stokes equations, the governing equations for the behaviour of fluid particles, are solved iteratively in each control volume within the computational domain until the solution converges. The field solutions of pressure, velocity, air temperature and other properties can be calculated for each control volume at cell centres and interpolated to out points in order to render the flow field.

Post-processing involves graphing the results and viewing the predicted flow field in the CFD model at selected locations, surfaces or planes of interest. The Navier-Stokes equations, used within the CFD analysis, apply a numerical representation to approximate the laws of physics to produce extremely accurate results, providing the scenario modelled is representative of reality.

As part of the computational process, the domain was divided into a total of 16 million cells. The cells range in size from 0.4 m at the Dublin Docklands tall building to 3.2 m at the outer domain (**Fig. 1**). Closed boundary conditions were applied on the bottom face of the domain, representing the ground. Open boundary conditions were modelled elsewhere.

Fig. 1

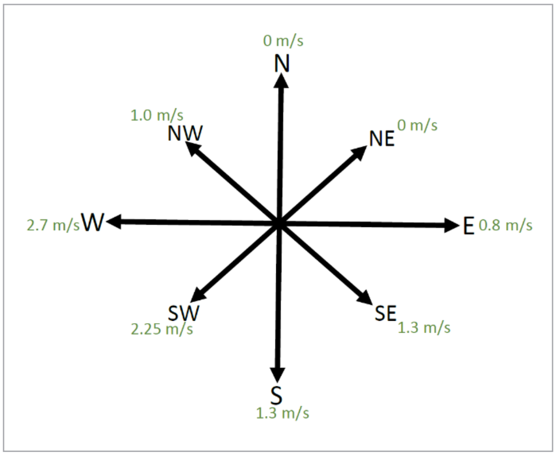
Computational Domain



As with any computer simulation, the quality of the results is dependent on the quality of the inputs; the assumptions, modelling characteristics employed and the equations used to represent the phenomena. There will inevitably be approximations, and a robust model validation process is essential. A high-level understanding of the modelling process and of the phenomena being modelled is necessary for the output to be of any practical use.

Fig. 2

Wind Speeds – Comfort Criteria

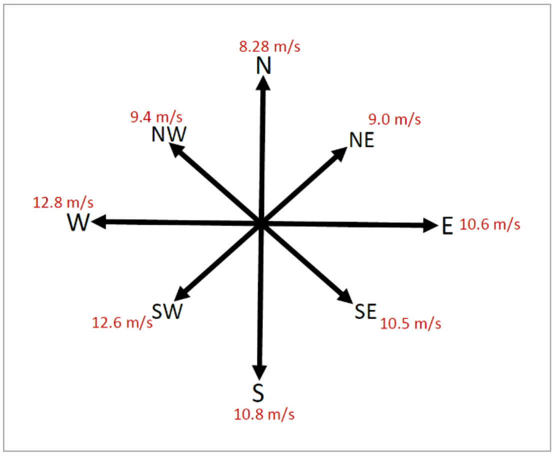


Assessment of the climate

The local wind climate was determined from historical meteorological data recorded at Dublin Airport. Two different datasets were analysed, namely; the data associated with the maximum daily wind speeds recorded over a 30-year period between 1985 and 2015, and the mean hourly wind speeds recorded over a 10-year period between 2005 and 2015. The wind speeds in the vicinity of the development will differ from the wind recorded at Dublin Airport. It is necessary to transform the wind speeds to take account of local conditions (Simiu, 2001). From this, a single wind speed profile was determined for each direction for both comfort and distress criteria, as illustrated in **Fig. 2** and **Fig. 3**.

Fig. 3

Wind Speeds – Distress Criteria



Verification by Sensitivity Analysis

A verification of the model used in this research investigated the effects of five parameters; the upstream length, the downstream length, the model height, the cross-stream width and mesh size. In essence this captures the sensitivity of the results to the size and shape of the domain. Using a Modified Partial Design Technique adapted from (Box, 2005), nine models were created using variations in these parameters, the combinations of which are shown in **Table 1**.

Table 1

Nine combinations for use in the Partial Design Technique

Model	Upstream Length (m)	Downstream Length (m)	Height (m)	Cross-Stream Width (m)
	- = 150 + = 250	- = 35 + = 245	- = 78 + = 128	- = 170 + = 415
1	-	-	-	-
2	+	-	-	+
3	-	+	-	+
4	+	+	-	-
5	-	-	+	+
6	+	-	+	-
7	-	+	+	-
8	+	+	+	+
9	200	140	103	293

The results of the nine models were analysed to assess sensitivity of the results of wind velocity to each of the four parameters. **Fig. 4** shows the sensitivity of the recorded velocity at sensor locations H2, B2, E11 and E9. H2 is placed at the north-east corner of the building, B2 is placed on the north-west corner of the building, and sensors E11 and E9 are located in the undercroft. All sensors are at a height of 1.6m.

From each of the sup plots of **Fig. 4**, it is observed that the same trend of sensitivities emerge as the upstream length, downstream length, height and cross-section width are altered. Examining

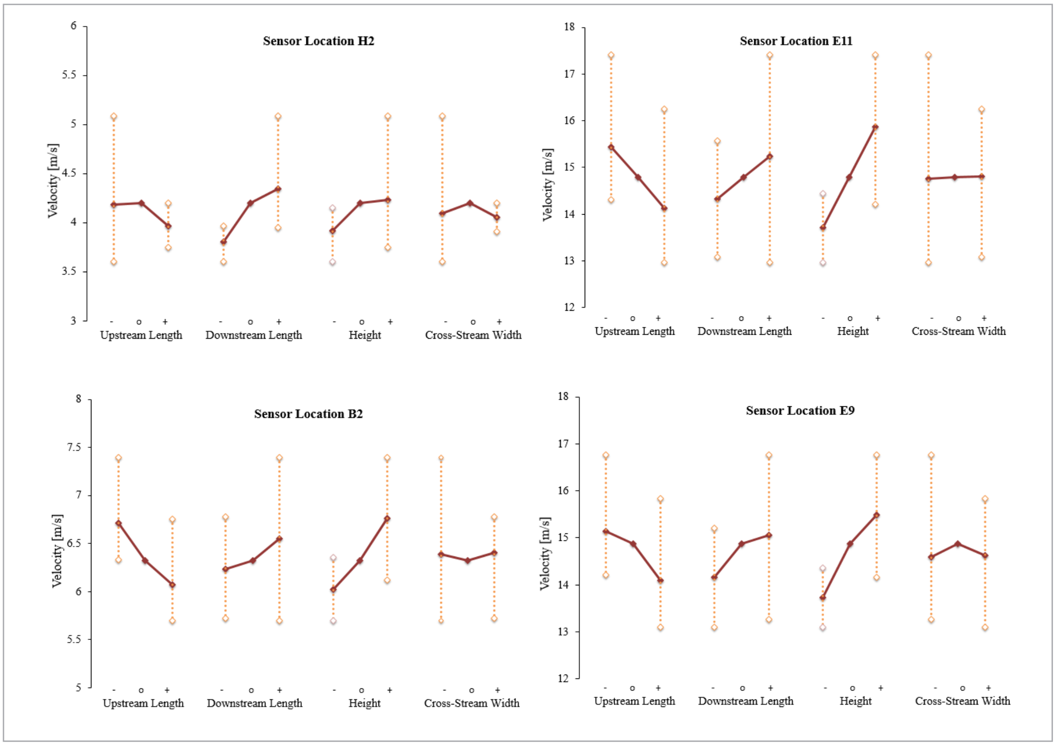


Fig. 4

Verification of results from four sensors placed at grid reference points H2, E11, B2, and E9 one of these plots, in the case of sensor location H2, as the upstream length increases, less than a 5% decrease in velocity is observed. It was found that the recorded velocities were also slightly sensitive to changes in downstream length. For sensor location H2 as the downstream length increases, the velocities range from 3.8 m/s to 4.25 m/s respectively. Less than a 5% increase is observed in the velocities of this sensor as the domain height increases. In relation to the effect of the cross-stream width on results, the velocities recorded at the twelve locations were found to be insensitive to changes in the cross-steam width. The trend seen in these velocities are replicated for eleven other sensors placed at various locations throughout the model.

A tenth verification model was created to assess the sensitivity of velocity results to changes in mesh size. In this model, the domain size matches that of the 9th model, provided in the **Table 1**; however, the mesh size was half as fine (0.2 m as opposed to 0.4 m). Even with this increase in granularity the velocities observed by the twelve sensor locations were found to be insensitive to decreasing the mesh size.

Validation

To validate the CFD modelling process the environment was recreated in the wind tunnel analysis predetermined by the external company. For the purposes of validation of the models, the original Dublin Docklands tall building model was considered. The exterior of the building was considered to be smooth, which is consistent with the wind tunnel tests and therefore, it neglects any influence of the external truss on the flow. The equivalent average hourly gust speed is calculated based on 5% turbulence intensity and a K value of 1.5. The data sampling locations (**Fig. 5** and **6**), have been selected to be as close as possible to the exact sensor locations used in the wind tunnel tests. This study focuses on Points 18 to 28 and is confined to comparing, at these locations, the CFD results with the findings of the previous microclimate study. The comfort criteria and distress criteria adopted in this study are consistent with the previous wind assessment carried out by the external company.

The validation results of the CFD simulation of the Dublin Docklands tall building shows good consistency with the original wind tunnel test results. As indicated in **Fig. 7** and **8**, the CFD simulation results suggest that many of the same locations identified using wind tunnel testing suffer from pedestrian discomfort and distress. Therefore, the results of the CFD models are considered to be consistent with the original wind tunnel test results.

5

Fig. 5

CFD Data Sampling Locations at Pedestrian Level

6

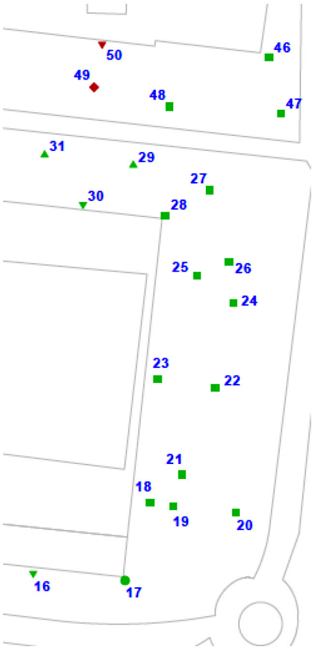
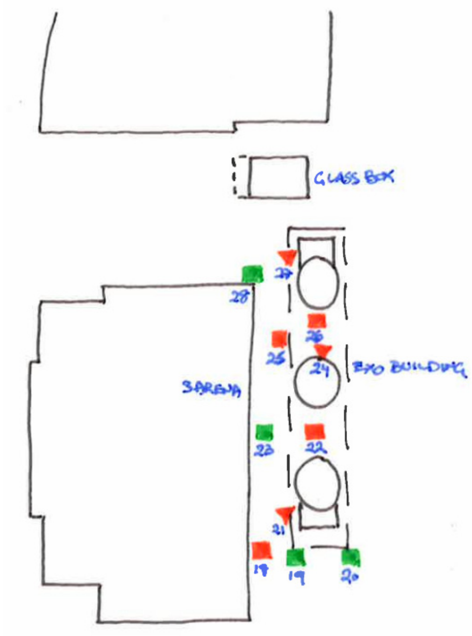


Fig. 6

Data Sampling Locations at Pedestrian Level of the external company

7



8

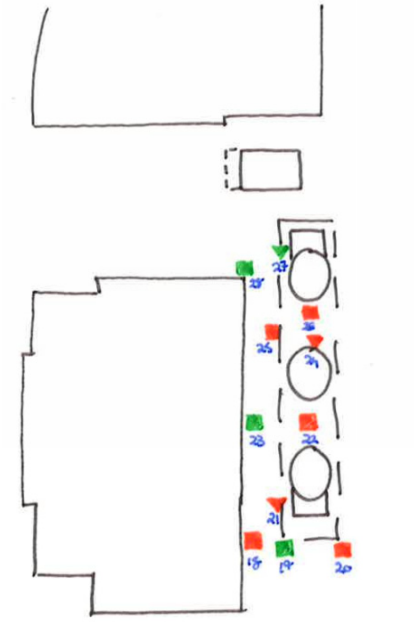


Fig. 7

Wind Tunnel Tests Wind Microclimate Results Summary for Original Dublin Docklands tall building with Mitigation Measures in Future Environment

Fig. 8

CFD Simulation Wind Microclimate Results Summary for Original Dublin Docklands tall building with Mitigation Measures in Future Environment

Results

The assessment of the pedestrian comfort and distress in the pedestrian thoroughfare between the 3Arena and the Dublin Docklands indicates that the main areas of concern are at the southern end. The equivalent wind speeds from the perspective of comfort and distress are 12 m/s and 24 m/s respectively. These speeds arise when high westerly winds cause discomfort and distress between the 3Arena and the Dublin Docklands tall building (**Fig. 9**). Midway along the building, the equivalent hourly average gust wind speed from a comfort perspective is 8.3 m/s. at the northern end, the analysis reveals that the wind speeds are insufficient to cause either discomfort or distress.

In addition, it is possible that winds from the south and north will be of distress to the public. The equivalent hourly average gust speed is estimated at 15.4 m/s and 16.3 m/s from the North and Southwest, respectively. These wind speeds exceed the distress threshold for the public of 15 m/s.

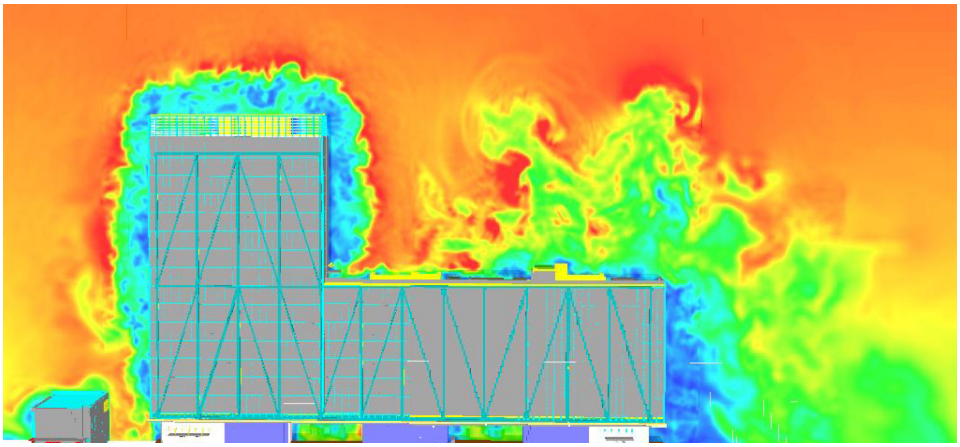


Fig. 9

Distress Criteria, Wind from the West, Minimum values in blue (0m/s), Maximum values in red (20m/s)

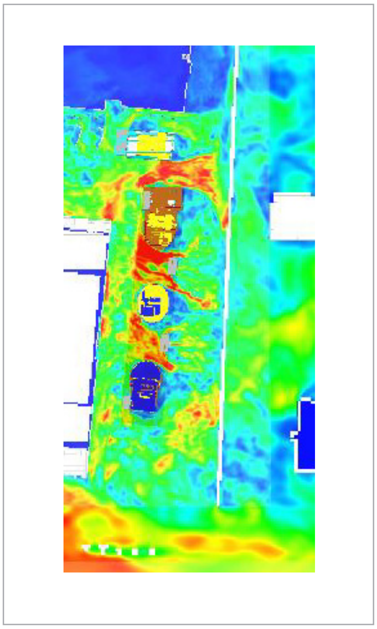


Fig. 10

Distress Criteria, Wind from the West, Minimum values in blue (0m/s), Maximum values in red (20m/s)

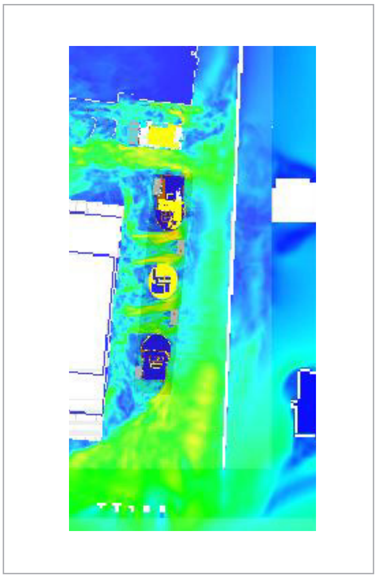


Fig. 11

Distress Criteria, Wind from the East, Minimum values in blue (0m/s), Maximum values in red (20m/s)

The assessment of the pedestrian comfort and distress in the passageways between the Dublin Docklands tall building reveals that the wind conditions might be discomforting and distressing to pedestrian. However, the level of discomfort and distress is related to the wind direction. For instance, while westerly winds with an annual return period may produce conditions unsuitable for undertaking any activity within the undercroft, a slight shift in direction to the south results in an acceptable environment. It would appear that much of the pedestrian discomfort and distress is due to westerly winds. From the perspective of comfort, the equivalent hourly average gust speed in the undercroft passageways range between 10 m/s and 13.9 m/s for westerly winds, which is considered uncomfortable irrespective of the activity being undertaken. The main source of distress is due to westerly winds which range between 15 m/s and 30 m/s along the length of the building. These high wind speeds near ground level are due to the building funnelling high level winds downward. The wind speeds are further increased through the undercroft passageways as the wind is forced through narrower openings underneath the building (**Fig.** 10). Although it might be expected that easterly winds might cause similar pedestrian discomfort and distress within the building undercroft, it is apparent from **Fig.** 11 that this is not the case. The wall on the western boundary of Dublin Port acts to disturb the wind. The bluff nature of the wall causes the flow to separate and the formation of large vortex between the wall and the Dublin Docklands tall building (**Fig.** 12). The vortex acts to push much of the wind over the Dublin Docklands tall building. As a consequence, there is less flow passing under the Dublin Docklands tall building.

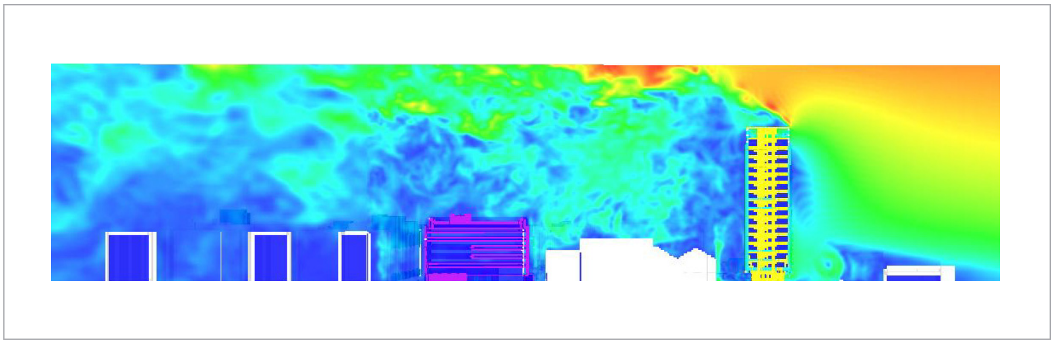


Fig. 12

Distress Criteria, Wind from the East, Minimum values in blue (0m/s), Maximum values in red (20m/s)

Modifications to the design

The assessment of the wind microclimate indicates that westerly winds are responsible for most of the pedestrian discomfort and distress associated with this development. Furthermore, the high-speed winds present at ground level are largely due to downdrafts. These high-speed winds are further exacerbated by the narrower openings between the cores within the undercroft. It should be possible to improve the quality of the public realm near the Dublin Docklands tall building with respect to the wind microclimate by preventing these high-speed air flows in reaching the ground.

The downdraft can be mitigated through the provision of a canopy above ground level along the western edge the building. The design was modified to include a 3.0 m canopy. The purpose of this modification is to enable the canopy to act as a wind gutter. The extension of the canopy to the edges of the building helps the development of a positive pressure gradient along the canopy with the objective of driving the flow around the building rather than underneath it. The modifications to the canopy were considered in a further simulation. In addition, while the original CFD models utilised a relatively coarse mesh, which permitted a crude representation of the exterior truss in the model, this model adopted a finer mesh of moderate refinement, which enables the truss structure to be represented more accurately.

The results of this simulation reveal that the ground level wind speeds are considerably lower than the earlier simulations beneath the building and along the pedestrian thoroughfare between the 3Arena and the Dublin Docklands tall building. For instance, a significant decrease in wind speed was identified underneath the building near the northern core, where the equivalent hourly average gust speed reduced from 30 m/s to 14.5 m/s. This reduction in wind speed is attributed to the provision of a larger canopy.

It is apparent from **Fig. 13** that the canopy does not confine the flow completely. However, it does indicate the presence of a large wake region below the canopy. This wake region does indicate that the canopy disrupts the downdraft. The overall effect is to reduce the velocity of the flow through the undercroft as illustrated in **Fig. 14** and **15** with the effect of significantly improving pedestrian comfort to acceptable levels. Furthermore, the canopy proposed in the design is 3 m wide which enhances its effectiveness. This will further reduce the wind speeds within the undercroft and improve pedestrian comfort to more acceptable levels.

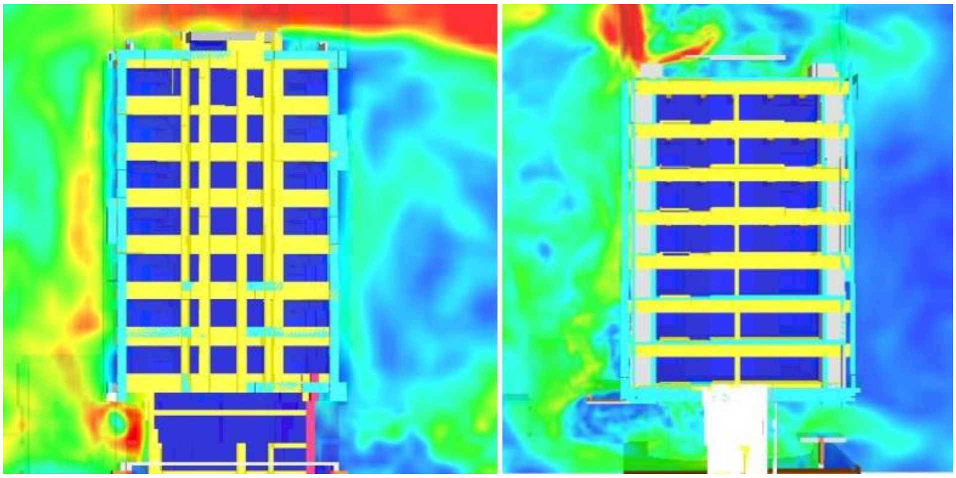


Fig. 13

Comparison of 1.5 m canopy (left) and 2.5 m wind gutter (right) for Distress Criteria, Wind from West, Elevation View from the West, Minimum Values in Blue (0m/s), Maximum Values in Red (20m/s)

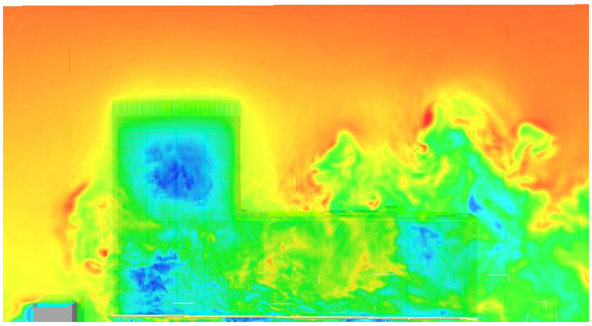
Fig. 14

Distress Criteria, Wind from West, Elevation View from the West, Minimum Values in Blue (0m/s), Maximum Values in Red (20m/s)

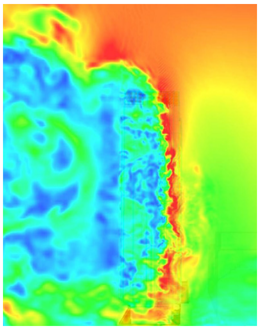
Fig. 15

DistressCriteria, Wind from West, Elevation View from the North, Minimum Values in Blue (0m/s), Maximum Values in Red (20m/s)

14



15



Conclusions

This research has validated that CFD obtains equivalent results, comparable to and in agreement with a wind tunnel test. Further, as potential wind problems were uncovered in the design stage of a building submitting for planning permission, mitigation measures were proposed and tested in CFD to verify the proposed changes. These changes were incorporated into the final design and as a result planning permission was awarded for the development. This case study is exemplar of how, from the very conception of the project design, new technological advances lead to a better built and sustainable environment for all. This paper shows that CFD has a role to play in informing design to mitigate unpleasant wind conditions. In summary, CFD is a strand of applied research that has the potential to improve quality of design, is of immediate practical use and has a significant role to play in sustainable consulting engineering.

Acknowledgment

The authors wish to acknowledge the support of Arup Ireland in the completion of this work.

References

Apperly, L.W. and Vickery, B.J. The prediction and evaluation of the ground level wind environment. In Proceedings of the Fifth Australasian Conference of Hydraulics and Fluid Mechanics, University of Canterbury, Christchurch, New Zealand, 1974.

Blocken, B., Janssen, W.D., van Hooff, T. CFD simulation for pedestrian wind comfort and wind safety in urban areas: general decision framework and case study for the Eindhoven University Campus. Environmental Modelling and Software, 2012; 30: 15-34. https://doi.org/10.1016/j.envsoft.2011.11.009

Box, G. E.; Hunter, W. G.; Hunter, J. S. (2005). Statistics for Experimenters: Design, Innovation, and Discovery (2nd ed.). Wiley. ISBN 0-471-71813-0.

Fadl, M.S. and Karadelis, J. CFD simulation for wind comfort and safety in urban area: a case study of Coventry University central campus. International Journal of Architecture, Engineer and Construction, 2013; 2(2): 131-143. https://doi.org/10.7492/IJAEC.2013.013

Ferziger J.H. and Peric M. Computational methods for fluid dynamics. 3rd ed. Springer; 2002. https://doi.org/10.1007/978-3-642-56026-2

Fachsbart, O. Wind pressure on closed and open buildings. The results of the aerodynamic experiment at Gottingen, L. Prandtl and A. Betz (eds.), Publisher of R. Oldenbourg, Munich and Berlin, 1932.

He, J. and Song, C.S.C. Evaluation of pedestrian winds in urban area by numerical approach. Journal of Wind Engineering and Industrial Aerodynamics, 1999; 81: 295-309. https://doi.org/10.1016/S0167-6105(99)00025-2

Isyumov, N. and Davenport, D.G. The ground level wind environment in built-up areas. In Proceedings of the Fourth International Conference on Wind Effects on Buildings and Structures, London, 1975, Cambridge University Press, pp. 403-422.

Janssen, W.D., Blocken, B., and van Hooff, T. Pedestrian wind comfort around buildings: comparison of wind comfort criteria based on whole-flow field data for a complex case study. Building and Environment, 2013; 59 547-562. https://doi.org/10.1016/j.buildenv.2012.10.012

Kobayashi, N. and Chen, Q. Floor-Supply displacement ventilation in a small office. Indoor and Built

Environment, 2003; 12(2): 281-292. https://doi.org/10.1177/1420326X03035918

Lawson T.V. Building aerodynamics. London UK. Imperial College Press, 2001. https://doi.org/10.1142/p161

Lawson, T.V. and Penwarden, A.D. The effects of wind on people in the vicinity of buildings. In: Proceedings 4th International Conference on Wind Effects on Buildings and Structures, 1975. Cambridge University Press, Heathrow, pp. 605-622.

Lien, J. and Ahmed, N. Indoor air quality measurement with the installation of a rooftop turbine ventilator. Journal of Environmental Protection, 2012; 3: 1498-1508. https://doi.org/10.4236/jep.2012.311166

Melbourne, W.H. and Joubert, P.N. Problems with wind flow at the base of tall buildings. In Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, 1971, pp. 105-114.

Meroney, R.N. CFD prediction of airflow in buildings for natural ventilation. In Proceedings of the 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico 2009.

Montazeri, H. and Blocken B. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis. Building and Environment, 2013; 60: 137-149. https://doi.org/10.1016/j.buildenv.2012.11.012

Murakami, S. and Deguchi, K. New criteria for wind effects on pedestrians. Journal of Wind Engineering and Industrial Aerodynamics, 1981; 7: 289-309. https://doi.org/10.1016/0167-6105(81)90055-6

NEN, 2006. Wind comfort and wind danger in the built environment, NEN 8100 (in Dutch) Dutch Standard.

Penwarden, A.D. Acceptable wind speeds in towns. Building Science, 1973; 8 259-267. https://doi.org/10.1016/0007-3628(73)90008-X

Prasad, K., Li, K., Moore, E.F., Bryant, R.A., Johnson, A. and Whetstone, J.R. Greenhouse gas emissions and dispersion. NIST special publication 1159, 2013.

Senveli, A., Dizman, T. and Celen, A. CFD analysis of smoke and temperature control system of an indoor parking lot with jet fans. Journal of Thermal Engineering, 2014; 1(2): 116-130. https://doi.org/10.18186/jte.02276

Simiu E. The design of buildings for wind: a guide for ASCE 7-10 standard users and designers for special structures. 2nd ed. New Jersey, USA: John Wiley & Sons Inc, Hoboken; 2001.

Simiu, E. and Scanlan R.H. Wind effects on structures. 3rd ed. New York. Wiley; 1996.

Soligo, M.J., Irwin, P.A., Williams, C.J. and Schuyler, G.D. A comprehensive assessment of pedestrian comfort including thermal effects. Journal of Wind Engineering and Industrial Aerodynamics, 1998; 77 & 78: 753-766.

Willemsen, E. and Wisse, J.A. Design for wind comfort in The Netherlands: procedures, criteria and open research issues. Journal of Wind Engineering and Industrial Aerodynamics, 2007; 95: 1541-1550. https://doi.org/10.1016/j.jweia.2007.02.006

Wise, A.F.E. Wind effects due to groups of buildings. In: Proceedings of the royal society symposium architectural aerodynamics, session 3, effect of buildings on the local wind, London, pp 26-27 February 1970.

About the authors

JENNIFER KEENAHAN

Assistant Professor[1] and Project Engineer[2]

[1]School of Civil Engineering,
University College Dublin and
[2]Arup Dublin

Main Research Area

Computational Fluid Dynamics for the Built Environment

Address

50 Ringsend Road,
Ringsend, Dublin 4.
Tel. 01 2334455
E-mail: jennifer.keenahan@ucd.ie

REAMONN MAC REAMOINN

Senior Engineer

Arup Dublin

Main Research Area

Computational Fluid Dynamics for the Built Environment

Address

50 Ringsend Road,
Ringsend, Dublin 4.
Tel. 01 2334455
E-mail: reamonn.macreamoinn@arup.com

CRISTINA PADUANO

Senior Engineer

Arup Dublin

Main Research Area

Computational Fluid Dynamics for the Built Environment

Address

50 Ringsend Road,
Ringsend, Dublin 4.
Tel. 01 2334455
E-mail: cristina.paduano@arup.com