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Extension of generalized forced convective heat transfer coefficient expressions for isolated buildings taking into account oblique wind directions

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ABSTRACT

The surface-averaged forced Convective Heat Transfer Coefficient ($CHTC_{avg}$) at a windward building facade is influenced by the complex interaction between a wide range of parameters. Existing CHTC expressions, however, consider the impact of these parameters either incompletely or not at all. Earlier studies have shown that this shortcoming can lead to significant errors in Building Energy Simulations. In this paper, therefore, the combined impacts of wind speed (U_{10}), building height (H) and width (W), and wind direction (θ) on the $CHTC_{avg}$ for the windward facade of buildings are systematically investigated. High-resolution CFD simulations of wind flow and forced convective heat transfer, validated with wind-tunnel measurements, are performed for 64 building geometries (10 m ≤ H and W ≤ 80 m), 8 wind directions (0° ≤ θ ≤ 78.75°) and 4 reference wind speeds (1 m/s ≤ U_{10} ≤ 4 m/s). The 3D steady RANS equations with the realizable k-ε turbulence model and the low-Re number Wolfshtein model are used. The results show that for a given building geometry and U_{10}, the $CHTC_{avg}$ decreases as θ increases from 0° to 78.75°. The maximum reduction of about 42% occurs for the building with H = 8W = 80 m. In addition, for a given θ and U_{10}, by increasing H, the $CHTC_{avg}$ increases, while increasing W has the opposite impact on the $CHTC_{avg}$. Finally, a new generalized CHTC expression is presented as a function of U_{10}, H, W and θ, and its accuracy is confirmed by detailed in-sample and out-of-sample evaluations.

1. Introduction

Research and practice in urban physics, building energy and building component durability require the knowledge of the exterior forced convective heat transfer (CHT) at the building facades. For building energy studies, for example, the convective heat transfer coefficient (CHTC) is typically used to model the CHT between buildings and their environment as part of the calculation of the heating and cooling demand of buildings and to assess the energy performance of the building envelope. Knowledge of the CHTC is also important for modeling of heat waves in urban areas, the urban heat island effect, indoor and outdoor heat stress, etc., which are topics that are strongly related to the grand societal challenges energy, health and climate [1,2].

The CHTC distribution across the facades of a building is complex as it is influenced by a wide range of parameters including building geometry [3–6], wind speed [7–9] and wind direction [9–11], etc.

Earlier CFD studies have shown that the impact of building geometry on the forced CHTC can be very large and to some extent counter-intuitive [4,6]. For example, for a 10 m wide windward facade, as the building height (H) increases from 10 m to 80 m, the forced surface-averaged CHTC ($CHTC_{avg}$) on the windward facade increases by about 20% [4]. For H = 10 m, however, increasing the building width from 10 to 80 m has the opposite impact on the forced surface-averaged CHTC, which decreases by more than 33% [4]. The first trend can be explained by the increase of wind speed with height in the atmospheric boundary layer. The second trend is attributed to the so-called wind-blocking effect that refers to the upstream wind deceleration due to the blockage by the building [12,13].

Previous experimental and numerical studies have indicated that the forced CHTC changes as a function of Reynolds number. For example, a power-law dependence was found between the CHTC at the surfaces of wall-mounted rectangular prisms and the Reynolds number. For windward building facades, several power-law correlations between the $CHTC_{avg}$ and U_{10} have been provided (e.g., $CHTC = 5.15U_{10}^{0.81}$ [8], $CHTC = 4.6U_{10}^{0.89}$ [9], $CHTC = 5.01U_{10}^{0.85}$ [14]), where U_{10} is the mean wind speed in the undisturbed flow at a height of 10 m above the ground.

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The impact of wind direction on the CHTC was investigated in previous CFD studies (e.g. Refs. [8,9]). In each of these studies, only one specific low-rise isolated building was investigated while the simultaneous impact of building geometry was not taken into account. It was shown that the surface-averaged CHTC at the windward building facades varies substantially as a function of the wind direction. For example, Blocken et al. [9] showed that for a low-rise cubic building (10 m × 10 m × 10 m) and for U_{10} = 3 m, by increasing the wind direction from 0° to 78.75°, the $CHTC_{avg}$ reduces by more than 25%.

Because of the complexity involved in obtaining accurate values of the CHTC, a large number of empirical and semi-empirical expressions have been established using on-site (full-scale) measurements (e.g. the Mobile Window Thermal Test (MoWiTT) model [15], and the model by Liu and Harris [16]) or wind-tunnel (reduced-scale) measurements (e.g. the McAdams [17] and CIBS (Chartered Institute of Building Services) models [18]) as well as Computational Fluid Dynamics (CFD) simulations (e.g. the models by Emmel [8] and Montazeri & Blocken [6]). Many of these expressions are implemented in Building Energy Simulation (BES) programs [19,20]. However, the accuracy and reliability of these expressions are of concern because:

- Many of these expressions are based on invalid assumptions: an example is that the CHTC is often assumed constant across a building facade and that a measurement resulting from a single point is considered to be valid for the whole facade. Further, some expressions have been derived based on wind-tunnel measurements over a flat plate. For example, the McAdams [17] and CIBS models [18] that are widely used in BES tools have been derived based on wind-tunnel experiments for a vertical square copper plate (0.5 × 0.5 m^2) in a uniform air flow parallel to the plate [21]. The flow structure around buildings, however, is more complex than the one over flat plates.
- Generally, the influence of important parameters such as wind direction, surrounding buildings, and surface roughness is taken into account either incompletely, or not at all. In addition, a vast majority of these expressions do not contain the complex interaction between these parameters. An example is the correlation proposed in the CIBS Guide [18]: CHTC = $4.1U_{loc}+5.8$, where $U_{loc} = 2/3U_R$. In this correlation, U_{loc} is the wind speed at a certain distance from the building facade and at a certain height from the ground, and U_R is the wind speed at a certain height from the roof surface.
- Many expressions are case-specific, i.e., they were derived for specific building characteristics, and under specific meteorological conditions (wind speed and wind direction) and they are therefore strictly only applicable to the conditions for which they were derived. For example, the model by Liu & Harris [16] is based on full-scale measurements for a one-storey building in a rural area that is partially sheltered by a nearby building. The model provides three CHTC expressions based on U_{loc} (CHTC = $6.31U_{loc}+3.32$), U_R (CHTC = $2.08U_R+2.97$), and U_{10} (CHTC = $1.53U_{10}+1.43$), which were measured 0.5 m away from the wall surface, 1 m above the roof and 10 m above the ground level, respectively. Since a copper sheet (smooth surface) was used to measure the CHTC at the facades of this one-storey building, it is expected that this model is accurate only for low-rise buildings with smooth surfaces.

The accuracy of these empirical or semi-empirical expressions, so-called secondary sources, depends on availability and accuracy of the above-mentioned so-called primary sources, i.e., on-site or wind-tunnel experiments, and CFD simulations. Table 1 presents an overview of the wind-tunnel experiments and CFD simulations of convective heat transfer performed on wall-mounted rectangular prisms. It can be observed that:

- Most of the available high-resolution wind-tunnel data of CHTC are based on measurements at relatively low Reynolds numbers (10^3–10^4) [22–25], which limits the applicability of the available data for building applications.
- CFD simulations have been used to investigate CHTC at realistic Reynolds numbers for building applications (Re ~ 10^6–10^7) as, unlike wind-tunnel testing, CFD does not suffer from potentially incompatible similarity requirements because simulations can be conducted at full scale [26,27]. The impact of the reference wind speed (or Re), building geometry and urban surroundings have been investigated. However, not all studies have resolved the flow in the thin viscous sublayer at the building surfaces that constitutes the largest resistance to surface convective heat transfer, as this requires very small cells in the near wall region (typically a few ten or hundreds of micrometer).
- The combined effects of different parameters on CHTC have been taken into account in only a few studies. Natarajan and Chyu [23], Emmel et al. [8], and Blocken et al. [9] investigated the combined effect of Re and wind direction and presented CHTC expressions as a function of Re for different approaching wind directions. Montazeri et al. [4] and Montazeri and Blocken [6] investigated the combined impact of Re and building dimensions. The results of the latter studies led to new generalized expressions for the surface-averaged CHTC for different building surfaces as a function of reference wind speed, and height and width of the windward facade.

Earlier studies have shown that the use of existing CHTC expressions may lead to incorrect results in building energy simulations (BES). For example, using different expressions has revealed deviations of more than 30% in the yearly cooling energy demand of a simple low-rise building [20]. For high-rise buildings, the deviations could go up to 42% [28]. The above-mentioned shortcomings of the existing CHTC expressions and these of their underlying primary data sources indicate the need for more research efforts in terms of wind-tunnel testing, CFD simulations and the establishment of new and more generally applicable CHTC expressions. This paper is intended to provide a further step in that direction.

In this paper, new high-resolution CFD simulations of wind flow and forced convective heat transfer are performed, and a new generalized CHTC expression is presented that yields the surface-averaged forced CHTC for the windward facade of buildings as a function of four parameters: wind speed, building height, building width and wind direction.

It should be noted that in BES (building energy simulation) and BE-HAM (building envelope heat, air and moisture transfer) tools, generally three categories of CHTC models (expressions) are implemented with respect to surface orientation regarding the wind direction, i.e., CHTC models for windward facades, leeward facades and roofs. The focus in the present paper is on windward building facades because previous experimental and numerical studies indicated that the highest surface-averaged CHTC for wall-mounted rectangular prisms is obtained for the windward surface (e.g. Ref. [37]). The lowest CHTC is found for the leeward surfaces where the CHTC is rather insensitive to the wind direction and the building geometry [6,23]. In addition, in BE-HAM programs, the windward facade is the one that is wetted by wind-driven rain and for which knowledge of CHTC and of the related CMTC (convective moisture transfer coefficients) is of particular importance [38–40].

The results of this study will bring a better understanding of the interaction between the CHTC and its influencing parameters wind speed, building height, building width and wind direction at the windward facades of buildings. In addition, this study will lead to a new generalized CHTC expression for windward building facades, intending to support more accurate BES and BE-HAM simulations.

The outline of the paper is as follows. The wind-tunnel experiments of surface temperature at the surfaces of a wall-mounted cube by Meinders et al. [24] and the validation study are briefly presented in Section 2. Section 3 describes the computational settings and