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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Abstract

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.

Keywords

convective heat transfer coefficient; building facade; building orientation; wind climate; CFD; low-Reynolds number modelling; RANS

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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 to 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, 2006b), interstitial condensation, etc. 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/m²) 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/m²K) is defined as:

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

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., 2010a, 2010b). A concise review and discussion on these *CHTCs* for buildings can be found in Defraeye et al. (2010b). 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.

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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 $CHTC$ s (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 $CMTC$ s, 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 Figure 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 (H_{meteo}), i.e. the height at which the wind speed is measured, is not equal to the reference height at the building site (H_{site}), which is 10 m in this study, the wind speed data of this meteorological station (U_{meteo} at height H_{meteo}) have to be transformed to be representative for the wind speeds at the building site (U_{site} at height H_{site}) for a specific wind direction. Information on this transformation of the meteorological data to the wind conditions near the building site can be found in Blocken et al. (2004). The wind speed data at the building site are obtained by scaling the data of the meteorological station with a factor

U_{site}/U_{meteo} :

$$U_{site} = U_{meteo} \frac{U_{site}}{U_{meteo}} = \gamma(j) U_{meteo} \quad (2)$$

This scaling factor $\gamma(j)$, which is a function of the specific wind direction (j), can be determined by assuming a logarithmic law for the vertical profile of the mean horizontal wind speed:

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$$\gamma(j) = \frac{U_{site}}{U_{meteo}} = \frac{u_{ABL,site}^* \ln\left(\frac{H_{site} + z_{0,site}}{z_{0,site}}\right)}{u_{ABL,meteo}^* \ln\left(\frac{H_{meteo} + z_{0,meteo}}{z_{0,meteo}}\right)} \quad (3)$$

where u_{ABL}^* is the friction velocity (m/s) in the atmospheric boundary layer (ABL) for a specific wind direction. The ratio of the friction velocities can be approximated by (Simiu and Scanlan, 1986):

$$\frac{u_{ABL,site}^*}{u_{ABL,meteo}^*} = \left(\frac{z_{0,site}}{z_{0,meteo}}\right)^{0.0706} \quad (4)$$

Note that this transformation has to be performed for each wind direction category since for every category, both at the meteorological station and at the building site, a different terrain roughness can be found. For the sake of simplicity, it is assumed in this case that the cubic building is located in a uniform terrain, i.e. with similar terrain roughness for each wind direction, with $z_{0,site} = 0.03$ m. Thereby, the available U_{pot} data of the meteorological station of Eindhoven are representative for U_{10} at the building site in this case, i.e. without the use of any transformation.

Note that if the building of interest is located well within the urban environment, the ABL wind speed profile near the building site will differ to some extent from a classical logarithmic law (e.g. Reynolds and Castro, 2008), especially in the lower region of the urban canopy, i.e. the region in between the ground and the characteristic building height. Transformation of the wind speed profiles at the meteorological station to the building site is thereby less straightforward as in the case of an isolated building since Eq.(4) cannot be used anymore. A transformation can however still be achieved in several ways: (1) If a (larger) computational domain is provided where the buildings in the proximity of the building of interest are modelled explicitly, the flow features characteristic for the lower canopy region are explicitly resolved. This technique is frequently applied in many large environmental studies (e.g. Hussein and El-Shishiny, 2009; van Hooff and Blocken, 2010). In this case, a logarithmic ABL profile can be imposed at the inlet of the computational domain (with $z_{0,site}$ and U_{site} at height H_{site}), by which Eq.(4) can be used for the transformation of the wind speed profiles of the meteorological station; (2) Instead of using Eq.(3) combined with Eq.(4), a specific scaling factor $\gamma(j)$ can be determined which accounts for the non-logarithmic ABL profile at the building site.

2.3 $CHTC-U_{10}$ correlations

Apart from these statistical meteorological data, the surface-averaged $CHTC-U_{10}$ correlations have to be determined for the building surface of interest for each of the 12 wind directions in order to estimate the $CHTC$ for all wind speeds of each wind direction category (see Table 1). The use of available correlations (see Defraeye et al., 2010b) is not always justified since these correlations are derived for a specific building geometry and building surroundings and they are therefore not always representative for the building under consideration. For full-scale measurements, the use of only one or a few particular measuring locations provides an additional source of arbitrariness on the correlations. Moreover, the influence of the wind direction has been generally taken into account by classifying a surface only as windward or leeward in these measurements, which is a rather coarse classification.

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If no representative correlations can be found in literature, with sufficiently detailed wind direction dependency, the $CHTC-U_{10}$ correlations could also be determined directly by means of full-scale experiments, wind-tunnel experiments or CFD simulations for the building surface of interest. Some remarks have to be kept in mind if $CHTCs$ are determined with these techniques: (1) Full-scale experiments have a limited spatial resolution since the $CHTCs$ are only measured at one or a limited number of locations on the building surface so an actual surface-averaged value cannot be obtained. This technique is also only suitable for existing buildings, for example for studies on the preservation of historical buildings, but it cannot be used during the design of buildings. Note that the measurement period for the full-scale experiments can be quite limited since only the correlations have to be obtained (for different wind directions) and statistical information on the occurrence of the wind speed and wind direction is not required. Given a sufficiently long measurement period however, it is also possible to measure the $CHTC_{SM}$ directly; (2) Wind-tunnel tests usually have a higher spatial resolution, which allows to estimate surface-averaged $CHTC$ values to some extent. The thermal measurements however introduce additional difficulties (e.g. Meinders, 1998) with respect to model design, wind-tunnel air conditioning, accessibility of surfaces (e.g. for infrared thermography) and measurement equipment, in comparison with for example pressure measurements, which make these thermal measurements less attractive for practical applications for more complex building configurations; (3) With CFD, the applied turbulence modelling approach determines to a large extent the accuracy of the calculated flow field and thus of the $CHTCs$, which can be quantified by means of validation experiments. On the other hand, CFD provides a very high spatial resolution and imposes few restrictions to building geometry and surface details by which surface-averaged $CHTC$ values can be obtained for all surfaces of interest at once.

Since CFD exhibits advantages with respect to determining (surface-averaged) $CHTCs$ for complex building configurations, compared to other techniques, and since it is used frequently to evaluate flow fields in environmental studies (Hussein and El-Shishiny, 2009; Neofytou et al., 2006; Solazzo et al., 2009; van Hooff and Blocken, 2010; Wakes et al., 2010), the surface-averaged $CHTC-U_{10}$ correlations in this study will be determined by means of CFD (see Section 3). These correlations will be represented by following power-law correlation:

$$CHTC = A_j U_{10}^{B_j} \quad (5)$$

where A_j and B_j are respectively a coefficient and exponent, which are determined for every wind direction j . Note that, due to the symmetry of the cubic building, only two wind directions have to be evaluated with CFD to obtain the $CHTC-U_{10}$ correlations for all 12 wind directions, namely 0° and 30° .

2.4 Calculation of $CHTC_{SM}$

These $CHTC-U_{10}$ correlations allow to determine the $CHTC$ for a given wind direction j , with corresponding factors A_j and B_j , for every wind speed ($U_{10,i}$) that is found for this direction (see Table 1), namely $CHTC_{ij}$:

$$CHTC_{ij} = A_j U_{10,i}^{B_j} \quad (6)$$

Note that for every wind speed category, for example 3-4 m/s, the mean wind speed of that category (3.5 m/s) is used to determine $CHTC_{ij}$ with the correlation. The $CHTC_{SM}$ for the building surface of interest is obtained by averaging these $CHTC_{ij}$ values by taking into account the occurrence of each wind speed i for a certain wind direction j , i.e. x_{ij} :

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$$CHTC_{SM} = \sum_j \sum_i x_{ij} CHTC_{ij} \quad (7)$$

Note that the average $CHTC$ for a certain wind direction j ($CHTC_{AVG,j}$) for the building surface of interest can also be obtained, based on the occurrence of each wind speed i :

$$CHTC_{AVG,j} = \sum_i \frac{x_{ij}}{x_{tot,j}} CHTC_{ij} \quad (8)$$

Here $x_{tot,j}$ is the percentage of occurrence of a certain wind direction j :

$$x_{tot,j} = \sum_i x_{ij} \quad (9)$$

These values are related to the $CHTC_{SM}$ by:

$$CHTC_{SM} = \sum_j x_{tot,j} CHTC_{AVG,j} \quad (10)$$

Although the proposed methodology relies on CFD in this study, the $CHTC-U_{10}$ correlations for different wind directions can be obtained as well by wind-tunnel tests or full-scale experiments. Furthermore, the methodology could also be applied to evaluate the $CHTC_{SM}$ of an entire building, instead of a single building surface, by using the building-averaged $CHTC-U_{10}$ correlation.

3. Calculation of $CHTC-U_{10}$ correlations by means of CFD

3.1. Numerical model

A cubic building with a height (H) of 10 m is considered. The size of the computational domain is determined according to the guidelines of Franke et al. (2007) and Tominaga et al. (2008) and is presented in Figure 2, which allows to evaluate different wind directions. The height of the domain is $6H$. At the inlet of the domain, the vertical profiles of the mean horizontal wind speed U (logarithmic law), turbulence kinetic energy k (m^2/s^2) and turbulence dissipation rate ε (m^2/s^3) are imposed, according to Richards and Hoxey (1993), representing a neutral ABL, i.e. where turbulence in the ABL originates only from friction and shear and not from thermal stratification:

$$\begin{aligned} U(z) &= \frac{u_{ABL}^*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \\ k &= 3.3 u_{ABL}^{*2} \\ \varepsilon &= \frac{u_{ABL}^{*3}}{\kappa(z+z_0)} \end{aligned} \quad (11)$$

where κ is the von Karman constant (0.4187), z is the height above the ground (m). The friction velocity u_{ABL}^* is linked to a reference wind speed, namely U_{10} in this study, which is taken equal to 0.5 m/s. Note that other wind speeds ($U_{10} = 1$ and 2.5 m/s) are also evaluated (Section 3.3), resulting in Reynolds numbers from 3.4×10^5 to 1.7×10^6 . The parameter z_0 is 0.03 m, which corresponds to a land surface with low vegetation (e.g. grass) and isolated obstacles (Wieringa, 1992). The temperature of the approach flow is 10°C, which is taken as the reference temperature in Eq.(1). From the ABL temperature profiles over a flat terrain (Panofsky and Dutton, 1984), it can be shown that assuming a constant temperature over the height of the ABL is a relatively good approximation for a neutral ABL with a zero heat flux at the ground, if a limited height is considered ($6H = 60$ m in this case). Wind at two different incidence angles is evaluated in the simulations, namely at incidence angles of 0° and 30° (Figure 2). The incidence angle (φ) is the angle between the approach flow wind direction and the

normal to the surface of interest. It is 0° for flow perpendicular to the surface and increases in a clockwise manner.

The ground boundary is modelled as a no-slip boundary with zero roughness since surface roughness values cannot be specified if low-Reynolds number modelling (LRNM) is used to model the boundary layer (Fluent, 2006). This is one of the major drawbacks of using the LRNM approach, which is explained in Section 3.2. This restriction will inevitably introduce streamwise gradients in the vertical profiles of mean horizontal wind speed and turbulence (Blocken et al., 2007) but this could not be avoided. This change in the vertical profiles was assessed by performing a CFD simulation in an empty computational domain. This simulation is not reported in this paper but showed a change in the profiles in the first meters near the ground surface, which alters the flow field around the building to some extent. This effect is however limited since a short upstream fetch is considered. The ground boundary is taken adiabatic. The exterior surfaces of the building are modelled as no-slip boundaries with zero roughness and have an imposed constant temperature of 20°C.

For the top boundary of the computational domain, a symmetry boundary condition (slip wall) is used, which assumes that the normal velocity component and the normal gradients at the boundary are zero. Note that other ways to model the top boundary in a more optimised way have been reported by Blocken et al. (2007). This modelling technique however is considered less important in the present case, since a relatively short upstream fetch is considered. Zero static pressure is imposed at the outlet. Note that symmetry boundary conditions are used for the lateral boundaries for an incidence angle of 0° and inlet or outlet boundary conditions are used for an incidence angle of 30° (Figure 2).

An appropriate grid is built, based on a grid sensitivity analysis. The grid is a hybrid grid (hexahedral and prismatic cells) consisting of about 3.3×10^6 cells (Figure 2). In order to resolve the boundary layer appropriately, LRNM grids require a high cell density in the wall-normal direction and a small y^+ value (dimensionless wall distance) of the wall-adjacent cell ($y^+ \approx 1$), compared to wall functions ($30 < y^+ < 500$), where y^+ is defined as:

$$y^+ = \frac{\sqrt{\frac{\tau_w}{\rho}} y_P}{\nu} \quad (12)$$

where y_P is the distance (normal) of centre point P of the wall-adjacent cell to the wall (m), τ_w is the shear stress at the wall (kg/ms²), ρ is the air density (kg/m³) and ν is the kinematic viscosity of air (m²/s). The highest y^+ values are attained at the edges of the windward surface but are smaller than 3 at the highest wind speed that is evaluated in this study.

Since τ_w increases with increasing velocity (U_{10}), the evaluation of higher wind speeds requires that the grid is also sufficiently fine in the boundary-layer region at these wind speeds to have a y^+ value of about 1. Thereby, the required y_P can become very small at high Reynolds numbers (≈ 0.05 mm for $U_{10} = 7.5$ m/s, Defraeye et al., 2010b) which can entail considerable problems for grid generation and convergence rates. However, Defraeye et al. (2010b) showed that relatively low wind speeds could be used, for ABL flow, to evaluate the forced convective $CHTC-U_{10}$ correlations, since the flow field becomes quasi independent of the Reynolds number at Reynolds numbers above approximately 10^5 . Here the Reynolds number was based on the cube height (H) and U_{10} . Therefore low wind speeds, and hence a relatively large y_P , will be used in this study, for LRNM purposes, to determine the $CHTC-U_{10}$ correlations (in Section 3.3).

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3.2. Numerical simulation

The simulations are performed with the CFD code Fluent 6.3, which uses the control volume method. Steady Reynolds-Averaged Navier-Stokes (RANS) is used in combination with a turbulence model. The realizable k- ϵ model (Shih et al., 1995) is used together with LRNM to take care of the viscosity-affected region, for which the one-equation Wolfshtein model (Wolfshtein, 1969) is used.

Since the accuracy of CFD simulations depends to a large extent on the turbulence-modelling and boundary-layer modelling approach that is used, it is imperative that this accuracy is quantified by means of validation experiments. The accuracy of the realizable k- ϵ turbulence model with LRNM was evaluated by means of a CFD validation study (Defraeye et al., 2010a) using wind-tunnel measurements of convective heat transfer on the surfaces of a cube placed in turbulent channel flow at a Reynolds number of 4.6×10^3 , based on the cube height and the bulk velocity, of Meinders et al. (1999). A part of the results of this validation study is shown in Figure 3, where the *CHTCs* on the surfaces of the cube in a vertical and horizontal centreplane from experiments and CFD simulations are given, and where only the results in the central region of the surfaces are shown since discrepancies near the edge zones were attributed to the limited resolution of the experiments in these zones. The simulations produced accurate *CHTC* predictions, both in magnitude and distribution over the surface, for the windward surface (within the experimental uncertainty of 5% in the overall part of the central region of the surface) and to a lesser extent for the leeward surface (differences with experimental data < 10% in the overall part of the central region of the surface).

For the side and top surfaces, the distribution of the *CHTC* over these surfaces was less accurate. This discrepancy is due to the less accurate flow predictions around bluff bodies, in zones of separation and recirculation (Iaccarino et al., 2003; Murakami et al., 1996), which is a generally known deficiency of the steady RANS approach combined with two-equation turbulence models and is attributed to steady-flow and turbulence modelling of the unsteady flow features. The surface-averaged *CHTC* values for all vertical surfaces however show an acceptable agreement with the experimental data (see Table 2), especially given the fact that the experimental averaging of the *CHTC* was quite coarse, particularly at the edge zones. The top surface, which shows a significantly larger discrepancy with the experimental data, is not considered in this study.

Although more advanced turbulence modelling approaches, for example Large-Eddy Simulation (LES), could result in more accurate *CHTC* results on these surfaces, steady RANS is used to predict the surface-averaged *CHTCs* in this study for several reasons: (1) The previously mentioned validation study showed that an acceptable agreement could be obtained for the surface-averaged *CHTC* for the vertical surfaces, especially when taking into account that with other techniques, i.e. full-scale or wind-tunnel measurements, this *CHTC* cannot necessarily be determined more accurately, due to the surface averaging. Note however that the discrepancies of CFD with experimental data can be significantly larger if point values would be compared (see Defraeye et al., 2010a); and (2) Steady RANS is much less computationally expensive than more advanced modelling techniques (e.g. LES) and is therefore frequently used in large-scale building aerodynamics studies (Hussein and El-Shishiny, 2009; Neofytou et al., 2006; Solazzo et al., 2009; van Hooff and Blocken, 2010) and other environmental studies (Wakes et al., 2010), which is within the area of interest of the proposed methodology. Also note that wall functions, which are still often used in building aerodynamics, can lead to significant errors in the predicted *CHTC* compared to LRNM (differences of $\pm 50\%$, Defraeye et al., 2010a),

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which are larger than the errors introduced by using steady RANS, when looking at surface-averaged $CHTCs$ (see Table 2).

Note that focus of the CFD study is only on forced convection. The reason for this is that if buoyancy effects are taken into account in the simulations, the flow field and consequently the $CHTC$ would be strongly dependent on the imposed thermal boundary conditions, which would make the obtained correlations less generally applicable. For forced convection, the $CHTC$ (Eq.(1)) is actually not dependent on the magnitude of the imposed surface temperatures (T_w) and reference temperatures (T_{ref}). Note that for the “Var/Calm” conditions in Table 1, which represent wind conditions at very low wind speeds or of fluctuating wind direction, the $CHTC$ is taken into account by assuming a constant (low) $CHTC$ value, namely $3.5 \text{ W/m}^2\text{K}$, which is a representative value for low wind speeds. Apart from buoyancy, radiation is also not considered in the simulations since fixed temperature boundary conditions are used for the building surfaces.

Second-order discretisation schemes are used throughout. The SIMPLE algorithm is used for pressure-velocity coupling. Pressure interpolation is second order. Convergence was assessed by monitoring the velocity, turbulence kinetic energy and temperature on specific locations in the flow field and heat fluxes on the surface of the cube.

3.3. Results

In order to obtain a surface-averaged $CHTC-U_{10}$ correlation for a specific incidence angle, simulations at different wind speeds have to be performed for this incidence angle. As already mentioned before, these simulations can be performed at relatively low wind speeds (Defraeye et al., 2010b) for building aerodynamics. Moreover, Defraeye et al. (2010b) also showed that only two or three wind speeds were sufficient to obtain the required correlations with sufficient accuracy. Therefore, simulations were performed for $U_{10} = 0.5, 1$ and 2.5 m/s . Due to the symmetry of the building, the evaluation of only two incidence angles was sufficient to provide information on the other incidence angles since they can all be related to one of the surfaces in the two simulated cases. The obtained $CHTC-U_{10}$ correlations are shown in Figure 4 for all incidence angles, namely for φ from 0° to 330° in steps of 30° and the factors A_φ and B_φ , namely the coefficient and exponent (Eq.(5)) for a certain incidence angle φ , are given in Table 3. Note that the coefficient A_φ only has an influence on the magnitude of the $CHTC$ whereas the exponent B_φ also determines the slope and curvature of the $CHTC-U_{10}$ function. It is clear that the magnitude of the coefficient A_φ differs significantly with the incidence angle but the exponent B_φ is relatively constant, with an average of 0.86. The highest values of the $CHTC$ for a given wind speed are obtained for windward surfaces ($\varphi = 0^\circ$). Note that these $CHTC-U_{10}$ correlations are only valid for isolated cubic bodies in a neutral ABL at high Reynolds and low Richardson numbers, or for comparable configurations. Nevertheless, such correlations can be determined with CFD in a similar way for more complex configurations, for example buildings in an urban environment.

4. Results

4.1. $CHTC_{SM}$

Using the methodology described in Section 2, the $CHTC_{SM}$ is determined for a vertical surface of the cubic building, i.e. a building facade, for the local wind conditions of Eindhoven. The orientation of the building surface (β) is required to determine the $CHTC_{SM}$ (Eq.(7)), since the factors A_φ and B_φ have been determined

(Section 3.3) for different incidence angles (φ) (see Table 3), with respect to the building surface of interest, where the incidence angles are however not the same as the wind directions (ω) (see Table 1), except for a building surface oriented to the north ($\beta = 0^\circ$). Note that a wind direction (e.g. north or 0°) always is defined as the direction from which the wind is coming and that a surface orientation (e.g. to the west or 90°) is defined as that wind direction to which the surface is perpendicular to (i.e. west or 90°), as specified in Figure 5, so for windward conditions. Thereby, the surface orientation (β) and the wind direction (ω) are related to the incidence angle (φ) by $\varphi = \omega - \beta$, where φ increases in a clockwise manner. For a specific surface orientation β , the factors A_φ and B_φ (Table 3), which are known for different incidence angles φ , can thereby be linked to the appropriate wind direction $\omega (= \varphi + \beta)$, after which the $CHTC_{ij}$ values can be determined for each wind direction j by means of Eq.(6). For wind coming from the direction of the surface orientation, i.e. a windward surface, the factors A_j and B_j are the ones at an incidence angle of 0° .

In order to indicate the variability of the $CHTC_{SM}$ with the building surface orientation, the $CHTC_{SM}$ is determined for different surface orientations, namely for surfaces oriented to each of the 12 different wind directions specified in Table 1. No additional CFD simulations are required to determine these $CHTC_{SM}$'s since the $CHTC-U_{10}$ correlations, and thereby the factors A_φ and B_φ , were already determined for the relevant incidence angles.

The resulting $CHTC_{SM}$ values are specified in Figure 6 for the 12 surface orientations, together with the occurrence of each specific wind direction ($x_{tot,j}$) for the wind climate of Eindhoven. First of all, the variation of the $CHTC_{SM}$ with the surface orientation is discussed. The $CHTC_{SM}$ varies between about 10 and 13 W/m²K, which indicates that, for an “anisotropic” wind climate, i.e. a wind climate with specific dominant wind directions, the building orientation has a noticeable influence on the magnitude of the $CHTC_{SM}$ of that building surface. The relative difference between the maximal ($CHTC_{SM,max}$) and minimal ($CHTC_{SM,min}$) values, namely $(CHTC_{SM,max} - CHTC_{SM,min})/CHTC_{SM,min}$, is 39%. For a more isotropic wind climate, i.e. with a uniform wind rose, this variability with building orientation will be less. It is also clear that the highest $CHTC_{SM}$ values are found for surfaces oriented to the most dominant wind directions, due to the fact that the highest $CHTC$ s were found for windward surfaces ($\varphi \approx 0^\circ$) (see Figure 4). As a result, the large peak of $CHTC_{SM}$ in Figure 6 is found at the same angles (at 210° - 240°) as that of $x_{tot,j}$. The smearing out of this $CHTC_{SM}$ peak to nearby surface orientations is due to the fact that the influence of the dominant wind directions is still present at these orientations since the surface is still considered to be quite “windward”, resulting in high $CHTC$ s (Figure 4). Furthermore, it should be mentioned that, apart from the variation of the $CHTC_{SM}$ value with the surface orientation, its overall magnitude, i.e. the height of the curve in Figure 6, is determined by the magnitude of the overall mean wind speed at that building site, which can be significantly higher for coastal sites for example. This is investigated more in detail in Section 5.

4.2. $CHTC_{SM}$ using average wind speeds

In the previous section, the $CHTC_{SM}$ was calculated by determining the $CHTC_{ij}$ at each wind speed i . It is however possible that only measurement data of the average wind speed for a certain wind direction j ($U_{AVG,j}$) are available, e.g. from a wind rose. In this case, a simplified $CHTC_{SM}$, called $CHTC_{SM,S}$, could be determined by calculating the average $CHTC$ for each wind direction ($CHTC_{AVG,S,j}$), only using the average wind speed:

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$$CHTC_{AVG,S,j} = A_j (U_{AVG,j})^{B_j} = A_j \left(\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i} \right)^{B_j} \quad (13)$$

Thereby, the following $CHTC_{SM,S}$ value is obtained:

$$CHTC_{SM,S} = \sum_j x_{tot,j} CHTC_{AVG,S,j} = \sum_j x_{tot,j} A_j \left(\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i} \right)^{B_j} \quad (14)$$

This simplified approach could however lead to discrepancies with the previously specified method to calculate $CHTC_{AVG,j}$ (Eq.(8)) and could therefore be less correct in predicting the $CHTC_{SM}$, since by combining Eq.(6) and Eq.(8):

$$CHTC_{AVG,j} = \sum_i \frac{x_{ij}}{x_{tot,j}} A_j U_{10,i}^{B_j} = A_j \left(\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i}^{B_j} \right) \quad (15)$$

Thereby, $CHTC_{SM}$ can be written as:

$$CHTC_{SM} = \sum_j x_{tot,j} CHTC_{AVG,j} = \sum_j x_{tot,j} A_j \left(\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i}^{B_j} \right) = \sum_j \sum_i x_{ij} A_j U_{10,i}^{B_j} \quad (16)$$

It is clear that Eq.(14) and Eq.(16) do not give the same result unless the exponents B_j are equal to one, since:

$$\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i}^{B_j} \neq \left(\sum_i \frac{x_{ij}}{x_{tot,j}} U_{10,i} \right)^{B_j} \quad (17)$$

To quantify the accuracy of the simplified approach, the $CHTC_{SM,S}$ values are compared with the original $CHTC_{SM}$ values for a building surface in Figure 6. The difference is however very small which is due to the fact that both factors specified in Eq.(17) are found to differ only about 1.5% for all surface orientations. The difference is to some extent dependent on the value of the exponent B_j and is maximal if B_j should be taken equal to about 0.5 but is still below 5%. This indicates that for a certain wind direction, average wind speeds could be used as well, which simplifies the analysis of $CHTC_{SM}$ to some extent and requires less detailed wind climate data.

4.3. $CHTC_{SM}$ using multiplication factors

The proposed methodology requires that the $CHTC-U_{10}$ correlations are determined for each of the 12 wind directions, by performing simulations at different wind speeds, which required 6 simulations in this case. Due to the computational expense of CFD simulations and the increase of the required number of simulations with increasing complexity of the building (less symmetry), often simplified methods are explored in building aerodynamics to reduce the number of simulations. A typical example from wind-driven rain research is the cosine projection method, which calculates the wind-driven rainfall intensity on a building surface for oblique wind directions as a (cosine) function of the incidence angle and the wind-driven rainfall intensity at an incidence angle of 0° . Thereby only one simulation at $\varphi = 0^\circ$ is required. Note that the accuracy of this simplified method is however not always satisfactory, as discussed by Blocken and Carmeliet (2006).

A similar approach could be applied for calculating the $CHTC_{SM}$ by determining the $CHTC-U_{10}$ correlation only for $\varphi = 0^\circ$, and thus A_{0° and B_{0° , and by determining the factor $\chi_\varphi = CHTC_{i,\varphi}/CHTC_{i,0^\circ}$ for each incidence angle φ at a certain wind speed $U_{10,i}$, where $CHTC_{i,\varphi}$ and $CHTC_{i,0^\circ}$ are the surface-averaged $CHTC$ s at a certain

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wind speed i for an incidence angle of φ and of 0° respectively. Assuming that this multiplication factor χ_φ is quasi independent of the wind speed, which is required since χ_φ is only determined using $CHTC$ data at a single wind speed, the $CHTC_{i,\varphi}$ value for a certain incidence angle φ and wind speed $U_{10,i}$ could be calculated out of $CHTC_{i,0^\circ}$:

$$CHTC_{i,\varphi} = \chi_\varphi CHTC_{i,0^\circ} = \chi_\varphi A_{0^\circ} U_{10,i}^{B_{0^\circ}} \quad (18)$$

This avoids determining the correlations for all wind directions, which can reduce the number of CFD simulations significantly. For the cubic building of this study, the number of simulations would reduce from 6 (2 wind directions, each at 3 wind speeds) to 4 (1 wind direction at 3 wind speeds and 1 wind direction at 1 wind speed). The reduction is even more significant for more complex buildings with less symmetrical shapes. For a rectangular-shaped building for example, the number of simulations reduces from 12 (4 wind directions, each at 3 wind speeds) to 6 (1 wind direction at 3 wind speeds and 3 wind directions at 1 wind speed).

To check the accuracy of this simplified approach, the $CHTC_{SM}$ is determined, called the $CHTC_{SM,\chi}$, for all 12 surface orientations and is shown in Figure 6. Note that in this case the correct χ_φ factors have to be linked (see Figure 5) to the appropriate wind direction ($\omega = \varphi + \beta$) for a specific building orientation (β), instead of the A_φ and B_φ factors, as in Section 4.1. For all surface orientations, these χ_φ factors are equal to 1 for incidence angles of 0° and are specified for all incidence angles in Table 4 for $U_{10} = 0.5$ m/s. The differences with the previously determined $CHTC_{SM}$ values are very small. The reason for this good agreement is that the factors χ_φ are quasi independent of the magnitude of the wind speed at which they have been determined (0.5 m/s in this case) for all incidence angles. This is a result from the fact that the exponent B of the correlations (Eq.(5)) has almost the same value for all incidence angles, namely about 0.86, by which the $CHTC_{i,\varphi}$ value increases proportionally to the $CHTC_{i,0^\circ}$ value (Eq.(18)) at higher wind speeds for all incidence angles, resulting in approximately the same values of χ_φ for different wind speeds. This can also be noticed from Figure 7, where the variation of these χ_φ factors with the wind speed is presented for all incidence angles, where the $CHTCs$ are determined by using the $CHTC-U_{10}$ correlations (Eq.(5) and Table 3).

Defraeye et al. (2010b) however showed that for the leeward surface, the exponent B varies significantly over this surface (between about 0.74 and 0.89 with an average of 0.83) where it was about constant (0.85) for the windward surface. Thereby, this simplified approach is not necessarily valid if the $CHTC$ at a single point is considered, which could not be noticed from the present approach since surface-averaged $CHTCs$ are used, apparently leading to a biasing of this phenomenon. Also note that a more distinct variation of the exponent B with the incidence angle could be found for buildings with a more complex and asymmetrical shape.

5. Application to other wind climates

In this section, the proposed methodology will be applied to analyse the variability of the $CHTC_{SM}$ with the building orientation for the cubic building for other wind climates than that of Eindhoven. Note that the building is still assumed to be located in the same terrain as in Section 4, namely a uniform terrain with $z_{0,site} = 0.03$ m. Meteorological data, similar to those of Table 1, of the stations of Ferrel (Portugal), Granada (Spain) and Cairngorm (United Kingdom) are taken from the European Wind Atlas (Troen and Petersen, 1989). The local wind conditions are presented in Figure 8, where it has to be noted that the scale of Ferrel differs from that of Granada and Cairngorm. Note that all these stations are located in a uniform terrain and that wind speeds (U_{meteo})

are measured at a height of 10 m. For stations Ferrel and Cairngorm, $z_{0,meteo} = 0.03 \text{ m} = z_{0,site}$ by which $U_{meteo} = U_{pot} = U_{site} = U_{10}$. For Granada, $z_{0,meteo} = 0.01 \text{ m}$, by which the wind speed data of this station (U_{meteo}) have to be corrected in order to be representative for U_{site} , where a different terrain roughness is found ($z_{0,site} = 0.03 \text{ m}$). This can be done by using the transformation explained in Section 2.2. Thereby a scaling factor $\gamma(j)$ equal to 0.91 is obtained for all wind directions for the station of Granada. This scaling factor indicates that the wind speeds at the building site will be lower than those recorded at the meteorological station of Granada (see Eq.(2)), which is a result from the larger terrain roughness at the building site. This scaling factor is used to scale the wind speed categories $U_{10,i}$ (see Table 1), by which the overall mean wind speed decreases.

Using the same methodology as in Section 4.1, the $CHTC_{SM}$ values are determined and are specified in Figure 9a for the 12 surface orientations for all wind climates. In Figure 9b, the average wind speed for each wind direction ($U_{AVG,j}$) is given for all wind climates. As in Section 4, the influence of building surface orientation on the $CHTC_{SM}$ can clearly be distinguished, especially for highly anisotropic wind climates, such as that of Ferrel: a distinct $CHTC_{SM}$ peak at building orientations to the north originates from the high occurrence of wind speeds for this direction (see Figure 8a). The relative differences between the maximal and minimal values ($(CHTC_{SM,max} - CHTC_{SM,min})/CHTC_{SM,min}$) are: 39% for Eindhoven, 59% for Ferrel, 54% for Granada and 86% for Cairngorm. Apart from that, also a distinct variation in the magnitude of the $CHTC_{SM}$, i.e. the height of the $CHTC_{SM}$ curve, can be noticed for the different wind climates, which is related to the magnitude of the overall mean wind speed (U_{mean}) at that building site. This overall mean wind speed (U_{mean}) is given by:

$$U_{mean} = \sum_j \sum_i x_{ij} U_{10,i} \quad (19)$$

In Table 5, the overall mean wind speeds at the building sites of the different wind climates are given together with the mean value of the $CHTC_{SM}$, which is obtained by averaging the $CHTC_{SM}$ for all building orientations. Significant differences, i.e. by a factor 4, are found for the mean $CHTC_{SM}$ between building sites with a low mean wind speed (Granada) and those with a high mean wind speed (Cairngorm). If this mean value of the $CHTC_{SM}$ at the different building sites is correlated with the respective mean wind speed, a very good correlation is obtained: $CHTC_{SM} = 2.85 U_{mean}^{0.90}$ with a correlation coefficient of 0.999. Thereby, the overall mean wind speed seems to be a good indicator of the mean value of the $CHTC_{SM}$ that could be expected at a building site, whereas this correlation seems to be rather independent of the characteristic percentage of occurrence of each wind direction (i.e. $x_{tot,j}$), which are actually quite different for the wind climates that are considered (Figure 8).

6. Future perspectives

In this study, the proposed methodology focussed on convective heat transfer, namely on determining the $CHTC_{SM}$ value for a building surface. The methodology can also be applied for other building-related applications to account for the influence of local wind conditions and building orientation. A typical example can be found for wind pressures at building surfaces. Information on these wind pressures is important for building ventilation and air infiltration through the building envelope (Costola et al., 2009), for air flow through wind towers (Karakatsanis et al., 1986) and for many other ventilation applications (see Khan et al., 2008). Statistical mean values for pressure coefficients or wind-driven ventilation rates, similar to the $CHTC_{SM}$, could be useful for the choice of the location of ventilation openings in buildings for passive cooling by night ventilation, for the orientation of wind towers, etc. Note that, compared to $CHTCs$, it could be more straightforward and also more

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accurate to obtain information on wind pressures, e.g. pressure coefficients, by means of wind-tunnel tests. Another example is the analysis of the statistical mean ventilation rate or pollutant exchange rate of courtyards or street canyons in urban areas (Liu et al., 2005; Gromke et al., 2008). Furthermore, the spatial distribution of the deposition velocity of particles on building surfaces (e.g. Jonsson et al., 2008) can be analysed with the proposed methodology in order to identify the most critical deposition locations, for example for long-term predictions of pollutant-related damage processes on exterior surfaces of cultural heritage sites. Actually, statistical mean values of all flow quantities on surfaces, e.g. $CHTCs$, or in the flow field, e.g. wind speeds, can be determined with the proposed methodology, giving a representative value of the “average” quantity which is experienced for a specific building under specific climatic conditions.

7. Conclusions

A simple methodology was proposed to obtain an estimate of the statistical mean $CHTC$ ($CHTC_{SM}$) for a building surface by combining local wind climate information and information on the surface-averaged $CHTC$, namely forced convective $CHTC-U_{10}$ correlations, for different wind directions, where U_{10} is the mean wind speed at a height of 10 m above the ground. An entire building facade was considered in this study but the application of the methodology for a smaller surface, e.g. a solar collector, or a specific point on the facade is straightforward. The $CHTC-U_{10}$ correlations were obtained by means of validated CFD simulations (RANS) in this study, although they can also be determined from wind-tunnel tests or full-scale experiments. Note that more advanced turbulence-modelling approaches, such as LES, can improve the accuracy of the $CHTC$ predictions. Nevertheless, LES is more computationally expensive and thus less practical for large-scale environmental studies. Also note that buoyancy and radiation effects were not taken into account in the CFD simulations, by which the focus was only on forced convection, since otherwise the obtained $CHTC-U_{10}$ correlations would be strongly dependent on the imposed thermal boundary conditions, thus less generally applicable.

In this study, a facade of a cubic building was considered, which was located in a wind climate with a few dominant wind directions. It was shown that the $CHTC_{SM}$ varied significantly with the orientation of the building surface for these “anisotropic” wind conditions and that high values were found for surfaces oriented towards the prevailing wind directions, thus for windward conditions. Moreover, different wind climates were evaluated which clearly showed that the local wind conditions can have a significant impact on the overall magnitude of the $CHTC_{SM}$, which is related to the overall mean wind speed found at the building site. Although a very generic building configuration was considered, namely an isolated cubic building, the application of the methodology for more complex building configurations is straightforward, and only requires that the $CHTC-U_{10}$ correlations are determined for the building surface of interest.

Two approaches were proposed to simplify the determination of the $CHTC_{SM}$: (1) Using average wind speed data for a given wind direction instead of considering the distribution of occurrence of each wind speed for that wind direction; and (2) Determining the $CHTC-U_{10}$ correlation only for an incidence angle of 0° and determining a multiplication factor χ_ϕ for all other incidence angles, which is calculated at one specific wind speed. Both simplified approaches gave a good agreement with the original $CHTC_{SM}$ results. The main advantage of the second approach is that less CFD simulations are required since the $CHTC-U_{10}$ correlations do not have to be determined for every incidence angle.

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Note that once the $CHTC-U_{10}$ correlations are known (i.e. the factors A and B) for a specific building type at different incidence angles, the proposed methodology allows to determine the $CHTC_{SM}$ for any local wind climate of interest, given that the surrounding terrain roughness is approximately similar, which can be beneficial for design purposes. Therefore future work could focus on determining such $CHTC-U_{10}$ correlations for common building types and terrain roughness classes.

Apart from $CHTCs$, the methodology is also applicable for the assessment of other building-related quantities, such as pressure coefficients, wind-driven ventilation rates or $CMTCs$.

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Figure captions

Figure 1: Wind conditions measured at the meteorological station in Eindhoven for the period 1971-2000. Percentage of occurrence (indicated in bold) of hourly wind speeds for different wind speed intervals at specific wind directions (north = 0°, east = 90°). The data are obtained from the Royal Dutch Meteorological Institute.

Figure 2: Top view of the computational domain and grid (H = cube height) with specification of the boundary conditions. The height of the domain is $6H$.

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Figure 3: Comparison of the $CHTC$ on the surfaces of the cube of the wind-tunnel experiment of Meinders et al. (1999) ($CHTC_{EXP}$) and the CFD validation study of Defraeye et al. (2010a) ($CHTC_{SIM}$) in a vertical (a) and horizontal (b) centreplane. Note that only the results in the central region of the surface ($0.2 < x/H < 0.8$) are shown.

Figure 4: Surface-averaged $CHTC$ s, from CFD simulations, at different wind speeds (U_{10}) for different incidence angles. The power-law approximation curves are represented by the solid lines, indicating a good correlation.

Figure 5: Definition of the building surface orientation (β), wind direction (ω) and incidence angle (ϕ).

Figure 6: $CHTC_{SM}$, $CHTC_{SM,S}$ (see section 4.2) and $CHTC_{SM,\chi}$ (see section 4.3) as a function of building surface orientation; and percentage of occurrence of a specific wind direction ($x_{tot,j}$) as a function of wind direction.

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Figure 7: Multiplication factors (χ_ϕ) for different incidence angles, determined for different wind speeds U_{10} , using the $CHTC-U_{10}$ correlation (Eq.(5) and Table 3).

Figure 8: Wind conditions measured at the meteorological stations in: (a) Ferrel (Portugal); (b) Granada (Spain); (c) Cairngorm (United Kingdom). Percentage of occurrence (indicated in bold) of wind speeds for different wind speed intervals at specific wind directions (north = 0°, east = 90°). The data are obtained from the European Wind Atlas (Troen and Petersen, 1989). Note that the scale of Ferrel differs from that of Granada and Cairngorm.

Figure 9: Comparison of different wind climates: (a) $CHTC_{SM}$ as a function of building surface orientation; (b) Average wind speed ($U_{AVG,j}$) as a function of wind direction.

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Tables

Table 1: Percentages of occurrence (x_{ij}) of U_{pot} ($= U_{10}$ in this study) for several wind speeds categories (i) and for 12 wind direction categories (j), for the meteorological station of Eindhoven for the period 1971-2000. $U_{10,i}$ indicates the average wind speed of a certain wind speed category. Var/Calm 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.

x_{ij}		Wind direction														$\sum_j x_{ij} \downarrow$
i $\downarrow$	$j \rightarrow$	Var/ Calm	N 0°	NNE 30°	NEE 60°	E 90°	SEE 120°	SSE 150°	S 180°	SSW 210°	SWW 240°	W 270°	NWW 300°	NNW 330°		
Interval	$U_{10,i}$															
0-1	0.5	2.2	0.12	0.11	0.07	0.07	0.11	0.19	0.13	0.15	0.16	0.13	0.14	0.15	3.73	
1-2	1.5	1.54	0.72	0.85	0.66	0.58	0.79	1.12	0.93	1.02	0.81	0.8	0.76	0.69	11.27	
2-3	2.5	0.34	0.92	1.37	1.35	0.92	1.37	1.56	1.41	1.76	1.52	1.39	0.98	0.93	15.82	
3-4	3.5	0.03	0.98	1.42	1.21	0.92	1.25	1.46	1.57	2.21	2	1.4	1	0.88	16.33	
4-5	4.5		0.79	1.1	1.34	0.84	1.05	1.05	1.44	2.09	2.06	1.34	0.89	0.74	14.73	
5-6	5.5		0.4	0.66	0.99	0.57	0.63	0.46	1.02	1.82	1.69	1.02	0.53	0.46	10.25	
6-7	6.5		0.39	0.6	0.84	0.44	0.4	0.26	0.84	2.18	2.35	0.98	0.62	0.47	10.37	
7-8	7.5		0.25	0.36	0.56	0.27	0.21	0.13	0.57	1.72	1.76	0.87	0.56	0.37	7.63	
8-9	8.5		0.1	0.15	0.2	0.1	0.08	0.04	0.29	0.97	1.2	0.58	0.28	0.18	4.17	
9-10	9.5		0.05	0.07	0.11	0.04	0.04	0.02	0.13	0.68	0.7	0.37	0.19	0.09	2.49	
10-11	10.5		0.03	0.02	0.05	0.02	0.02	0.01	0.08	0.44	0.48	0.23	0.1	0.04	1.52	
11-12	11.5		0.01	0.01	0.02				0.03	0.21	0.28	0.12	0.05	0.02	0.75	
12-13	12.5								0.01	0.15	0.16	0.11	0.05	0.01	0.49	
13-14	13.5									0.06	0.08	0.06	0.02		0.22	
14-15	14.5									0.03	0.04	0.03	0.02		0.12	
15-16	15.5									0.02	0.02	0.02			0.06	
16-17	16.5										0.01	0.01			0.02	
17-18	17.5											0.01			0.01	
18-higher																
$\sum_i x_{ij} \rightarrow$		4.11	4.76	6.72	7.4	4.77	5.95	6.3	8.45	15.51	15.32	9.47	6.19	5.03	100	

Table 2: Relative difference of the surface-averaged $CHTC$ on the surfaces of a cube in channel flow between the CFD validation study of Defraeye et al. (2010a) ($CHTC_{SIM}$) and the wind-tunnel experiment of Meinders et al. (1999) ($CHTC_{EXP}$).

Surface	$ CHTC_{SIM} - CHTC_{EXP} / CHTC_{EXP}$
Windward	7%
Leeward	21%
Side	12%
Top	33%

Table 3: Coefficient A_φ , exponent B_φ and correlation coefficient R_φ of the $CHTC-U_{10}$ power-law correlations for a building surface, for different incidence angles φ , obtained by CFD simulations.

Incidence angle φ	A_φ	B_φ	R_φ
0°	4.90	0.86	1.000
30°, 330°	4.63	0.87	1.000
60°, 300°	4.25	0.88	1.000
90°, 270°	2.78	0.87	1.000
120°, 240°	1.44	0.83	1.000
150°, 210°	1.85	0.84	1.000
180°	2.25	0.84	0.999

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Table 4: Multiplication factors (χ_φ) for different incidence angles φ (determined for $U_{10} = 0.5$ m/s).

Incidence angle φ	χ_φ
0°	1.00
30°, 330°	0.94
60°, 300°	0.86
90°, 270°	0.56
120°, 240°	0.30
150°, 210°	0.38
180°	0.47

Table 5: Mean wind speed U_{mean} and mean $CHTC_{SM}$ for different building sites.

Location	U_{mean} (m/s)	Mean $CHTC_{SM}$ (W/m ² K)
Eindhoven	4.5	11.3
Ferrel	5.1	12.3
Granada	2.1	5.5
Cairngorm	9.7	21.5