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An adjusted temperature wall function for turbulent forced convective heat transfer for bluff bodies in the atmospheric boundary layer

Thijs Defraeye [a,b,*], Bert Blocken [c], Jan Carmeliet [d,e]

[a] Division of Mechatronics, Biostatistics and Sensors, Department of Biosystems, Katholieke Universiteit Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium
[b] Laboratory of Building Physics, Department of Civil Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, 3001 Heverlee, Belgium
[c] Building Physics and Systems, Eindhoven University of Technology, P.O. Box 513, 5600 Eindhoven, The Netherlands
[d] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Wolfgang-Pauli-Strasse 15, 8093 Zürich, Switzerland
[e] Laboratory for Building Science and Technology, Swiss Federal Laboratories for Materials Testing and Research (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland

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Accurate convective heat transfer predictions are required in building engineering and environmental studies on urban heat islands, building energy performance, building-envelope durability or conservation and (natural) ventilation of buildings. When applying computational fluid dynamics (CFD) for these computationally-expensive studies at high-Reynolds numbers, wall functions are mostly used to model the boundary-layer region. In this study, an adjustment to the standard temperature wall function is proposed for forced convective heat transfer at surfaces of typical wall-mounted bluff bodies in turbulent boundary layers, such as the atmospheric boundary layer, at moderate to high Reynolds numbers. The methodology to determine this customised temperature wall function (CWF) from validated numerical data of CFD simulations using low-Reynolds number modelling (LRNM) is explained, where a logarithmic-law behaviour is found. The performance of this CWF is evaluated for several bluff-body configurations. Standard wall functions (SWFs) yield deviations of about 40% for the convective heat transfer coefficient, compared to LRNM. With the CWF however, these deviations are reduced to about 10% or lower. The CWF therefore combines increased (wall-function) accuracy for convective heat transfer predictions with the typical advantage of wall functions compared to LRNM, being a lower grid resolution in the near-wall region, which increases computational economy and facilitates grid generation. Furthermore, this CWF can be easily implemented in existing CFD codes, and is implemented in the commercial CFD code Fluent in this study.

1. Introduction

Forced convective heat transfer at surfaces of wall-mounted bluff bodies in turbulent boundary layers at moderate to high Reynolds numbers ($Re = 10^4$–10^7) is of interest in many engineering applications, such as the evaluation of wind-induced convective heat losses from building surfaces or building components (e.g. solar collectors) in the atmospheric boundary layer (ABL). In building and urban engineering, convective heat transfer predictions are especially relevant for ABL flow applications on urban heat islands [1,2], building (component) energy performance [3,4], building-envelope durability or conservation [5,6] and (natural) ventilation of buildings [7]. Furthermore, they can be used to estimate the convective moisture transfer from building surfaces, by using the heat and mass transfer analogy [8]. Convective moisture transfer is especially of interest for hygrothermal analysis of building envelopes and for urban applications involving evaporation of water from ponds, roof ponds, green roofs, green walls or surfaces which are wetted by (wind-driven) rain [9].

Convective heat transfer research for this type of flow problem is mainly performed by wind-tunnel experiments [10–14] and by computational fluid dynamics (CFD) studies [15–17] for both isolated bodies as well as arrays of bluff bodies. Compared to wind-tunnel experiments, CFD simulations have the advantage that usually a higher spatial resolution is obtained. With CFD also no restrictions are imposed regarding scaling and accessibility of certain surfaces, in contrast to wind-tunnel infrared thermography measurements [11] for example, which is especially important for more complex configurations. On the other hand, the applied numerical modelling approaches determine to a large extent the accuracy of CFD simulations.

* Corresponding author. Division of Mechatronics, Biostatistics and Sensors, Department of Biosystems, Katholieke Universiteit Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium. Tel.: +32 (0) 16 321618; fax: +32 (0) 16 322966.
E-mail address: thijs.defraeye@biw.kuleuven.be (T. Defraeye).

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Nomenclature

A	slope
B	intercept
c_p	specific heat capacity of air (J/kg.K)
C_μ	coefficient used in the k-ε turbulence models (0.09)
E	constant in wall-function expression (9.793)
H	cube height (m)
k	turbulent kinetic energy (m^2/s^2)
k_P	turbulent kinetic energy in cell centre point P of wall-adjacent cell (m^2/s^2)
P	cell centre point of wall-adjacent cell
P_J	empirically-determined coefficient (function of Pr_t)
Pr	molecular Prandtl number
Pr_t	turbulent Prandtl number
$Pr_{t,CWF}$	turbulent Prandtl number used by CWF
$q_{c,w}$	convective heat flux at the surface (W/m^2)
Re	Reynolds number
T	air temperature (°C)
T_P	temperature in cell centre point P of wall-adjacent cell (°C)
$T_P{*}$	dimensionless temperature in cell centre point P of wall-adjacent cell
T_{ref}	reference temperature (°C)
T_w	wall temperature (°C)
T^+	dimensionless temperature, $\rho c_p u_\tau (T_w\text{-}T)/q_{c,w}$
$T{*}$	dimensionless temperature
$u_{ABL}{}^*$	ABL friction velocity (m/s)
u_τ	boundary-layer friction velocity, $(\tau_w/\rho)^{1/2}$ (m/s)
U	mean air speed (m/s)
U_{10}	mean air speed in the undisturbed flow at a height of 10 m above the ground (m/s)
U^+	dimensionless mean air speed, U/u_τ
$U{*}$	dimensionless mean air speed
y	distance (normal) from the wall (m)
y_P	distance (normal) of cell centre point P of wall-adjacent cell to the wall (m)
$y_P{}^+$	dimensionless wall (normal) distance of cell centre point P of wall-adjacent cell, $u_\tau y_P/\nu$
$y_P{*}$	dimensionless wall (normal) distance of cell centre point P of wall-adjacent cell
$y_T{*}$	lower limit for temperature wall function
y^+	dimensionless wall (normal) distance, $u_\tau y/\nu$
$y{*}$	dimensionless wall (normal) distance
z	height above the ground (m)
z_0	aerodynamic roughness length (m)

Greek symbols

ε	turbulence dissipation rate (m^2/s^3)
κ	von Karman constant (0.4187)
μ	dynamic viscosity of air (kg/ms)
ν	kinematic viscosity of air (m^2/s)
ρ	density of air (kg/m^3)
τ_w	wall shear stress (kg/ms^2)
φ	incidence angle (°)

Abbreviations

ABL	atmospheric boundary layer
CFD	computational fluid dynamics
CHTC	convective heat transfer coefficient
CWF	customised wall function
DNS	direct numerical simulation
LES	large-eddy simulation
LRNM	low-Reynolds number modelling
RANS	Reynolds-averaged Navier-Stokes
SWF	standard wall function
WF	wall function

Subscripts

LRNM	low-Reynolds number modelling
P	cell centre point P of wall-adjacent cell
WF	wall function

At high Reynolds numbers ($Re \approx 10^6$–10^7), CFD computations for this type of flow are often performed with (steady) Reynolds-averaged Navier-Stokes (RANS) combined with wall functions (WFs) [18], especially for complex configurations, for example in large-scale environmental studies [6,7,19–22]. WFs are used here to take care of the boundary-layer region, instead of low-Reynolds number modelling (LRNM), mainly for reasons of computational economy: at high Reynolds numbers, the use of WFs, which model the flow quantities in the boundary-layer region by calculating them by means of semi-empirical functions, avoids an extremely high grid resolution here, which would be required for LRNM, where the boundary layer is resolved explicitly. Both boundary-layer modelling approaches are described more in detail below (section 3).

The standard formulation for WFs [23], referred to as standard wall functions (SWFs), however has two main limitations:

1. SWFs impose strict requirements to the computational grid: the cell centre point P of the wall-adjacent cell has to be located outside of the viscosity-affected region (viscous sublayer and buffer layer), i.e. $y_P{}^+ > 30$. On the other hand, the point P has to be located close enough to the wall for it to be in the logarithmic layer, i.e. $y_P{}^+ < 500$ [24], and to ensure a sufficiently high grid resolution in the boundary layer. The dimensionless wall distance of point P ($y_P{}^+$) is defined as:

$$y_P{}^+ = \frac{\sqrt{\frac{\tau_w}{\rho}}\, y_P}{\nu} \tag{1}$$

where y_P is the distance (normal) from the cell centre point P of the wall-adjacent cell to the wall, τ_w is the shear stress at the wall, ρ is the air density and ν is the kinematic viscosity of air. For complex flows, these $y_P{}^+$ criteria are difficult to achieve throughout the entire computational domain, especially if automated grid generation is used, by which WFs are sometimes used outside of their specified validity range.

2. The wall-function concept of SWFs is based on a universal behaviour of the boundary layer, in terms of velocity, turbulence and temperature profiles. These SWFs are derived for wall-attached boundary layers under so-called equilibrium conditions, i.e. small pressure gradients, local equilibrium between generation and dissipation of turbulent energy and a constant (uniform) shear stress and heat flux in the near-wall region [25]. This wall-function concept breaks down for more complex flows, such as flow around bluff bodies where the boundary layer does not remain attached to the surface. SWFs can therefore lead to inaccurate predictions, especially for wall friction and convective heat transfer [25,26].