Impact of exterior convective heat transfer coefficient models on the energy demand prediction of buildings with different geometry

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Abstract

Accurate models for exterior convective heat transfer coefficients (CHTC) are important for predicting building energy demand. A detailed review of the literature indicates that existing CHTC models take into account the impact of building geometry either incompletely, or not at all. To the best of our knowledge, research on the impact of exterior CHTC models on the predicted energy performance of buildings with different geometry has not yet been performed. This paper, therefore, investigates the influence of CHTC models on the calculated energy demand of buildings with varying geometry. Building energy simulations are performed for three groups: buildings with H_b (building height) $> W_b$ (building width), buildings with $H_b < W_b$ and buildings with $H_b = W_b$. Six commonly used CHTC models and a new generalized CHTC model are considered. The generalized CHTC model is expressed as a function of H_b and W_b . The simulations are performed for low and high thermal resistances of the building envelope. The results show that the different CHTC models provide significantly different predictions for the building energy demand. While for annual heating demand, deviations of -14.5% are found, for the annual cooling demand a maximum deviation of $+42.0\%$ is obtained, compared to the generalized CHTC model. This study underlines the need for the CHTC models to consider building geometry in their expressions, especially for high-rise buildings. For low-rise buildings, the observed deviations between the existing and the generalized CHTC model are less pronounced.

Keywords

convective heat transfer coefficient (CHTC), building geometry, energy demand prediction, computational fluid dynamics (CFD), building performance simulation (BPS)

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1 Introduction

Building energy simulation (BES) programs are widely used for predicting the energy demand and energy consumption of buildings (Lam et al. 2008). They provide support for design and development of innovative heating, ventilation and air conditioning (HVAC) concepts under a range of dynamic operating conditions, increasing thus the effectiveness of the whole engineering design process (Malkawi and Augenbroe 2003). In BES programs, the dynamic energy processes in buildings are described by the combination of several first-principle and empirical approaches (Clarke 2001). The accuracy of these approaches can, therefore, influence the performance gap between building design and operation (Hensen and Lamberts 2011; Obyn and van Moeseke 2015). This is of particular importance given the

estimated future increase in global cooling demand of the residential sector (Santamouris 2014; van Hooff et al. 2015; Vasaturo et al. 2018).

A significant portion of the total building energy balance can derive from the convective heat gains or losses from the exterior building facades (Palyvos 2008). The convective heat gains or losses are normally estimated based on a temperature difference ΔT , between the building surface and the air, and the exterior convective heat transfer coefficients (CHTC). Determination of the CHTC at the exterior facades of buildings is not a straightforward procedure, as they depend on a wide range of parameters including building geometry, surrounding buildings, surface roughness, wind speed, wind direction, local airflow patterns and surface-to-air temperature (Blocken et al. 2009; Montazeri et al. 2015). BES programs use CHTC models (or correlations, as they are generally

List of symbols

A	surface area (m^2)	x	distance to the surface centroid from where the wind begins to intersect the roof (m)
ACH	air changes per hour (h^{-1})	z	height above the ground (m)
A_s	exterior facade area (m^2)	z_0	aerodynamic roughness length (m)
D_b	building depth (as used in BES) (m)	z_{met}	height of the meteorological station (m)
g	gravitational constant ($\approx 9.81 \text{ m/s}^2$)	α	wind speed profile exponent (–)
Gr_{L_n}	Grashof number, based on the characteristic length L_n (–)	α_{met}	wind speed profile exponent at the meteorological station (–)
H	height of the windward facade (as used in CFD) (m)	δ	boundary layer thickness (m)
H_b	building height (as used in BES) (m)	δ_{met}	boundary layer thickness at the meteorological station (m)
k	turbulent kinetic energy (m^2/s^2)	ΔT	temperature difference between surface and outdoor air (K)
L	cube root of the building total volume (m)	ε	turbulence dissipation rate (m^2/s^3)
L_n	characteristic length for natural convection (area-to-perimeter ratio) (m)	η	weighting factor for natural convection (suppressed at high forced convection rates) (–)
P	perimeter (m)	θ	angle between wind direction and normal to the wall ($^\circ$)
Pr	Prandtl number (–)	λ	thermal conductivity of air (W/m K)
q_{cooling}	annual cooling demand ($\text{kWh/m}^2 \text{ a}$)	λ_p	plan area density (–)
$q_{\text{cooling, max}}$	hourly cooling peak loads (W/m^2)	μ	dynamic viscosity of air (N s/m^2)
q_{heating}	annual heating demand ($\text{kWh/m}^2 \text{ a}$)	ρ	density of air (kg/m^3)
Q_{ext}	convective heat flux between exterior surface and outdoor environment (W)	Abbreviations	
R^2	coefficient of determination (–)	ABL	atmospheric boundary layer
Ra_{L_n}	Rayleigh number, based on the characteristic length L_n (–)	ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
R_c	thermal resistance ($\text{m}^2 \text{ K/W}$)	BES	building energy simulation
Re	Reynolds number (–)	BESTEST	building energy simulation test
Re_x	Reynolds number, based on the characteristic length x (–)	BPS	building performance simulation
R_f	surface roughness multiplier (–)	CFD	computational fluid dynamics
T_f	temperature of the air (K)	CHTC	convective heat transfer coefficients
U	thermal transmittance ($\text{W/m}^2 \text{ K}$)	HVAC	heating, ventilation and air conditioning
U_{10}	reference wind speed at 10 m height (in the upstream undisturbed flow) (m/s)	IB	isolated building
U_{loc}	local wind speed (m/s)	LES	large eddy simulation
U_{met}	reference wind speed at the meteorological station (m/s)	LRNM	low-Reynolds number modelling
V	conditioned volume (m^3)	RANS	Reynolds-averaged Navier-Stokes (equations)
W	width of the windward facade (as used in CFD) (m)	SSW	south-southwest
W_b	building width (as used in BES) (m)	UA	urban area

referred to in the literature) to estimate the exterior CHTC. These models, that generally appear in the form of linear or power-law expressions, present the CHTC as a function of a reference wind speed and/or other parameters. These expressions are mainly derived from either wind-tunnel experiments (McAdams 1954; Nusselt and Jürges 1922; Sparrow et al. 1979) or full-scale measurements (Cole and Sturrock 1977; Hagishima and Tanimoto 2003; Jayamaha et al. 1996; Liu and Harris 2007; Loveday and Taki 1996; Nicol 1977; Sharples 1984). The wind-tunnel measurements

were often performed for flat plates at relatively low Reynolds numbers and for a few wind incidence angles. The full-scale measurements, on the other hand, often used heated plates that were placed on one or a few positions on actual building facades. CHTC models obtained this way are strictly only valid for the specific building geometry and the local surroundings. Consequently, the aforementioned CHTC models are primarily applicable for specific configurations and geometries of flat plates or buildings (Defraeye et al. 2011). For example, it has been shown that the use of

different CHTC models for the same isolated building can lead to deviations of up to $\pm 30\%$ for annual cooling energy demand and $\pm 14\%$ hourly peak cooling loads (compared to the average results of the BES performed in (Mirsadeghi et al. 2013)).

Given the limitations of wind-tunnel and full-scale measurements, computational fluid dynamics (CFD) is increasingly used to develop CHTC models (Blocken 2014, 2015; Blocken et al. 2009; Defraeye et al. 2010, 2011; Emmel et al. 2007; Hu et al. 2018; Liu et al. 2013). This is because CFD provides the advantage of obtaining high-resolution data of the flow and thermal field at every point in the computational domain and is very suitable for parametric studies. Moreover, as opposed to reduced-scale tests, CFD allows complex buildings and building configurations to be analyzed at full scale and high Reynolds numbers ($Re = 10^5 - 10^7$) (e.g. Hanna et al. (2006); Karava et al. (2011); Mochida et al. (1997)). Table 1 provides an overview of CHTC models derived based on CFD simulations. Different models have

focused on different parameters affecting the exterior forced or mixed CHTC, including wind speed (Blocken et al. 2009; Defraeye et al. 2010, 2011; Emmel et al. 2007), wind direction (Blocken et al. 2009; Emmel et al. 2007), urban surroundings (Allegrini et al. 2012), plan area density (Liu et al. 2015) and building geometry (Montazeri and Blocken 2017).

Earlier studies have shown the important impact of the building geometry on the CHTC (Meroney 1978; Montazeri et al. 2015; Montazeri and Blocken 2017). However, existing CHTC models take into account the impact of building dimensions either incompletely, or not at all. Inevitably and nevertheless, they are also used in BES tools for buildings with different sizes and geometries regardless of the extrapolation errors that can be introduced due to this practice. Therefore, a better understanding of the influence of different exterior CHTC models on the predicted energy demand of buildings with various geometries is needed.

Note that the focus of the present research is on the exterior CHTC. Earlier experimental and numerical studies

Table 1 CHTC models for building surfaces derived from CFD simulations

Reference	Building geometry (height) $\times$ (width) $\times$ (depth)/ terrain	Studied parameters	CHTC expression ($W/m^2 K$)	Notes
Emmel et al. 2007	2.7 m $\times$ 8 m $\times$ 6 m / IB	$\theta, U_{10}, \Delta T$	aU_{10}^b	Vertical walls: for $\theta = 0^\circ$, $a = 5.15$ and $b = 0.81$; for $\theta = 45^\circ$, $a = 3.34$ and $b = 0.84$; for $\theta = 90^\circ$, $a = 4.78$ and $b = 0.71$; for $\theta = 135^\circ$, $a = 4.05$ and $b = 0.77$; for $\theta = 180^\circ$, $a = 3.54$ and $b = 0.76$ Roof: for $\theta = 0^\circ$, $a = 5.11$ and $b = 0.78$; for $\theta = 45^\circ$, $a = 4.60$ and $b = 0.79$; for $\theta = 90^\circ$, $a = 3.67$ and $b = 0.85$
Blocken et al. 2009	10 m $\times$ 10 m $\times$ 10 m / IB	θ, U_{10}	aU_{10}^b	Windward: for $\theta = 0^\circ$, $a = 4.6$ and $b = 0.89$; for $\theta = 22.5^\circ$, $a = 5.0$ and $b = 0.80$; for $\theta = 45^\circ$, $a = 4.6$ and $b = 0.84$; for $\theta = 67.5^\circ$, $a = 4.5$ and $b = 0.81$
Defraeye et al. 2010	10 m $\times$ 10 m $\times$ 10 m / IB	U_{10}	aU_{10}^b	Windward: $a = 5.14$ and $b = 0.82$
Defraeye et al. 2011	10 m $\times$ 10 m $\times$ 10 m / IB	U_{10}	aU_{10}^b	Windward: for $\theta = 0^\circ$, $a = 5.01$ and $b = 0.85$ Leeward: for $\theta = 0^\circ$, $a = 2.27$ and $b = 0.83$
Liu et al. 2013	10 m $\times$ 10 m $\times$ 10 m / UA	$U_{10}, \Delta T, \lambda_p$	$[(B + C\lambda_p)U_{10}^d]$	Windward: for $\lambda_p = 0$, $B = 3.88$ and $d = 0.82$; for $0.04 \leq \lambda_p \leq 0.25$, $B = 4.45$, $C = 2.42$ and $d = 0.78$ Leeward: for $\lambda_p = 0$, $B = 2.09$ and $d = 0.79$; for $0.04 \leq \lambda_p \leq 0.25$, $B = 2.36$, $C = 1.71$ and $d = 0.79$ Side: for $\lambda_p = 0$, $B = 3.45$ and $d = 0.82$; for $0.04 \leq \lambda_p \leq 0.25$, $B = 4.39$, $C = -3.33$ and $d = 0.78$ Top: for $\lambda_p = 0$, $B = 3.67$ and $d = 0.81$; for $0.04 \leq \lambda_p \leq 0.25$, $B = 4.32$, $C = 1.86$ and $d = 0.79$
Montazeri and Blocken 2017	Buildings with different geometry and size / IB	U_{10}, H, W	$U_{10}^b \cdot (a_0 + a_1W + a_2W^2 + a_3W^3 + a_4W^4 + a_5H + a_6H^2 + a_7H^3 + a_8H^4 + a_9WH + a_{10}WH^2 + a_{11}WH^3 + a_{12}W^2H + a_{13}W^2H^2 + a_{14}W^2H^3 + a_{15}W^3H + a_{16}W^3H^2 + a_{17}W^3H^3)$	Windward: for $\theta = 0^\circ$, $b = 0.84$ Leeward: for $\theta = 0^\circ$, $b = 0.89$ Side: for $\theta = 0^\circ$, $b = 0.88$ Roof: for $\theta = 0^\circ$, $b = 0.90$ Due to space limitations, the coefficients are not mentioned here but can be found in (Montazeri and Blocken 2017)

have shown that the use of different interior CHTC models can also have a considerable impact on the estimated annual energy demand of three-dimensional enclosures (Beausoleil-Morrison 2000; Fisher and Pedersen 1997; Obyn and van Moeseke 2015).

This paper investigates the impact of exterior CHTC models on the predicted energy performance of buildings with a wide range of geometries. BES are performed (in total 302) for buildings with H_b (building height) $> W_b$ (building width), buildings with $H_b < W_b$ and buildings with $H_b = W_b$. Seven CHTC models are used, among which six commonly used CHTC models (Emmel et al. 2007; McAdams 1954; Mitchell 1976; Nusselt and Jürges 1922; Sparrow et al. 1979; Yazdani and Klems 1994). A new generalized CHTC model is also used in which the exterior CHTC is expressed as a function of the reference wind speed at a height of 10 m (U_{10}) and of the height (H) and width (W) of the windward facade (Montazeri and Blocken 2017). The simulations are performed for two types of building envelopes, i.e. envelopes with high and low thermal resistance using the BES tool EnergyPlus 8.5. EnergyPlus was developed by the US Department of Energy and is widely used by researchers and practicing engineers (US Department of Energy 2016). The target parameters are the annual space heating and cooling demand, as well as hourly cooling peak loads.

It is noted that, in EnergyPlus, a facade is assumed to be windward when the angle between the incident wind direction and the normal to the wall is within the range of $+90^\circ$ to -90° (Liu et al. 2015). In this case, and for that specific facade, the CHTC model developed for windward facades is applied. Otherwise, the facade is considered as leeward and therefore the CHTC model developed for leeward facades is used. This standard treatment of windward/leeward facades in EnergyPlus is also adopted in the present study. EnergyPlus does not incorporate any cosine-correction for the CHTC models that do not take into account variations in the wind direction.

EnergyPlus allows the selection of individual CHTC models (among a list of available models in (US Department of Energy 2016)) to be used separately for windward, leeward facades and roofs. For the purposes of the present study, the seven CHTC models introduced above (Emmel et al. 2007; McAdams 1954; Mitchell 1976; Montazeri and Blocken 2017; Nusselt and Jürges 1922; Sparrow et al. 1979; Yazdani and Klems 1994) are employed for the windward facades, while for the leeward facade and roofs the CHTC models by Emmel et al. (2007) and Clear et al. (2003) are used for all the BES. This way, differences in building heating and cooling demand will only result from differences in CHTC models applied to the windward facade.

Moreover, not all CHTC models implemented in EnergyPlus account for the total (mixed) convection

coefficient. In this case, and for the CHTC models that take into account only the forced convection portion, the natural convection portion is added to it in order to define the total (mixed) convection coefficient. Here, the model developed by Walton (1983) is considered. The model by Walton is based on the equations for natural convection heat transfer coefficients in the turbulent range found in the ASHRAE Handbook (ASHRAE 1981). The total convection coefficient is afterwards used to model the convective heat transfer from exterior facades through the classical expression (US Department of Energy 2016):

$$Q_{\text{ext}} = A \cdot \text{CHTC} \cdot \Delta T \quad (1)$$

where Q_{ext} (W) is the convective heat flux between exterior surface and outdoor environment, A (m^2) is the surface area and ΔT (K) is the difference between the surface temperature and the outdoor air temperature.

The paper is structured as follows. In Section 2, some information concerning a new and probably less well-known generalized CHTC model (Montazeri and Blocken 2017) is briefly provided. Section 3 describes the settings and parameters of the BES as well as information concerning the aforementioned CHTC models and their implementation within the framework of this study. The results of the BES are reported in Section 4. Section 5 presents a discussion on the limitations of the presented work along with prospects for future studies. The main conclusions are provided in Section 6.

2 New generalized CHTC model

The CHTC expression by Montazeri and Blocken (2017) focuses on forced convection. It is a trivariate polynomial as a function of U_{10} , windward facade width and building height. As the numerical procedure for the determination and the expression of the new generalized CHTC model are reported in earlier publications (Montazeri et al. 2015; Montazeri and Blocken 2017), this information is only briefly summarized here.

2.1 Numerical procedure

First, a 3D steady Reynolds-averaged Navier-Stokes (RANS) CFD validation was performed with wind-tunnel measurements of surface temperature for a wall-mounted cubic obstacle (Meinders 1998; Meinders et al. 1999). Afterwards, 3D steady RANS simulations of forced convective heat transfer at the facades of isolated buildings with different geometries were performed using high-resolution grids to resolve the thin laminar sublayer which provides the largest resistance to convective heat transfer (Montazeri and Blocken 2017). Low-Reynolds number modelling (LRNM)

was performed by combining the realizable k - ε turbulence model (Shih et al. 1995) for the core flow with the single-equation Wolfshtein model (Wolfshtein 1969) for the near-wall region. Three CFD simulation groups were defined and for each group the focus was on the windward facade:

- (i) Simulations for 12 building geometries to establish the CHTC expression as a function of the reference wind speed at the height of 10 m (U_{10}). U_{10} ranges from 1 m/s to 4 m/s;
- (ii) Simulations for 81 building geometries to establish the CHTC expression as a function of building height (H) and windward facade width (W) and evaluate the in-sample accuracy. H and W range from 5 m to 80 m;
- (iii) Simulations for 6 building geometries to evaluate the out-of-sample accuracy of the CHTC expression.

2.2 Results

The following observations were obtained from each group of simulations:

- (i) The results of the first group showed that the facade-averaged forced CHTC is a power-law function of U_{10} with an exponent 0.84 for the windward facade. In this case, the ratio $\text{CHTC}/(U_{10}^{0.84})$ is nearly independent of U_{10} , which allows the expression between CHTC, H and W to be formed based on simulations for a single value of the reference wind speed U_{10} . Note that this CHTC expression only represents forced convection.
- (ii) The second group of simulations provided the forced CHTC distribution across the windward facade as a function of H and W . Figure 1 shows the facade-averaged ratio $\text{CHTC}/(U_{10}^{0.84})$ as a function of H and W for the windward facade. The new generalized CHTC model is derived using a trivariate polynomial and is a function of the reference wind speed U_{10} , H and W . The coefficient of determination R^2 for the in-sample accuracy evaluation of the polynomial is 0.9977.
- (iii) The third group of simulations was intended for out-of-sample evaluation. It was shown that high coefficient of determination was obtained for the out-of-sample evaluations, establishing thus confidence in this CHTC model for use in BES tools beyond the building dimensions included in the two above-mentioned simulation groups (Montazeri and Blocken 2017). In this case, the maximum and average deviations derived from the application of the CHTC expression on the windward facade for the six out-of-sample combinations are 6.1% and 3.5%, respectively. The corresponding coefficient of determination R^2 is 0.9925.

Note that in the study by Montazeri and Blocken (2017), CHTC models are defined for all building facades

Fig. 1 Profile of surface-averaged $\text{CHTC}/(U_{10}^{0.84})$ on the windward facade for wind perpendicular to the facade for buildings with different building dimensions H and W ($D = 20$ m for all cases) (modified from Montazeri and Blocken (2017))

and roofs. However, since the focus of the present study is on the windward facade, reference is made solely to the CHTC model for the windward facade. The large number of CFD simulations underlying this model and its detailed parameterization render it, at least at the time of writing this paper, the most complete forced CHTC model for windward facades in Table 1. For these reasons and because of the validation of the CFD simulations (Montazeri and Blocken 2017), this new model is considered to be the reference model for the remainder of this study to which the performance of other models will be compared.

It should be noted that the validation was performed based on wind-tunnel experiments for a very small cubic wall-mounted obstacle in channel flow. However, the flow was fully turbulent and it contained the salient features present in the wind flow around buildings, such as impingement, horse-shoe vortex, separation, shear layers, recirculation and reattachment (Meinders 1998; Meinders et al. 1999). Our choice for these experimental data was attributed to the fact that there is a strong lack of available and fully documented high-resolution on-site or wind-tunnel data at realistic Re numbers for building applications. Note that the same methodology and the same experimental data set were also used by other researchers pursuing the development of CHTC expressions for building applications with CFD (e.g. Hu et al. (2018); Liu et al. (2013)). Furthermore, when forced convection is concerned, the CHTC is independent of the magnitude of the imposed thermal boundary conditions i.e. surface temperature and air temperature (Lienhard IV and Lienhard V 2008; Siegel and Sparrow 1960).

3 Building energy simulations

3.1 Building description

For the BES, three groups of south-oriented residential buildings are considered: buildings with (i) H_b (building

height) $> W_b$ (building width); (ii) $H_b < W_b$; (iii) $H_b = W_b$ (square windward facade). All buildings (in total 22) consist of multiple apartments. Each apartment is inspired by the BESTEST case 600 (Judkoff and Neymark 1995) with dimensions H_a (apartment height) $\times W_a$ (apartment width) $\times D_a$ (apartment depth) = 3.33 m $\times$ 10 m $\times$ 20 m, single thermal zone and no interior partitions. Moreover, 12 m² of windows are present, all in the south-facing facade. The exterior surfaces of all the building envelopes are exposed to ambient conditions, i.e. outdoor air temperature, relative humidity, wind and solar radiation. Internal floors or internal walls are used to connect adjacent apartments. The buildings are assumed to be located in Eindhoven, the Netherlands, and the meteorological data for the year 2015 are used (KNMI 2015). According to these weather data, the average mean wind speed and prevailing wind direction throughout this year are approximately 4 m/s and south-southwest (SSW), respectively (Fig. 2). It should be underlined that although during the selected year a heat wave occurred, the focus of the present study is not on the magnitude of the estimated energy demand in the year 2015 but rather on the relative differences between the energy demand predictions of the different CHTC models. Moreover, since the CHTC models investigated here consider mainly the wind speed as input from the weather data file, it is expected that extreme variations in the air temperature should not yield considerable

Fig. 2 Eindhoven airport (at 10 m height, aerodynamic roughness length $z_0 = 0.03$ m), the Netherlands, for the year 2015

impact on the performance of the individual CHTC models to calculate exterior CHTC and in turn of the BES software to calculate the energy demand. For all the above-mentioned building groups, the smallest building, i.e. $H_b = 10$ m and $W_b = 10$ m, is considered in all building groups for reasons of comparison.

For the building group with $H_b > W_b$, eight buildings are considered in which H_b varies from 10 m to 80 m, while $W_b = 10$ m and D_b (building depth) = 20 m. The buildings consist of one apartment per story. Figure 3 shows a front view of this group of buildings. Similarly, for the building group with $H_b < W_b$, W_b varies from 10 m to 80 m, whereas $H_b = 10$ m and $D_b = 20$ m. Eight buildings are considered here, as shown in Fig. 4. In this case, each building consists of three stories. Depending on the width of the buildings, each story consists of a different number of apartments ranging from one to eight. Figure 5 shows the front view of the buildings with $H_b = W_b$ (square windward facade). Eight buildings are considered, and $H_b = W_b$ varies from 10 m to 80 m and $D_b = 20$ m. In this case, the buildings consist of apartments per story that range in number from one to eight in accordance with the width of the building.

3.2 Building envelope components and thermal resistance

Two different insulation levels, low and high, are considered

Fig. 3 Front view of buildings with $W_b = 10$ m and H_b varying from 10 m to 80 m ($D_b = 20$ m for all cases)

Fig. 4 Front view of buildings with $H_b = 10$ m and W_b varying from 10 m to 80 m ($D_b = 20$ m for all cases)

Fig. 5 Front view of buildings with $H_b = W_b$ (square windward facade) varying from 10 to 80 m ($D_b = 20$ m for all cases)

for the building envelope. The low insulation and high insulation levels represent buildings in the Netherlands (i) built before the year 1964 and (ii) built in the year 2012, respectively (Bouwbesluit 2012). Note that about 40% of the total residential building stock in the Netherlands

belongs to the low insulation level category (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2016). Table 2 provides an overview of the building envelope components and their thermal resistance for the buildings with low and high insulation levels. The ground floor insulation is made very thick ($R_e = 25.3 \text{ m}^2 \text{ K/W}$) to thermally decouple the lower story of the buildings from the ground, as done in (Judkoff and Neymark 1995).

3.3 Exterior CHTC models in EnergyPlus

Various CHTC models are present in EnergyPlus 8.5 to calculate the exterior convective heat transfer at building facades (US Department of Energy 2016). In the present study, seven CHTC models are considered: TARPWindward (Sparrow et al. 1979), MoWiTTWindward (Yazdanian and Klems 1994), Nusselt-Jürges (Nusselt and Jürges 1922), McAdams (McAdams 1954), Mitchell (Mitchell 1976), EmmelVertical (Emmel et al. 2007) and Montazeri & Blocken (Montazeri and Blocken 2017). These models are imposed on the facades that, depending on the oncoming wind direction, are considered as windward. The CHTC models applied for the windward facade are briefly explained below, and their expressions are presented in Table 3:

- TARPWindward model: This model is based on the wind-tunnel experiments by Sparrow et al. (1979) for rectangular plates. The model implicitly takes the impact of building geometry into account by means of the perimeter P (m) and the area A (m^2) of the windward surface. It only considers forced convection.

Table 2 Construction details for building envelopes with low and high insulation levels

Low insulation level		
Element	Details	R_e value ($\text{m}^2 \text{ K/W}$)
External walls (inside to outside)	Cavity walls with: limestone inner leaf, air cavity, brick outer leaf	0.36
Internal walls	Limestone wall	0.10
Roof (inside to outside)	Concrete, insulation layer, roofing material	0.39
Internal floor	Concrete	0.31
Ground floor	Timber flooring, insulation layer	25.3*
Windows	Single pane glazing. Solar transmittance coefficient = 0.7	U value: $5.2 \text{ W/m}^2 \text{ K}$
High insulation level		
Element	Details	R_e value ($\text{m}^2 \text{ K/W}$)
External walls (inside to outside)	Cavity walls with: limestone inner leaf, air cavity, insulation, brick outer leaf	4.5
Internal walls	Limestone wall	0.10
Roof (inside to outside)	Concrete, insulation layer, roofing material	6
Internal floor	Concrete	0.31
Ground floor	Timber flooring, insulation layer	25.3
Windows	Double pane glazing. Solar transmittance coefficient = 0.7	U value: $1.65 \text{ W/m}^2 \text{ K}$

* Note that a very high value is chosen to thermally decouple the lower story of the buildings from the ground in line with (Judkoff and Neymark 1995).

Table 3 Exterior CHTC models considered for the BES

CHTC model	CHTC expression (W/m ² K)	Portion of the total CHTC	Surface	Notes
TARPWindward (Sparrow et al. 1979)	$2.53R_f \left(\frac{PU_{loc}}{A} \right)^{\frac{1}{2}}$	Forced convection	Windward	
MoWiTTWindward (Yazdanian and Klems 1994)	$\sqrt{(0.84 \Delta T ^{\frac{1}{3}})^2 + (2.38U_{loc}^{0.89})^2}$	Mixed convection	Windward	
Nusselt-Jürges (Nusselt and Jürges 1922)	$5.8 + 3.94U_{loc}$	Mixed convection	Windward	
McAdams (McAdams 1954)	$5.7 + 3.8U_{loc}$	Mixed convection	Windward	
Mitchell (Mitchell 1976)	$\frac{8.6U_{loc}^{0.6}}{L^{0.4}}$	Forced convection	Windward	
EmmelVertical (Emmel et al. 2007)	aU_{10}^b	Forced convection	Windward/leeward	For $\theta \leq 22.5$, $a = 5.15$ and $b = 0.81$; for $22.5 < \theta \leq 67.5$, $a = 3.34$ and $b = 0.84$; for $67.5 < \theta \leq 112.5$, $a = 4.78$ and $b = 0.71$; for $112.5 < \theta \leq 157.5$, $a = 4.05$ and $b = 0.77$; for $157.5 < \theta \leq 180.0$, $a = 3.54$ and $b = 0.76$
Montazeri & Blocken (Montazeri and Blocken 2017)	$U_{10}^{0.84} \cdot (a_0 + a_1W + a_2W^2 + a_3W^3 + a_4W^4 + a_5H + a_6H^2 + a_7H^3 + a_8H^4 + a_9WH + a_{10}WH^2 + a_{11}WH^3 + a_{12}W^2H + a_{13}W^2H^2 + a_{14}W^2H^3 + a_{15}W^3H + a_{16}W^3H^2 + a_{17}W^3H^3)$	Forced convection	Windward	Due to space limitations, the coefficients can be found in Montazeri and Blocken (2017)
ClearRoof (Clear et al. 2003)	$\frac{\eta\lambda}{L_n} 0.15Ra_{L_n}^{\frac{1}{3}} + \frac{\lambda}{x} R_f 0.0296Re_x^{\frac{4}{3}}Pr^{\frac{1}{3}}$	Mixed convection	Roof	x : in EnergyPlus this is currently simplified to half the square root of the roof surface area; $L_n = \frac{\text{area}}{\text{perimeter}}$; $\eta = \frac{\ln(1 + \frac{Gr_{L,x}}{Re_x^2})}{1 + \ln(1 + \frac{Gr_{L,x}}{Re_x^2})}$; $Ra_{L_n} = Gr_{L_n}Pr$; $Gr_{L_n} = \frac{g\rho^2 L_n^3 \Delta T}{T_f \mu^2}$; $Re_x = \frac{U_{loc} \rho x}{\mu}$
ASHRAEVerticalWall (ASHRAE 1981; Walton 1983)	$1.31 \Delta T ^{\frac{1}{3}}$	Natural convection	Windward/leeward	

- MoWiTTWindward model: This model is derived based on the on-site measurements performed by Yazdanian and Klems (1994) using the MoWiTT facility. The model is applicable for low-rise buildings (Yazdanian and Klems 1994) and does not take into account variations in building geometry. It considers mixed convection, i.e. the combination of forced and natural convection.
- Nusselt-Jürges model: The model is based on the wind-tunnel experiments on a square heated copper plate (0.5 m × 0.5 m) performed by Nusselt and Jürges (1922).

The influence of building geometry is not taken into account. In EnergyPlus the constant 5.8 (Table 3) is assumed to represent the natural convection portion and therefore this CHTC model considers both forced and natural convection (US Department of Energy 2016).

- McAdams model: This model, developed by McAdams (1954), is based on the above-mentioned experiments by Nusselt and Jürges (1922). Consequently, the expression for the McAdams model is very similar to that of the Nusselt-Jürges model (Table 3) for which the influence

of building geometry is also not considered. It should be noted that in both models, radiation loss is also taken into account. As this leads to rather high CHTC values, a correction is normally proposed (Oliphant 1980), which is however not included in EnergyPlus. As in the Nusselt-Jürges model, the constant 5.7 (Table 3) in the McAdams model is assumed to be the natural convection portion (US Department of Energy 2016). The model considers mixed convection.

- Mitchell model: This model is developed by Mitchell (1976) and is based on the convection equation for a sphere. The expression is initially developed for animal shapes ranging in volume from spiders to cows. In EnergyPlus, building geometry is accounted with the use of the cube root of the building volume. The model considers only forced convection.
- EmmelVertical model: This model is based on the (not validated) CFD simulations by Emmel et al. (2007). The simulations are performed for a single low-rise building, and for different wind directions. Therefore, variations in building size and geometry are not accounted for in the model. A coarse grid was used near the building facades and wall functions were employed for modelling flow parameters in the near-wall region that could compromise the accuracy of the CFD results (Blocken et al. 2009). This is mainly because of the use of wall functions that, as opposed to LRNM, provides an approximation for the influence of the wall on the flow and thermal field by bridging the wall region and the logarithmic layer with semi-empirical formulae. As a result, the most important part of the inner boundary layer, i.e. the very thin viscous sublayer and buffer layer, which dominate the convective surface resistance, is not resolved (Blocken et al. 2009). This model considers only forced convection.
- Montazeri & Blocken model: As presented in Section 2, this model provides CHTC for different building facades and roofs as a function of the width and height of the windward facade. It only considers forced convection.

As mentioned earlier, in the present study, for the leeward facades and roofs, the EmmelVertical (Emmel et al. 2007) and ClearRoof (Clear et al. 2003) models (Table 3) are imposed for all simulations, respectively.

Note that the TARPWindward, MoWiTTWindward, Nusselt-Jürges, McAdams and Mitchell models employ a local wind speed U_{loc} (Table 3). In EnergyPlus, the local wind speed is calculated with the following equation according to the ASHRAE Handbook of Fundamentals (ASHRAE 2005):

$$U_{loc} = U_{met} \cdot \left(\frac{\delta_{met}}{z_{met}} \right)^{\alpha_{met}} \cdot \left(\frac{z}{\delta} \right)^{\alpha} \quad (2)$$

where U_{met} (m/s) is the reference wind speed measured at

the meteorological station at height z_{met} (m). δ_{met} (m) and the exponent α_{met} are the boundary layer thickness and the power-law exponent at the meteorological station, respectively. The value for z_{met} is 10 m (US Department of Energy 2016). Therefore, the value of U_{met} is considered equal to U_{10} (m/s) and consequently, U_{loc} (m/s) is proportional to U_{10} . In addition, since most meteorological weather stations are located in an open field, the atmospheric boundary layer thickness δ_{met} and exponent α_{met} at the meteorological station are set to 270 m and 0.14, respectively (US Department of Energy 2016). In this study, the BES are performed for a flat and open country ($\delta = 270$ m and $\alpha = 0.14$) to be in line with the CFD simulations performed by Montazeri and Blocken (2017). The height z (m) above the ground is estimated at the centroid of the facade. Concerning the EmmelVertical and Montazeri & Blocken models, both models employ the wind speed at the height of 10 m U_{10} .

Depending on the reference wind speed employed by the CHTC model, two approaches exist in EnergyPlus to impose CHTC at the exterior building surfaces: (i) local CHTC values for the CHTC models employing U_{loc} that are imposed on the exterior surfaces of each thermal zone (apartment); (ii) facade-averaged CHTC values for the CHTC models employing U_{10} . For each approach, the following is noted:

- The use of U_{loc} as a reference wind speed in EnergyPlus, results in different exterior CHTC (local) values for the exterior surfaces of thermal zones that are situated at a different height z above the ground and share the same orientation to the wind (same facade). Thus, discretization of the exterior CHTC values is assumed over the different exterior thermal-zone surfaces of the same facade. In this case, as the thermal zone is positioned higher above the ground, the CHTC of the exterior surface of that zone receives higher values (Mirsadeghi et al. 2013). The increase of the exterior CHTC with building height is in line with the increase of the mean wind speed within the atmospheric boundary layer (ABL). However, this effect is counteracted by the so-called wind-blocking effect that was first defined by Blocken et al. in studies on wind-driven rain on building facades and that was later demonstrated to have important consequences for pedestrian-level wind conditions as well (Blocken et al. 2008b, a; Blocken and Carmeliet 2006). The wind-blocking effect refers to the upstream disturbance effectuated by a building on the approaching wind. Its consequences for the CHTC distribution across building facades were investigated by Montazeri et al. (2015), who showed that the upstream wind speed slow-down by the building reduces the wind speed near the windward facade and therefore also the CHTC. This effect becomes more important as the windward facade gets wider and

taller (Montazeri et al. 2015; Montazeri and Blocken 2017).

- (ii) The employment of U_{10} , for the EmmelVertical and Montazeri & Blocken model (Table 3) as the reference wind speed, implies that a single facade-averaged value of CHTC is considered for all the exterior surfaces that share the same orientation to the wind. Since no discretization of CHTC is assumed over the different exterior zone surfaces, the CHTC is the same for all the exterior surfaces of all the zones.

In this study, to provide a uniform use of all the CHTC models in EnergyPlus, the assumption of a single facade-averaged CHTC value is adopted for all exterior surfaces of the windward facades. Modifications are made in the source code to meet the assumption of facade-averaged CHTC values for the CHTC models that consider U_{loc} as reference wind speed. For these models, the CHTC value is calculated based on U_{loc} (Eq. (2)) at the height of the building facade centroid (hence not the centroid of the exterior surface of each thermal zone).

To assess the difference between the above-mentioned two approaches of CHTC implementation, BES are performed with both local and facade-averaged CHTC values for the CHTC models employing U_{loc} . The results show that the approach with facade-averaged CHTC values leads to maximum deviations of about 3.0% and 0.8% in annual space cooling and heating demand for all the studied building geometries, respectively, compared to the approach of local CHTC values. In the remainder of this study, to facilitate the analysis of CHTC with respect to building dimensions for specific wind speeds (Section 4.1), only facade-averaged CHTC values are considered.

3.4 Other simulation parameters

An ideal HVAC system (IdealLoadsAirSystem (US Department of Energy 2016)) is used to meet the heating and cooling demand of each zone. The cooling and heating set-points are 24 °C (ISSO 2011) and 20 °C (Ministerie van VROM 2009), respectively. The temperature of the soil is set to 10 °C (Judkoff and Neymark 1995). Note that an R_c value of 25.3 m² K/W is chosen for the ground floor insulation to thermally decouple the lower story of the buildings from the ground, as mentioned in Section 3.2. Regarding the amount of shortwave radiation being reflected by the ground, a value of 0.2 is set for the ground reflectance. The infiltration for each zone is 0.2 h⁻¹ air changes per hour (ACH) (ISSO 2011; van Hooff et al. 2015). Internal heat gains of 4 W/m² due to electric equipment and lighting are imposed for each apartment (NNI 2011). In addition, internal gains due to occupation (Table 4) of each apartment are assumed for 4 persons; two adults and two children (ISSO

Table 4 Heat gains due to occupation

Heat source	Time interval [h]			
	06:00–18:00	18:00–19:00	19:00–23:00	23:00–06:00
Persons	–	385 W	385 W	241 W

2011; van Hooff et al. 2015). The time-step is set to 10 minutes. The TARP algorithm (US Department of Energy 2016) is used for simulating the interior convective heat transfer coefficients (e.g. Ref (van Hooff et al. 2015)).

As presented in Table 3, not all CHTC models in EnergyPlus account for the total convection coefficient. For the CHTC models that consider only the forced convection coefficient, i.e. TARPWindward, EmmelVertical, Mitchell and Montazeri & Blocken, the ASHRAEVerticalWall (Table 3) model is enabled to account for the exterior natural convection. Note that the CHTC models MoWiTTWindward, Nusselt-Jürges and McAdams represent the mixed convection coefficient and include the natural convection portion. Therefore, they are not used in conjunction with a second natural convection model, i.e. the ASHRAEVerticalWall (US Department of Energy 2016).

4 Results

Results are presented for three target parameters: annual space heating demand $q_{heating}$ (kWh/m² a) (Section 4.2), annual space cooling demand $q_{cooling}$ (kWh/m² a) (Section 4.3) and hourly space cooling peak loads $q_{cooling,max}$ (W/m²) (Section 4.3). The CHTC model by Montazeri & Blocken, in which the impact of building geometry is taken into account, is considered as the reference model. For each building, the results are presented as the deviations between the target parameters that result from the use of the six commonly used CHTC models ($E_{CHTC,model}$) and those of the reference model (E_{ref}):

$$\text{Deviation}(\%) = \frac{E_{CHTC,model} - E_{ref}}{E_{ref}} \cdot 100 \quad (3)$$

4.1 Influence of wind speed on facade-averaged CHTC

The influence of wind speed U_{10} on the imposed facade-averaged CHTC value on the windward facade is evaluated for all the CHTC models and all buildings. As stated in Section 3.4, the CHTC models MoWiTTWindward, Nusselt-Jürges and McAdams include both the forced and the natural portion of the CHTC in their expressions (US Department of Energy 2016). More importantly, in the case of Nusselt-Jürges and McAdams, the implementation of these models in EnergyPlus does not allow for a clear identification and isolation of each portion of the CHTC (Table 3). To provide

a fair comparison between the CHTC models, the facade-averaged CHTC evaluated in this section represents the total (mixed) convection coefficient. For the CHTC models that take into account the calculation of only the forced CHTC (i.e. TARPWindward, Mitchell, EmmelVertical and Montazeri & Blocken), the natural portion of the CHTC is estimated based on the ASHRAEVerticalWall model (Section 3.4) and added to the forced CHTC.

The evaluation considers three mean wind speeds $U_{10} = 1, 4$ and 8 m/s and wind incidence angle $\theta = 0^\circ$, i.e. perpendicular to the windward facade. The temperature difference ΔT between the windward facade and air is assumed to be 3.5 K, representing an average value found during a warm day in summer. It should be noted that the abovementioned selections are made to facilitate the interpretation of the results in the following sections.

Figure 6 shows the facade-averaged CHTC (total convection coefficient) on the windward facade of buildings with $H_b > W_b$, when different CHTC models are considered. The following observations are made:

- For all the considered wind speeds, the reference model shows an increase in CHTC with an increase in building height. At the lower wind speed, $U_{10} = 1$ m/s, a rather small increase of facade-averaged CHTC of about $+15.0\%$ ($+1.2$ W/m² K) is observed as the building height increases from 10 m to 80 m, while this is about $+19.1\%$ ($+7.1$ W/m² K) for $U_{10} = 8$ m/s.
- The Nusselt-Jürges, McAdams and MoWiTTWindward models present an ascending trend, similar to the reference model. This ascending trend is related to the implementation of U_{loc} . By increasing the height of the buildings, U_{loc} also increases (because of the displacement of the windward facade centroid), resulting in higher values of facade-averaged CHTC. Note that the building geometry is not accounted for in these three models (Table 3).
- For the Nusselt-Jürges and McAdams models, the differences in facade-averaged CHTC with the reference model decrease with increasing height. For example, at $U_{10} = 4$ m/s, these differences vary from $+7.1\%$ ($H_b = 10$ m) to $+2.5\%$ ($H_b = 80$ m) for Nusselt-Jürges and from $+9.9\%$ ($H_b = 10$ m) to $+5.5\%$ ($H_b = 80$ m) for the McAdams model, respectively.
- MoWiTTWindward appears to be the CHTC model with the lowest values of facade-averaged CHTC, at low wind speeds ($U_{10} = 1$ m/s). Differences between MoWiTTWindward and reference model in facade-averaged CHTC, at $U_{10} = 1$ m/s, range from -61.9% to -57.7% for buildings with $H_b = 10$ m to 80 m, respectively.
- The TARPWindward and Mitchell models, in which the impact of building geometry is implicitly taken into account (Table 3), on the contrary, present an opposite trend

compared to the reference model as the facade-averaged CHTC decreases monotonically by increasing the building height. This trend can be explained by the inversely proportional relationship between facade-averaged CHTC and building geometry in these CHTC models. For wind speeds of 4 m/s and 8 m/s, TARPWindward and Mitchell models present the highest differences in facade-averaged CHTC with the reference model. In this case, a maximum difference of -74.9% and -68.3% is observed at $U_{10} = 4$ m/s for $H_b = 80$ m, respectively. These differences are -81.4% and -74.5% at $U_{10} = 8$ m/s, respectively.

- The EmmelVertical model estimates the facade-averaged CHTC based on U_{10} resulting in a constant value of CHTC for all the spectrum of building heights. For this model, the average deviations with the reference model are 19.4% , 25.7% and 28.1% for $U_{10} = 1, 4$ and 8 m/s, respectively.

The prediction of facade-averaged CHTC (total convection coefficient) on the windward facade of buildings, with

Fig. 6 Predicted surface-averaged CHTC (total convection coefficient) by different models for the windward facade for buildings with $W_b = 10$ m and H_b varying from 10 m to 80 m. (a) $U_{10} = 1$ m/s, (b) $U_{10} = 4$ m/s and (c) $U_{10} = 8$ m/s ($D_b = 20$ m, $\Delta T = 3.5$ K and wind incidence angle $\theta = 0^\circ$)

$H_b < W_b$, with different CHTC models is presented in Fig. 7. The following observations are made:

- For this group of buildings, the reference model presents a descending trend for all the investigated building widths. At $U_{10} = 1$ m/s, this reduction is about -25.4% as W_b increases from 10 m to 80 m, while it is about -30.4% and -31.9% for $U_{10} = 4$ m/s and 8 m/s, respectively.
- The Nusselt-Jürges, McAdams and MoWiTTWindward models predict constant values of the facade-averaged CHTC, which is attributed to the implementation of U_{loc} . As the width of the buildings increases, the height of the building remains constant resulting in a constant value of U_{loc} and facade-averaged CHTC.
- For the CHTC models Nusselt-Jürges and McAdams, at $U_{10} = 4$ m/s and 8 m/s, the maximum deviations, found for $W_b = 80$ m, are $+33.4\%$ and $+35.4\%$ respectively for Nusselt-Jürges while for McAdams these are $+29.3\%$ and $+31.1\%$.
- As observed in the building group where $H_b > W_b$, MoWiTTWindward presents the lowest values of facade-averaged CHTC at $U_{10} = 1$ m/s (Fig. 7a). The difference between the TARPWindward and the reference model ranges from -62.1% to -49.1% for buildings with $W_b = 10$ m and 80 m, respectively. For $U_{10} = 4$ m/s and 8 m/s, TARPWindward and Mitchell present the lowest values (Figs. 7b and 7c) compared to the reference model.
- The CHTC values predicted by the TARPWindward and Mitchell models, in which the impact of building geometry is implicitly considered, show a decreasing trend with the increase of the building width. The increase of building width results in lower differences between the two models and the reference model. In this case maximum deviations are found to be -67.4% and -59.7% , respectively, for $U_{10} = 4$ m/s and $W_b = 10$ m.
- A constant value of the facade-averaged CHTC is predicted by the EmmelVertical model. It is noted that the EmmelVertical shows similar values of facade-averaged CHTC with the reference model for buildings with $W_b = 30$ m and $W_b = 40$ m, for all wind speeds. On average, deviations of 10.6% , 11.5% and 11.6% are found between the reference and the EmmelVertical model for $U_{10} = 1$ m/s, 4 m/s and 8 m/s, respectively.

Figure 8 presents the prediction of the total facade-averaged CHTC with different CHTC models on the windward facade of buildings with $H_b = W_b$. The following observations are made:

- For the reference model, at $U_{10} = 1$ m/s, the imposed facade-averaged CHTC decreases by -7.9% , when $H_b (= W_b)$ increases up to 50 m. This reduction is about -9.7% and -10.1% for $U_{10} = 4$ m/s and 8 m/s, respectively. For $H_b (= W_b) > 60$ m a slight increase (less than $+1\%$) of the facade-averaged CHTC value is predicted for all wind speeds.

- The Nusselt-Jürges, McAdams and MoWiTTWindward models present an ascending trend. This is because, even though both height and width increase, the implementation of U_{loc} accounts only the variations of the building height.
- For the Nusselt-Jürges and McAdams models, the maximum difference with the reference model is found for $H_b (= W_b) = 80$ m.
- As opposed to the previous building groups, MoWiTTWindward presents the lowest values of facade-averaged CHTC at $U_{10} = 1$ m/s (Fig. 8a) only for $H_b (= W_b)$ up to 30 m. For higher $H_b (= W_b)$ and $U_{10} = 1$ m/s, TARPWindward presents the lowest values of CHTC.
- A decreasing trend of facade-averaged CHTC is observed for the TARPWindward and Mitchell models with the increase of height and width. It should be noted that, the decrease of the CHTC values for these models is more pronounced compared to the building group $H_b > W_b$, given the larger impact of the surface area and building volume considered in their expressions (Table 3). The maximum differences with the reference model occur for

Fig. 7 Predicted surface-averaged CHTC (total convection coefficient) by different models for the windward facade for buildings with $H_b = 10$ m and W_b varying from 10 to 80 m. (a) $U_{10} = 1$ m/s, (b) $U_{10} = 4$ m/s and (c) $U_{10} = 8$ m/s ($D_b = 20$ m, $\Delta T = 3.5$ K and wind incidence angle $\theta = 0^\circ$)

Fig. 8 Prediction of surface-averaged CHTC (total convection coefficient) by different models for the windward facade for buildings with $H_b = W_b$ (square windward facade) varying from 10 m to 80 m. (a) $U_{10} = 1$ m/s, (b) $U_{10} = 4$ m/s and (c) $U_{10} = 8$ m/s ($D_b = 20$ m, $\Delta T = 3.5$ K and wind incidence angle $\theta = 0^\circ$)

the building $H_b = W_b = 80$ m. In this case, the deviations are -59.9% ($U_{10} = 1$ m/s), -79.5% ($U_{10} = 4$ m/s) and -85.5% ($U_{10} = 8$ m/s) for the TARPWindward and -47.1% ($U_{10} = 1$ m/s), -66.7% ($U_{10} = 4$ m/s) and -73.5% ($U_{10} = 8$ m/s) for the Mitchell model, respectively.

- As for EmmelVertical, due to the use of U_{10} in EnergyPlus, no variations are observed in facade-averaged CHTC. The average deviation with the reference model is 6.6% at $U_{10} = 1$ m/s. This is 11.3% and 13.5% for $U_{10} = 4$ m/s and $U_{10} = 8$ m/s, respectively.

4.2 Space heating demand

Figure 9 shows the annual space heating demand obtained with the different CHTC models for the three groups of buildings. It can be seen that, regardless of the building type, the annual space heating reduces by increasing the building height and/or width. This reduction is more pronounced

Fig. 9 Annual space heating demand by different CHTC models for buildings with high insulation values of the building envelope and (a) $H_b > W_b$, (c) $H_b < W_b$ and (e) $H_b = W_b$. (b,d,f) Same for buildings with low insulation values of the building envelope ($D_b = 20$ m for all cases). For comparison reasons the building with $H_b = W_b = 10$ m is considered for all building groups

for smaller buildings and becomes less significant with further increase in H_b and/or W_b . This is a result of the compactness ratio of the buildings, i.e. the exterior facade (A_s) to the conditioned volume (V) ratio (Rodriguez-Ubinas et al. 2014), as shown in Fig. 10. In this case, for the buildings with $H_b > W_b$, a rather steep decrease in the A_s/V is found from the building with $H_b = 10$ m to $H_b = 20$ m that becomes less pronounced with further increase of H_b . The decrease of the building compactness ratio leads to the reduction of the heat losses from the building envelope and in turn of the energy consumption (Depecker et al. 2001). Similar observations are made for the other two building groups.

By increasing the insulation values of the building envelope, the contribution of the convective resistance at the exterior surfaces of the building envelope becomes small compared to the overall wall thermal resistance (Zhang et al. 2013). Therefore, the use of higher insulation values results in a much weaker impact of the facade-averaged CHTC on heating demand.

Fig. 10 Compactness ratio as a function of building geometry for buildings with (a) $H_b > W_b$, (b) $H_b < W_b$ and (c) $H_b = W_b$ ($D_b = 20$ m for all cases). For comparison reasons the building with $H_b = W_b = 10$ m is considered for all building groups

For the building group $H_b > W_b$ (Figs. 9a and 9b), the employment of the TARPWindward and Mitchell models leads to the maximum deviations with the reference case of about -11.1% and -8.8% ($H_b = 80$ m), respectively, for low-insulated buildings. In this case, the average deviations are about 9.6% and 7.4% for low insulation values, respectively. For higher insulation values, these deviations are 3.3% and 2.1% , respectively. Such observation is consistent with the findings in Section 4.1. On the other hand, the Nusselt-Jürges and McAdams model predict similar facade-averaged CHTC values with the reference model and therefore the implementation of these models results in negligible deviations (about $\pm 0.3\%$) with the reference model for both low-insulated and highly-insulated buildings.

The impact of different CHTC models on the predicted heating demand for the low-rise building group with $H_b < W_b$ is presented in Figs. 9c and 9d. Similar to the building group with $H_b > W_b$, the implementation of TARPWindward and Mitchell models results in the maximum deviations

with the reference case and low-insulated buildings, of about -6.4% and -4.8% respectively. For example, for the low-insulated buildings, the average deviations are 5.8% and 4.1% , respectively. For the highly-insulated buildings, these deviations are 3.2% and 1.7% , respectively. For the EmmelVertical model, the average difference is about 0.5% and 0.3% for the low-insulated and highly-insulated buildings, respectively.

Figures 9e and 9f present the impact of CHTC models on the heating demand of buildings where both H_b and W_b vary simultaneously. Given the high differences in facade-averaged CHTC mentioned in Section 4.1, the TARPWindward and Mitchell present the highest differences in heating demand with the reference model. In this case, when low insulation values of the building envelope are assumed, the average and maximum differences from the reference model are 11.4% and -14.5% for TARPWindward and 7.8% and -9.9% for the Mitchell model. The average differences for buildings with high insulation values are found to be 5.4% and 3.6% , respectively. The EmmelVertical model, which presents similar values of facade-averaged CHTC, gives average deviation of 0.9% and 0.3% for low-insulated and highly-insulated buildings, respectively.

4.3 Space cooling demand

Figure 11 presents the annual space cooling demand obtained with the different CHTC models. During summer, cooling is significantly influenced by the convective removal of solar gains from the exterior surfaces. On the other hand, during winter time, the solar gains are relatively smaller and the differences between the outdoor air temperatures and exterior surface temperatures are less. Consequently the estimation of the space cooling is found to be more sensitive to the various CHTC models than space heating (Mirsadeghi et al. 2013).

It can be observed that the application of high insulation leads to small variations in the cooling demand obtained by different CHTC models. In addition, for each building configuration, the cooling demand is higher for the highly-insulated buildings compared to the low-insulated buildings. For highly-insulated buildings, heat (e.g. solar radiation through the windows) is trapped inside the building that, as opposed to the case of low-insulated buildings, cannot be transferred easily through the building envelope to the outside environment (van Hooff et al. 2016). The accumulation of the heat is further enhanced with the increase of building dimensions, and consequently of the building compactness ratio decrease (Fig. 10), and results in an ascending trend of the cooling demand as shown in Figs. 11a, 11c and 11e. Similarly, this ascending trend is observed for the low-insulated buildings for buildings with $H_b < W_b$ (Fig. 11d)

Fig. 11 Annual space cooling demand by different CHTC models for buildings with high insulation values of the building envelope and (a) $H_b > W_b$, (c) $H_b < W_b$ and (e) $H_b = W_b$. (b,d,f) Same for buildings with low insulation values of the building envelope ($D_b = 20$ m for all cases). For comparison reasons the building with $H_b = W_b = 10$ m is considered for all building groups

and $H_b = W_b$ (Fig. 11f). However, the impact of building compactness ratio appears to be less significant and is found only in the case where H_b and/or W_b is higher than 20 m. For buildings up to 20 m, where a decreasing trend is observed, all conditioned zones have at least one of their side surfaces (facing east or west) exposed to wind (Figs. 4 and 5) allowing for more heat to be transferred to the outdoor environment and compensate for the added solar heat gains. This explains also the decreasing trend of cooling demand for buildings with $H_b > W_b$ (Mirsadeghi et al. 2013) where all the conditioned zones have both side surfaces being exposed to wind.

Concerning the impact of different CHTC models on space cooling demand of buildings with $H_b > W_b$ (Figs. 11a and 11b), the following observations are made:

- The increase of the building height is associated with a larger area exposure of the exterior windward facade to (i) solar radiation and (ii) higher wind speeds within the atmospheric boundary layer. In this case, determination of heat removal, due to convection, of the solar gains from

the windward facade becomes important. Consequently, variations in exterior CHTC values significantly affect the results (Fig. 11b).

- The highest differences with the reference model are observed for the TARPWindward and Mitchell models. Although the impact of building geometry is implicitly considered in these models, an increase in the building height from 10 m to 80 m leads to average deviations of 37% and 29% in annual space cooling demand of low-insulated buildings. The maximum deviations, which occur for the building with $H_b = 80$ m, are +42% and +33%, respectively.
- The Nusselt-Jürges and McAdams models predict similar cooling demand as the reference model for all building heights. As shown in Fig. 6, these models predict CHTC values that are similar to the reference model. In this case, the use of Nusselt-Jürges and McAdams results in average deviations of 1% and 2% for low-insulated buildings, and 0.3% and 0.4% for the highly-insulated buildings, respectively.

In Figs. 11c and 11d, the cooling demand obtained by the different CHTC models for buildings with $H_b < W_b$ are shown:

- In contrast to the previous building group, the impact of different CHTC models on the predicted cooling demand of buildings with varying width is less pronounced. This behaviour is attributable to the following observation. The increase of building width leads to larger roof area being exposed to solar radiation and wind. As opposed to the buildings with $H_b > W_b$, where the roof area remained constant for all the investigated H_b , in the case of buildings with $H_b < W_b$ the roof increases proportionally to the building width. Consequently, the contribution of the convective heat losses from the roof (and of the corresponding CHTC model) becomes important with respect to the overall building convective heat losses. Note that, as mentioned in Section 3.3, the CHTC model used for the prediction of the convective heat losses from the roof surfaces is the same for all buildings, i.e. ClearRoof.
- For low-insulated buildings, the TARPWindward and Mitchell models show average deviations of 16% and 12% in annual space cooling demand, respectively. In this case, maximum deviation of +25% is found at $W_b = 10$ m for TARPWindward. For the highly-insulated buildings, the deviations drop to +3% and +2%, respectively.
- The results for the EmmelVertical model, which is developed for a low-rise building, are very similar to those of the reference model. In this case, the average deviations in annual space cooling are 2.0% and 0.3% for the low and highly-insulated buildings, respectively.

Figures 11e and 11f show the annual cooling demand

variations obtained by the use of different CHTC models for buildings with $H_b = W_b$. The following points are identified:

- The variations can be explained as the combination of the individual impact of the CHTC models on annual cooling demand for buildings with $H_b > W_b$ and $H_b < W_b$. Consequently, a compensation between the increasing influence of the wind speed and removal of solar gains by convection on the windward facade with the increasing height and the augmenting importance of the convective heat losses from the roof with the increasing width is observed.
- The TARPWindward and Mitchell models, in which the impact of building geometry is implicitly taken into account, yield the highest deviations with the reference model. The average deviations are 26% and 19% for low-insulated buildings, and 4% and 3% for highly-insulated buildings, respectively. Maximum deviations of +29% are estimated with the TARPWinward, at $H_b = W_b = 80$ m.
- For the EmmelVertical model, similar results with the reference model are observed, regardless of the level of insulation. The average deviations are 2.1% for the low-insulated and 0.3% for the highly-insulated buildings.

The variation of the hourly space cooling peak loads of low-insulated buildings for the different CHTC models are presented in Fig. 12. Note that the estimation of the hourly peak cooling demand is of particular importance during the building design phase as miscalculations can lead to over-sizing or under-sizing of the HVAC systems (Ding et al. 2018).

The impact of the time step is evaluated. The evaluation is made for two additional time steps: 1 minute and 3 minutes. The analysis indicates a minor impact for all the building configurations. For example, the difference between the simulated hourly cooling peak loads with a 1 minute and a 10 minutes time step for the building with $H_b = 80$ m and $W_b = 10$ m is about 2%. The following are inferred from Fig. 12:

- For the building group with $H_b > W_b$ (Fig. 12a), the hourly cooling peak loads show the same trend as the annual cooling demand for the different CHTC models. In this case, for the TARPWinward and Mitchell models, the deviations increase as the building height increases and reach +15% and +13% at $H_b = 80$ m, respectively. On average, TARPWindward and Mitchell show deviations of 13% and 11% in hourly cooling peak loads for all building heights, respectively.
- The decreased influence of the CHTC models on the cooling energy demand of the $H_b < W_b$ building group is also depicted on the estimated hourly cooling peak loads (Fig. 12b). The use of different CHTC models results in small variations in the results. In particular, the use of

the CHTC model TARPWindward presents average and maximum deviations of about 4.6% and +9.1% ($W_b = 10$ m) with the reference model.

- Figure 12c indicates that the impact of CHTC models is slightly higher in the building group with $H_b = W_b$ than on the building group with $H_b < W_b$, yet smaller than with $H_b > W_b$. In this case, average deviations of 6.4% and 4.8% are found for the TARPWindward and Mitchell models for hourly cooling peak loads of buildings with $H_b = W_b$. For TARPWindward, the maximum deviation is +9.1% for $H_b = W_b = 10$ m.

Fig. 12 Peak hourly space cooling loads by different CHTC models for buildings with low insulation values of building envelope and (a) $H_b > W_b$, (b) $H_b < W_b$ and (c) $H_b = W_b$ ($D_b = 20$ m for all cases). For comparison reasons the building with $H_b = W_b = 10$ m is considered for all building groups

5 Limitations and future work

Several limitations in the present study can identify prospects for future research:

- In this study, the focus is on the CHTC models applied on windward facades. Future studies should focus on the impact of exterior CHTC models for leeward facades and roofs on the predicted energy demand. Such evaluations

can be based on CHTC models derived from CFD large eddy simulations (LES), given the transient and complex phenomena that occur over the roof and downstream of the leeward facade (Antonioni et al. 2017; Hu et al. 2018; Iousef et al. 2017; Rodi 1997).

- The building geometries investigated here vary in size, with respect to H and W , from 10 m up to 80 m. Although this range covers a large portion of the building stock, it should be noted that the implementation of the CHTC model Montazeri & Blocken, in BES, outside the aforementioned range should be treated with caution (Montazeri and Blocken 2017).
- An important parameter influencing the CHTC distribution across building facades is wind direction. This especially holds in the case of simultaneous change of building geometry (Montazeri and Blocken 2018). In the present study, only the CHTC model EmmelVertical takes into account wind direction. However, as mentioned in Section 3.3, EmmelVertical is derived based on a single low-rise building geometry (Emmel et al. 2007). Future studies should address the combined impact of wind direction and building geometry on the predicted energy demand.
- The focus of this study is on stand-alone buildings for which different size and geometry is considered. Liu et al. (2015) investigated the impact of exterior CHTC on the energy consumption of buildings in urban areas with different plan area densities. However, the urban area consisted of cubic buildings (height equal to 10 m) and did not take into account variations in the building size and geometry. Further studies should address the impact of CHTC models in urban areas with buildings varying in size and geometry. In these cases the urban microclimate (Allegrini and Carmeliet 2017; Liu et al. 2015) can be of significant importance for the building energy consumption.
- In the present study, simplified buildings are considered for which windows are placed on the exterior building surfaces facing South. Other geometrical features, such as chimneys, balconies and porticos are not taken into account. Given their importance on the wind flow around buildings (Chand et al. 1998; Evangelisti et al. 2017; Montazeri et al. 2013; Montazeri and Blocken 2013; Montazeri and Montazeri 2018; Murakami 1990; Stathopoulos and Zhu 1988), future studies should evaluate the impact of CHTC models on the prediction of energy demand for such cases.
- It is noted that the apartments have a relatively high window-to-wall ratio. The selection is in line with the BESTEST case (Judkoff and Neymark 1995) and is representative of a residence with multiple members and tertiary buildings. In this case, the convective heat losses

from the windows are of particular importance, especially for the low-insulated buildings with single glazing. Future studies should consider cases with varying window-to-wall ratios in order to investigate the influence on the simulated convective heat losses.

- CHTC models implemented in EnergyPlus are only considered in the present study. Several other models have been derived and implemented in different BES tools. For example, models are developed by Nicol (1977), Sharples (1984), Loveday and Taki (1996), Hagishima and Tanimoto (2003) and Liu and Harris (2007). However, none of these models take into account the impact of building geometry.

6 Conclusions

The present paper focuses on the impact of CHTC models on the energy performance of buildings with different geometry. Three building groups are considered: buildings with H_b (building height) $> W_b$ (building width), buildings with $H_b < W_b$ and buildings with $H_b = W_b$. The evaluation is made for 7 CHTC models. The new generalized CHTC model developed by Montazeri and Blocken (2017), which is a function of wind speed at a height of 10 m (U_{10}) and the building dimensions height (H) and width (W) of the windward facade, is considered as a reference model. Low and high thermal resistances of the building envelope are considered. The CHTC models are implemented and compared in the EnergyPlus BES tool. Annual space heating and cooling demand as well as hourly peak space cooling loads are used as target parameters with the focus being on the windward facade. The following conclusions are made:

- The selection of different CHTC model does not result in high deviations for the predicted annual space heating demand. Maximum deviations with the reference model, are found to be -11.1%, -6.4% and -14.5% for low-insulated buildings with $H_b > W_b$, $H_b < W_b$ and $H_b = W_b$, respectively.
- The predicted annual space cooling demand is significantly affected by the selection of different CHTC models, especially for buildings with varying height and constant width. In this case, for low-insulated buildings, maximum deviation of +42% is observed, compared to the reference model. The sensitivity of the predicted annual cooling demand to different CHTC models is less pronounced for low-rise buildings with varying width. For this building group, the maximum deviation with the reference model is +25% for low-insulated buildings. By increasing the building height and width simultaneously, the observed deviations for the annual cooling demand are defined by the individual impact of the CHTC model on buildings where height and width are treated separately. In this case,

maximum deviations with the reference model of about +29% are found for low-insulated buildings.

- The deviations in hourly space peak cooling loads present the same trend as the annual space cooling demand with respect to variations in the selected CHTC model. For buildings with $H_b > W_b$, the hourly space peak cooling loads shows maximum deviation of about +15% (for a high-rise building with $H_b = 80$ m and $W_b = 10$ m). For the building groups $H_b < W_b$ and $H_b = W_b$, this deviation is +9.1% (for a low-rise building with $H_b = 10$ m and $W_b = 10$ m).
- The use of different CHTC models influences the predicted energy demand. It is found here that the impact is higher on buildings with low insulation values of the building envelope. Therefore, it is advised that CHTC models used in BES tools should account building geometry in their expressions. This is especially the case for high-rise buildings.

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