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New generalized expressions for forced convective heat transfer coefficients at building facades and roofs

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ABSTRACT

Previous research indicated that the surface-averaged forced convective heat transfer coefficient (CHTC) at a windward building facade can vary substantially as a function of building width and height. However, existing CHTC expressions generally do not consider the building dimensions as parameters and are therefore strictly only applicable for the building geometry for which they were derived. Most CHTC expressions also categorize facades only as either windward or leeward. This indicates the need for new and more generally applicable CHTC expressions. This paper presents new generalized expressions for surface-averaged forced CHTC at building facades and roofs that contain the reference wind speed, the width and the height of the windward building facade as parameters. These expressions are derived from CFD simulations of wind flow and forced convective heat transfer for 81 different isolated buildings. The 3D Reynolds-averaged Navier-Stokes equations are solved with a combination of the high-Re number realizable k-ε model and the low-Re number Wolfshtein model. First, a validation study is performed with wind-tunnel measurements of surface temperature for a reduced-scale cubic model. Next, the actual simulations are performed on a high-resolution grid with a minimum near-wall cell size of 400 μm to resolve the entire boundary layer, including the viscous sublayer and the buffer layer, which dominate the convective surface resistance. The new CHTC expressions are analytical formulae (trivariate polynomials) that can easily be implemented in Building Energy Simulation (BES) and Building Envelope Heat-Air-Moisture (BE-HAM) transfer programs. The accuracy of the expressions is confirmed by in-sample and out-of-sample evaluations.

1. Introduction

Wind flow around buildings is very complex, as it is characterized by flow impingement, separation, recirculation, reattachment and von Karman vortex shedding in the wake (Fig. 1). This complexity also governs the exterior forced convective heat transfer coefficient (CHTC) at the building surfaces. Knowledge of the CHTC is essential for research and practice in building energy and building component durability [3,4]. It is known that using inappropriate CHTC expressions can lead to considerable errors in Building Energy Simulation (BES) [4] and Building Envelope Heat-Air-Moisture (BE-HAM) transfer simulations [5–9]. Values for the CHTC can be obtained either directly, by so-called primary sources such as measurements and numerical simulations, or indirectly, by secondary sources, in which case these sources have been derived from primary sources.

Direct assessment of the CHTC at building facades and roofs can be performed using either of three methods: on-site measurements (e.g. Refs. [10–14]), wind-tunnel experiments (e.g. Refs. [15–20]) or numerical simulation with Computational Fluid Dynamics (CFD) (e.g. Refs. [21–28]). Each approach has particular advantages and disadvantages. The main advantage of on-site measurements is that they allow capturing the full complexity of the problem under study. However, on-site measurements of CHTC that are often based on the one-dimensional energy balance for the building envelope surface [29] are generally only performed in a limited number of points in space and time [30]. Most on-site measurements of CHTC were performed using one or a few heated plates installed at the facades of a building [10–14]. Another well-known

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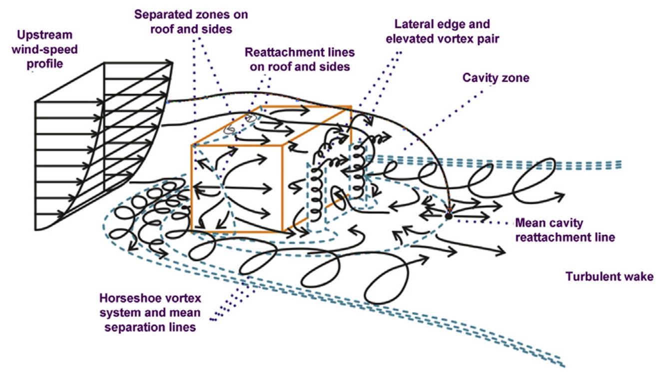

Fig. 1. Schematic illustration of the complexity of wind flow around an isolated rectangular low-rise building ([1] as modified by Ref. [2]).

problem of on-site measurements is that there is no or only very limited control over the boundary conditions such as the meteorological parameters (wind speed, wind direction, temperature, relative humidity, insolation, cloudiness). Wind-tunnel measurements allow a strong degree of control over the boundary conditions. Most available high-resolution wind-tunnel data of CHTC were obtained from measurements either on flat plates parallel or inclined to the approaching flow [15,16] or on bluff bodies, mostly cubes, at relatively low Reynolds numbers (10^3-10^4) and thin turbulent boundary layers [17–20]. Wind-tunnel experiments for flat plates could be considered as full-scale experiments performed on plates in their full dimensions. However, the flow structure around buildings is more complex than the one over flat plates, which casts doubt on the validity of expressions from flat-plate experiments for building applications. Wind-tunnel experiments for small wall-mounted obstacles could be used to obtain information for building applications, but then these wind-tunnel experiments are clearly reduced-scale experiments, where the building model can be at scale 1/20, 1/50 or smaller [18–20]. Due to the much lower Reynolds numbers than in reality ($Re = 10^5$-10^7) they can suffer from the inability to adhere to similarity requirements, which can also limit the applicability of the resulting data for building applications. Numerical simulation with CFD allows either to alleviate or to remove a number of the aforementioned limitations. CFD can provide whole-flow field data, i.e. data on the relevant parameters in all points of the computational domain. Unlike reduced-scale wind-tunnel testing, CFD does not suffer from potentially incompatible similarity requirements because simulations can be conducted at full scale. CFD simulations also easily allow parametric studies. However, the accuracy and reliability of CFD simulations should be ensured by verification, validation and adherence to best practice guidelines [31–36]. Because of these advantages, the use of CFD has rapidly increased in the field of computational wind engineering (CWE) throughout the past 50 years, as highlighted by several recent and not so recent review papers [2,37–47].

CWE also encompasses studies of convective heat transfer on building surfaces. CWE applied to buildings is considered difficult and challenging because of the specific difficulties associated with the flow field around bluff bodies with sharp edges, many of which are not encountered in CFD computations for simple flows such as channel flow and simple shear flow (see e.g. Refs. [37,40,48,49]). Murakami [40] meticulously outlined the main difficulties in CWE: (1) the high Reynolds numbers in wind engineering applications, necessitating high grid resolutions, especially in near-wall regions as well as accurate wall functions; (2) the complex nature of the 3D flow field with impingement, separation and vortex shedding; (3) the numerical difficulties associated with flow at sharp corners and consequences for discretization schemes; and (4) the inflow (and outflow) boundary conditions. Concerning the accurate and reliable CFD simulation of CHTC, the first difficulty is strongly amplified, because of the necessity to resolve the entire thermal boundary layer at all building surfaces, including the very thin viscous sublayer and the buffer layer, which dominate the convective surface resistance. This requires a y^* value smaller than 5 and preferably equal to 1 [50,51] which implies a very high near-wall grid resolution, yielding wall-adjacent cell sizes that can go down to 300 μm [22,23]. Note that the dimensionless wall distance y^* is defined as $u^* y_p / \nu$, where y_P is the distance from the center point P of the wall-adjacent cell to the wall, ν is the kinematic viscosity, and u^* is the friction velocity based on the turbulent kinetic energy k_P in the wall-adjacent cell center point P and on the constant C_μ ($u^* = C_\mu^{0.5} k_p^{0.25}$). Given the typical length scale of buildings (1–100 m) let alone that of cities (1–10 km), it is clear that accurately resolving all thermal boundary layers at building surfaces in an urban area is very challenging, both in terms of ensuring grid quality and grid economy. It should be noted that some authors have resorted to the development of adjusted temperature wall functions [52–54], which is a promising approach, but this approach needs to be investigated further before it can be applied with confidence for various types of buildings.

Because of the complexities and expenses involved in obtaining accurate CHTC information using the direct approach by measurement or simulations, the indirect approach is often pursued. This refers to the use of analytical expressions (often called "correlations") that have been established mostly based on previous on-site measurements or wind-tunnel measurements or on CFD simulations. Many of these expressions are implemented in Building Energy Simulation (BES) programs [3,4,55] and BE-HAM (Buildings Envelope Heat, Air an Moisture transfer) computational codes [5,7,56–58]. Comprehensive reviews on these expressions were presented by Palyvos [3] and Mirsadeghi et al. [4]. Although a wide range of such expressions exists, there are a few main shortcomings that most have in common, and which are described below. This discussion will be limited to forced convective heat transfer.

A first main shortcoming is that existing (forced) CHTC expressions focus on wind speed as the main (or only) parameter and do not consider the building dimensions or surface width and length as parameters. To the best of our knowledge, the only exception is the BLAST detailed convection expression in which the surface perimeter and surface area are included, mainly from the perspective of boundary layer development over a flat plate [59,60]. This inherently implies that every expression (except BLAST) is strictly only applicable for the building geometry (and other conditions) for which it was established. This implication would not be very important if the influence of building geometry on the forced CHTC statement would be limited. However, recent CFD research for a wide range of building geometries [28] has shown that this influence can be very large and to some extent counter-intuitive, as shown in Fig. 2. For example, for a 10 m wide windward facade, increasing the height from 10 m to 80 m increases the forced surface-averaged CHTC on the windward facade by about 20% (Fig. 2a). However, for H = 10 m, 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% (Fig. 2b). The first trend can be explained by the increase of wind speed with height in the atmospheric boundary layer. The second is attributed to the so-called wind-blocking effect. This effect was first defined in 2006 [61] and refers to the upstream wind deceleration due to the blockage by the building. The higher and wider the building, the stronger the wind-blocking effect, and the larger the upstream wind deceleration [28,62–64]. To the best knowledge of the