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A methodology to assess the influence of local wind conditions and building orientation on the convective heat transfer at building surfaces

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A B S T R A C T

Information on the statistical mean convective heat transfer coefficient ($CHTC_{SM}$) for a building surface, which represents the temporally-averaged *CHTC* over a long time span (e.g. the lifetime of the building), could be useful for example for the optimisation of the performance of solar collectors and ventilated photovoltaic arrays or for preservation analysis of cultural heritage sites. A methodology is proposed to estimate the $CHTC_{SM}$ for a building surface, by combining local wind climate information and information on the *CHTC*, namely $CHTC$-U_{10} correlations, where U_{10} is the mean wind speed at a height of 10 m above the ground. This methodology is applied to a cubic building for a specific wind climate, where the $CHTC$-U_{10} correlations are obtained by means of CFD simulations (CFD code Fluent 6.3, realizable k-ε turbulence model). It is shown that the $CHTC_{SM}$ varied significantly with the orientation of the building surface due to the rather anisotropic wind conditions, where high values are found for surfaces oriented towards the prevailing wind directions, thus for windward conditions. Moreover, the evaluation of the $CHTC_{SM}$ for other wind climates clearly shows that the local wind conditions also can have a significant impact on the overall magnitude of the $CHTC_{SM}$, where differences up to a factor 4 are found in this study. Different levels of complexity for determining the $CHTC_{SM}$ value are also evaluated and it is found that the required number of CFD simulations can be reduced significantly by using more simplified methods to calculate the $CHTC_{SM}$, without compromising its accuracy. The applicability of the proposed methodology for other building-related applications is also discussed, for example to assess statistical mean pressure coefficients, wind-driven ventilation rates or convective mass transfer coefficients.

1. Introduction

Knowledge on the convective heat transfer at exterior building surfaces is of interest for several building and urban engineering purposes. For energy performance analysis, it is especially relevant for glazed buildings (Sharples, 1984), double-skin facades, greenhouses (Roy et al., 2002), textile buildings (He and Hoyano, 2009) and membrane-cushion buildings or for building components like solar collectors (Sharples and Charlesworth, 1998), solar chimneys and ventilated photovoltaic arrays (Palyvos, 2008). In urban areas, the outdoor thermal climate and building cooling load are determined by the turbulent convective heat fluxes from building surfaces and streets (Barlow et al., 2004; Hagishima et al., 2005), which is particularly of interest for the analysis of urban heat islands (Sailor and Dietsch, 2007). Note that these wind-induced convective heat losses are usually much larger, namely 2–7 times, than the radiative losses (Davies, 2004; Loveday and Taki, 1998). Information on convective heat transfer is also often used to quantify convective moisture transfer at building surfaces, by using the heat and mass transfer analogy (Chilton and Colburn, 1934). Both transfer phenomena affect the hygrothermal behaviour within the building envelope since they determine: (1) the drying of facades wetted by wind-driven rain (Janssen et al., 2007a); (2) the risk of surface condensation by undercooling during clear cold nights (Aelenei and Henriques, 2008; Camuffo and Giorio, 2003); and (3) several physical, chemical and biological weathering processes such as microbiological vegetation (algae) and mould growth (Abuku et al., 2009), wet and dry deposition and reaction of pollutants on surfaces (Dolske, 1995; Jonsson et al., 2008), freeze-thaw degradation (Franke et al., 1998), moisture-induced salt transport, crystallisation and related deterioration (Franke et al., 1998; Poupeleer et al., 2006a,b), interstitial condensation, etc.

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This hygrothermal behaviour and the related surface phenomena are important factors for the assessment of durability of constructions and for the preservation of cultural heritage (Carmeliet et al., 2009; Hussein and El-Shishiny, 2009; Monforti et al., 2004; Steeman et al., 2009).

These phenomena can be investigated by means of (building) design guides and standards or numerical modelling, such as Building Energy Simulation (BES) programs (Energyplus; ESP-r), Heat-Air-Moisture transfer (HAM) models (Delphin; Janssen et al., 2007b) and Urban Canopy Models (UCM) (Kusaka et al., 2001; Kondo et al., 2005; Masson, 2000), where convective heat transfer is mostly taken into account by means of convective heat transfer coefficients (*CHTCs*). These *CHTCs* relate the convective heat flux normal to the wall $q_{c,w}$ (W/m^2) to the difference between the surface temperature at the wall T_w (°C) and a reference temperature T_{ref} (°C), which is generally taken as the outside air temperature. The convective heat flux is assumed positive away from the wall. The *CHTC* (W/m^{2}K) is defined as:

$$CHTC = \frac{q_{c,w}}{\left(T_w - T_{ref}\right)} \quad (1)$$

In the past, *CHTCs* for buildings have been mainly quantified by full-scale experiments (Hagishima and Tanimoto, 2003; Ito et al., 1972; Liu and Harris, 2007; Loveday and Taki, 1996; Sharples, 1984), wind-tunnel tests (Quintela and Viegas, 1995) and Computational Fluid Dynamics (CFD) studies (Blocken et al., 2009; Defraeye et al., 2010, submitted for publication). A concise review and discussion on these *CHTCs* for buildings can be found in Defraeye et al. (submitted for publication). Usually, these studies provide estimates for the *CHTC* by means of linear or power-law correlations of the *CHTC* with a reference wind speed U_{ref} (m/s), for example the mean wind speed at a height of 10 m above the ground U_{10}, for different wind directions.

Information on these *CHTC*-U_{ref} correlations however does not yet provide the actual statistical mean *CHTC* ($CHTC_{SM}$) for a certain surface or point on the building, where the $CHTC_{SM}$ represents the temporally-averaged *CHTC* over a long time span, e.g. the building or building component lifetime. This $CHTC_{SM}$ is determined by the local wind climate at the building site (wind climate: wind conditions, i.e. wind speed and wind direction, over a long period of time which can for example be monitored at a meteorological station), where the $CHTC_{SM}$ is characterised by a specific occurrence of wind speed, wind direction and terrain-related approach flow conditions, and by the orientation of the building surface with respect to these local wind conditions. Information of such $CHTC_{SM}$ values could be useful in the analysis of aforementioned building-related phenomena with numerical models which rely on *CHTCs* (e.g. HAM models), since the $CHTC_{SM}$ could provide more reliable long-term thermal convective boundary conditions. The $CHTC_{SM}$ could for example be applied to determine the optimal location of a solar collector or a ventilated photovoltaic array on a building, in terms of convective heat losses, in order to optimise their long-term (i.e. lifetime) performance. Another example is related to the preservation of cultural heritage sites, where the use of both the $CHTC_{SM}$ and the statistical mean convective moisture transfer coefficient ($CMTC_{SM}$) in numerical models could lead to a better prediction of the long-term hygrothermal behaviour in the future and of the related damage processes. Such statistical mean *CHTC* values can thus be very useful for many of these applications. For other applications, which are more focussed on dynamic effects, the use of "instantaneous" *CHTC* values, i.e. on an hourly or daily basis, could be more appropriate. Such instantaneous values could be derived by means of *CHTC*-U_{10} correlations, for example by using hourly wind climate data. This approach is sometimes used in BES and HAM programs, which however often consider a relatively short time period, e.g. a single year.

In this paper, a methodology is proposed to determine the $CHTC_{SM}$ for a building surface, by taking into account the specific local wind conditions. This is done by determining the surface-averaged *CHTC*-U_{10} correlations for a building surface for several wind directions, for which CFD simulations (validated against wind-tunnel experiments) are used in this study, and by relating them subsequently to the local wind climate, by means of statistical meteorological data. The main aims of this study are: (1) to determine a surface-averaged *CHTC* which reflects in a realistic way the actual surface-averaged *CHTC* experienced by a building surface over a long period of time, namely $CHTC_{SM}$, by using local wind climate information; (2) to show that, for specific local wind conditions, the building orientation can have a significant impact on the resulting $CHTC_{SM}$ value of a building surface; (3) to show that the magnitude of the $CHTC_{SM}$ of a specific building surface can also vary significantly for different wind climates; and (4) to indicate the influence of different levels of complexity for taking the local climate into account while determining the $CHTC_{SM}$ value. This methodology will be applied to the facades of a cubic building, which is a rather generic case study, but the application for more complex building configurations, e.g. in the urban environment, is straightforward. Although the focus will be on the surface-averaged *CHTC*, i.e. of an entire building facade, the methodology is also applicable for a part of a building surface, representing for example the surface of a solar collector, or for a specific point on the surface but also for the building as a whole. Therefore, *CHTC* denotes the surface-averaged *CHTC* in the remainder of this paper, unless specified otherwise. Finally, the use of the methodology for other applications, involving pressure coefficients, wind-driven ventilation rates or *CMTCs*, is discussed.

2. Methodology

2.1. Statistical meteorological data

In Section 2, the applied methodology to obtain the $CHTC_{SM}$ for a building surface with a specific orientation is explained, taking into account the local wind conditions. First of all, information on the local wind climate is required. In this study, the statistical meteorological data (hourly mean potential wind speed U_{pot} and wind direction), obtained in the meteorological station of Eindhoven (The Netherlands) for the period 1971–2000 (made available by the Royal Dutch Meteorological Institute), are used for the analysis, which thus provide a statistically reliable data set, representative for the wind climate at the meteorological station. U_{pot} is the wind speed at a height of 10 m for a terrain with an aerodynamic roughness length z_0 of 0.03 m, and is classified into 12 wind direction categories and 19 wind speed categories, in this case. These categories respectively represent intervals of 30° from which the wind blows (for wind direction) and intervals of 1 m/s (for wind speed). The northern wind direction (0°) contains for example all winds coming from −15° to 15° and the wind speed category 3.5 m/s contains all wind speeds within the range 3–4 m/s. These local wind conditions are represented in Fig. 1 and in Table 1. In Table 1, the horizontal rows (wind speeds) are denoted by index *i* and the vertical columns (wind directions) by index *j*. The table specifies the percentage of occurrence x_{ij} (%) of a certain wind speed (*i*) for a certain wind direction (*j*). It is clear that the wind directions between west and south are the most dominant ones. The indication Var/Calm in Table 1 indicates the percentage of occurrence of wind conditions where the wind direction could not clearly be determined due to strong fluctuations or where there is no or a very low wind speed. For the wind climate of Eindhoven, such conditions are found for 4.1% of the time (see Table 1). Note that often meteorological stations do not report wind speed data as potential wind speeds, i.e. for $z_0 = 0.03$ m and at 10 m height. This is not required since the wind speed data of the meteorological station (U_{meteo}) have to be transformed anyway to be representative for the wind speeds at the building site (U_{site}), which is explained in the next section. If requested, U_{pot} data can be determined by transformation of the original wind speed data at the meteorological station (U_{meteo}), using the same methodology as explained in Section 2.2.

2.2. Transformation to building site

If the terrain roughness length at the meteorological station ($z_{0,meteo}$) differs from that at the building site ($z_{0,site}$) or if the height of the meteorological station