Building and Environment 59 (2013) 547–562

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study

W.D. Janssen [a], B. Blocken [a,*], T. van Hooff [a,b]

[a] Building Physics and Services, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[b] Division of Building Physics, Department of Civil Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, P.O. Box 2447, 3001 Leuven, Belgium

A R T I C L E I N F O

Article history:
Received 19 August 2012
Received in revised form
23 October 2012
Accepted 25 October 2012

Keywords:
Wind nuisance and danger
Airflow
Urban area
Urban aerodynamics
Computational Fluid Dynamics (CFD)
Built environment

A B S T R A C T

Assessment of pedestrian wind comfort around buildings requires the combination of wind statistics from a meteorological station, aerodynamic information and a comfort criterion. A wide range of different comfort criteria exist. In the past, several comparison studies of comfort criteria have been made. In the present paper, a different approach is pursued. The goal of this paper is threefold: (1) to provide an illustrative case study based on CFD as a framework for the comparison of different criteria; (2) to compare and evaluate the results by the different criteria as part of a complete wind comfort assessment study; and (3) to stress the importance of standardization of the wind comfort assessment procedure. The case study area is the campus of Eindhoven University of Technology. The 3D steady Reynolds-averaged Navier–Stokes (RANS) equations and the realizable k–ε model are used to provide part of the aerodynamic information. The CFD simulations are performed on a high-resolution grid based on grid-sensitivity analysis. Validation is conducted with on-site measurements. Part of the wind comfort assessment procedure is performed with the Dutch wind nuisance standard NEN 8100. The criteria compared in this study are the four complete criteria by Isyumov and Davenport (1975), Lawson (1978), Melbourne (1978) and NEN 8100 (2006). It is shown that the different criteria can lead to very different conclusions about the wind comfort. Because the outcome of wind comfort studies is often decisive in granting building permits, this illustrates the importance of wind comfort standardization, in particular concerning the comfort criterion.

1. Introduction

Wind comfort assessment studies consist of combining statistical meteorological data with aerodynamic information and a comfort criterion. The aerodynamic information is needed to transform the statistical meteorological data from the weather station to the location of interest at the building site, after which it is combined with a comfort criterion to judge local wind comfort. The aerodynamic information usually consists of two parts: the terrain related contribution and the design related contribution. The terrain related contribution represents the change in wind statistics from the meteorological site to a reference location near the building site. The design related contribution represents the change in wind statistics due to the local urban design, i.e. the configurations of buildings. It can be obtained by either wind tunnel modelling or numerical simulation with Computational Fluid Dynamics (CFD). CFD has some specific advantages compared to wind tunnel modelling, which will be briefly addressed in Section 2, and which are the reasons for its use in the present paper.

A wide range of different wind comfort criteria exist. Most of these criteria consist of a threshold wind speed and a maximum allowed exceedance probability of this threshold. Many criteria also distinguish between various activities, such as sitting, strolling, walking fast, etc. In that case, either different values for threshold wind speed, or different maximum exceedance probabilities, or both, are imposed for these different activities. In the past, several comparisons of wind comfort criteria have been performed. Melbourne [1] suggested that the main difference in the early developed criteria was their way of presentation. Later studies [2,3] however suggested that Melbourne's criteria were much more restrictive than others. An extensive comparison study of wind comfort criteria was performed by Bottema [4]. Later, also Koss [5] provided a detailed overview of existing criteria. Bottema [4] compared most of the existing criteria based on a theoretical method, in which each criterion was converted to a maximum allowed wind amplification factor U/U_{pot}, where U is the local

* Corresponding author. Tel.: +31 (0) 40 247 2138; fax: +31 (0) 40 243 8595.
E-mail address: b.j.e.blocken@tue.nl (B. Blocken).

0360-1323/$ – see front matter
http://dx.doi.org/10.1016/j.buildenv.2012.10.012

hourly mean wind speed and U_{pot} is the so-called potential wind speed. The potential wind speed is the hourly mean wind speed at an ideal meteorological station, at 10 m height over uniformly rough terrain with an aerodynamic roughness length $z_0 = 0.03$ m. Based on this comparison, he concluded that considerable differences exist between different criteria. In particular, he stated that the criteria of Gandemer [6], Isyumov and Davenport [7], Lawson [8] and Visser [9] are generally suitable for use in the Netherlands, while those of Williams and Soligo [10] were judged too lenient, and those of Melbourne [1] were too restrictive for most activities. While Bottema's approach provides a very valuable and systematic way of comparing different criteria, it also has some limitations. The wind amplification factor was assumed to be wind-direction independent, and the practical consequences of differences between criteria were rather difficult to interpret, visualize and communicate. In this respect, analysis of differences between criteria by means of illustrative case studies would be beneficial.

The goal of this paper is threefold: (1) to provide an illustrative case study based on CFD as a framework for the comparison of different wind comfort criteria; (2) to compare and evaluate the results by the different criteria as part of a complete wind comfort assessment study; and (3) to stress the importance of standardization of the wind comfort assessment procedure.

This comparison study is different from previous comparison studies, because of several reasons: (1) it is based on a complex case study; (2) it is performed based on whole-flow field data obtained by CFD; (3) it includes the recently established criteria in the Dutch wind nuisance standard; (4) it is based on a detailed categorization of the four different comfort criteria based on the original articles and on the level of activities in these criteria.

The case study area is the campus of Eindhoven University of Technology in the Netherlands. The 3D steady Reynolds-averaged Navier–Stokes (RANS) equations and the realizable k–ε model [11] are used to provide part of the aerodynamic information. Part of the wind comfort assessment procedure is performed based on the Dutch wind nuisance standard NEN 8100 [12,13]. Note that this paper is at least a partial answer to the call by Willemsen and Wisse [14], co-developers of the Dutch wind nuisance standard, for research and demonstration projects related to this standard.

In Section 2, some comments are given on the use of CFD for wind comfort assessment studies. Section 3 briefly describes some main features of Dutch wind nuisance standard. Section 4 describes the four wind comfort criteria used in this study, as well as some main differences between these criteria. In Section 5, the computational settings and parameters of the CFD simulations are outlined. Section 6 briefly presents the grid-sensitivity analysis, the results of the CFD simulations and the validation study. The results of the wind comfort assessment with the Dutch wind nuisance standard are given in Section 7, while Section 8 compares the results obtained with the four different comfort criteria. Finally, Sections 9 (discussion) and 10 (conclusions) conclude the paper.

2. Some comments on the use of CFD for wind comfort assessment studies

In the past, several CFD studies of pedestrian-level wind conditions around buildings and/or in complex urban environments have been performed [15–32], generally based on the steady RANS equations. Most studies included a comparison of the CFD results with wind tunnel measurements for the same building or urban configuration [16–18,21–24,28,30]. Others applied so-called sub-configuration validation [26,31]. This refers to performing validation for simpler generic building configurations that represent sub-configurations of the more complex urban configuration. For these generic configurations, wind tunnel measurements are generally available in the literature. Pedestrian-level wind studies in complex urban environments in which CFD results are compared with field measurements – as opposed to wind tunnel measurements – are very scarce. One such study was performed by Yoshie et al. [30], who compared CFD simulations with field measurements performed with 3-cup anemometers in 1977 in the Shinjuku Sub-central Area in Tokyo [33,34]. Two other studies of this type were performed by Blocken and Persoon [32] and by Blocken et al. [29].

CFD has been employed on a few occasions in the past as part of complete wind comfort assessment studies, i.e. including the wind statistics and evaluation by a comfort criterion (e.g. [22,25,26,29,31,32]). CFD offers some specific advantages compared to wind tunnel testing. It does not suffer from scaling problems and similarity constraints, because simulations can be performed at full scale. This can become important for extensive urban areas/models, such as in the case study in this paper. The availability of whole-flow field data from CFD is particularly important for the comparison of different wind comfort criteria, as will be shown later in this paper. However, CFD also has some important disadvantages. Especially the reliability and accuracy of CFD are important concerns. In this respect, the use of CFD in wind comfort studies has received strong support from several international initiatives that focused on the establishment of best practice guidelines, which are either general guidelines (e.g. [35–38]) or guidelines specifically intended for pedestrian wind conditions around buildings [29,30,39–44]. Note that these best practice guidelines mainly focused on RANS simulations. Strong support has also been provided by specific guidelines such as those for the simulation of equilibrium atmospheric boundary layers (e.g. [27,42,45–49]) and the generation of high-resolution and high-quality computational grids (e.g. [50,51]). It is very important that the CFD simulations are accompanied by grid-sensitivity analysis and by validation by comparison with high-quality wind tunnel data and/or on-site measurements [29,30,35–38,41–44,52,53]. Important requirements for validation data have been provided by Schatzmann et al. [54] and Schatzmann and Leitl [55].

Studies to assess the accuracy of steady RANS CFD for predicting pedestrian-level wind speed have been reviewed by Blocken et al. [52]. Based on detailed comparison studies between CFD and wind tunnel experiments by Yoshie et al. [30] and Blocken and Carmeliet [31], the following common observation was found: steady RANS simulations with the standard k–ε model [56], the Kato–Launder k–ε model [57], the Renormalization Group (RNG) k–ε model [58] and the realizable k–ε model [11] all systematically showed that the amplification factor U/U_0 (which is the ratio of the local pedestrian-level wind speed U to the wind speed U_0 that would occur at the same position without buildings) is generally predicted with a high accuracy of 10–15% in the regions where $U/U_0 > 1$, while the predicted wind speed is generally significantly underestimated by CFD where $U/U_0 < 1$, at some locations by a factor 5 and more. Because the areas with high amplification factor are those that are most important in wind comfort studies, steady RANS could be considered a suitable method for such studies. The reason is that in case of wind comfort criteria with relatively high wind speed threshold value (e.g. $U_{THR} = 5$ m/s), regions with low U/U_0 will often not contribute substantially to the total exceedance discomfort probability, exactly because of their low amplification factor. In addition, it should be noted that RANS has some considerable advantages compared to Large Eddy Simulation (LES). On the one hand, LES has been shown – when applied correctly – to be more accurate, especially in regions with low U/U_0, because it can capture the inherently unsteady features of the flow field, such as separation regions on building facades and roofs and vortex shedding in the wake of buildings (e.g. [15,59,60]). On the other hand,