New Correlation for the CHTC of Building Surface Using Wind-Tunnel Measurement and Numerical Analysis

Hamed Agabalaee Fakhim (✉ hamed.fakhim2@gmail.com)

Islamic Azad University Tabriz Branch <https://orcid.org/0000-0002-9893-6215>

Kamiar Zamzamian

Islamic Azad University Tabriz Branch

Masoud Hanifi

Islamic Azad University Tabriz Branch

Research

Keywords: Convective heat transfer coefficient, Mathematical correlation extraction, Neural network design, Wind-tunnel Measurement, Computational Fluid Dynamics (CFD), Building Energy Simulation (BES)

Posted Date: March 1st, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1288822/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

New correlation for the CHTC of building surface using wind-tunnel measurement and numerical analysis

Hamed Agabalaie Fakhim*¹ Kamiar Zamzamian² Masoud Hanifi³

*1-Department of Mechanical Engineering, Tabriz Branch, Islamic Azad University,
Tabriz, Iran. Hamed.fakhim2@gmail.com

2-Department of Mechanical Engineering, Tabriz Branch, Islamic Azad University,
Tabriz, Iran. zamzamian@iaut.ac.ir

3- Department of Mechanical Engineering, Tabriz Branch, Islamic Azad University,
Tabriz, Iran. masoud.hanifi@gmail.com

ABSTRACT

This paper has been attempted to present a relation for CHTC based on effective parameters using numerical modeling and simulations, laboratory work, and mathematical analysis. Firstly, the experimental model in numerical analysis software was simulated and the results were compared with laboratory results. The influence of different parameters such as wind speed, wind angle, temperature difference, and roughness height on the CHTC of the top and windward faces of the building were investigated. Comparison of the effect of the parameters showed that for both the front and top of the cubic plane, the wind velocity and temperature difference had the highest and lowest effects on the upper and front faces, respectively. It was also found that in the front face, the angle effect was greater than the roughness, whereas in the upper face the roughness height had more influence on the CHTC. Finally, for the obtained results and considering the amount, two relational methods have been derived to calculate CHTC for the top and front face. Also, using the analyzed results, the neural network design was performed. It was found that using this neural network, the CHTC of building surfaces can be calculated with high accuracy.

Keywords: Convective heat transfer coefficient, Mathematical correlation extraction, Neural network design, Wind-tunnel Measurement, Computational Fluid Dynamics (CFD), Building Energy Simulation (BES)

1. INTRODUCTION

A large number of engineering applications find convective heat transfer fascinating. For instance, urban heat island mitigation strategy (Chandra. R, Goel. V.K., Raychaudhuri. B.C., 1983), building energy demand (Mirsadeghi, M., Cóstola, D., Blocken, B., Hensen, J.L.M., 2013), solar collectors (Chandra. R, Goel.V.K., Raychaudhuri. B.C., 1983), heat exchangers (Iacovides, H., Launder, B.E., 1995), etc. Convective heat transfer coefficients (CHTCs) usually evaluate the convective heat transfer. CHTCs is also defined as:

$$CHTC = \frac{Q_w}{T_w - T_{ref}} \quad (1)$$

with Q_w the heat flux normal to the wall, T_w the wall temperature, and T_{ref} the reference temperature. The energy performance of buildings is evaluated by CHTC. According to (Cooper, 1981) the external surfaces' convective heat losses are 3-4 times as much as the radiative heat losses, and a 30% deviation for cooling energy demand can be caused by different convective models (Mirsadeghi, M., Cóstola, D., Blocken, B., Hensen, J.L.M., 2013).

According to numerous studies, different choices of CHTC values for internal building surfaces can affect the simulated energy consumption to differ from 20% to 40% (Spittle, J.D., Pedersen, CO., Fisher, DE., 1991; Fisher DE, Pedersen CO., 1997; Beausoleil-Morrison, 2001). Moreover, considering the exterior surface CHTC correlations, a building in a street canyon's demand for space cooling can differ up to a factor of 1.8 (Allegrini, J., Dorer, V., Carmeliet, J., 2013). Furthermore, using computational fluid dynamics (CFD), outdoor and indoor airflow simulations can provide CHTC correlations for building energy simulations (BES) to enhance the result accuracy (Allegrini, J., Dorer, V., Carmeliet, J., 2012). To gain a more precise approximation of building energy

¹ Email address: Hamed.fakhim2@gmail.com

consumption and interior/exterior surface temperatures, a large number of recent surveys deployed the coupling of BES and CFD (Zhai, ZQ., Chen, QY., Haves, P., Klems, JH., 2002; Morrison, 2000; Zhang, R., Lam, KP., Yao, SC., Zhang, YJ., 2013). To sum up, the accuracy of simulated building energy consumption is affected by the interior/exterior surface CHTCs.

Correlations between CHTC and wind speed have been provided by a large number of studies. Moreover, several parameters such as the buoyancy effect (Marcelo, G.E., Marc, O.A., Nathan M., 2007; Liu, J., Heidarinejad, M., Gracik, S., 2015; Allegrini, J., Dorer, V., Carmeliet, J., 2012; Karava, P., Jubayer, C.M., Savory, E., 2012), building geometry (Montazeri, H., Blocken, B., Derome, D., 2015; Karava, P., Jubayer, C.M., Savory, E., 2012; Montazeri, H., Blocken, B., 2017), building densities (Liu, J., Srebric, J., Yu, N., 2013; Liu, J., Heidarinejad, M., Gracik, S., 2015; Allegrini, J., Dorer, V., Carmeliet, J., 2012), turbulence intensity (Hagishima, A., Tanimoto, J., 2003; Shao, J., Liu, J., Zhao, J., 2010), and wind direction (Marcelo, G.E., Marc, O.A., Nathan M., 2007; Meinders, E.R., Van Der Meer, T.H., Hanjalic, K., 1998; Liu, Y., Harris, D.J., 2007; Blocken, B., Defraeye, T., Derome, D., et al., 2009) were studied thoroughly.

Obtaining accurate values of the CHTC involves a high level of complexity. Thus, numerous semi-empirical and empirical expressions have been established using on-site (full-scale) measurements (e.g. the Mobile Window Thermal Test (MoWiTT) model (Yazdanian, M., Klems, J.H., 1994), Computational Fluid Dynamics (CFD) simulations (e.g. the models by Emmel (Marcelo, G.E., Marc, O.A., Nathan M., 2007) and Montazeri & Blocken (Montazeri, H., Blocken, B., 2017), CIBS (Chartered Institute of Building Services) models (Institute of Building Service, 1979.), and the model by Liu and Harris (Y. Liu, D.J. Harris, 2007) or wind-tunnel (reduced-scale) measurements (McAdams, 1954).

Building Energy Simulation (BES) programs implement a large number of these expressions (Palyvos, J.A., (2008); Mirsadeghi, M., Cóstola, D., Blocken, B., Hensen, J.L.M., 2013). Nevertheless, the reliability and accuracy of these expressions are of a source of concern as:

- A large number of such expressions have an invalid assumption basis: for instance, sometimes, the CHTC is presumed to be constant across the façade of a building and as a result, the measurement which is taken from a single point is accepted as valid for the whole façade. Moreover, based on wind-tunnel measurements over a flat face, some expressions have been derived. For instance, the McAdams (McAdams, 1954) and CIBS models (Institute of Building Service, 1979.) which are utilized in BES tools widely have been obtained according to wind-tunnel experiments conducted on a vertical square copper face ($0.5 \times 0.5\text{m}^2$) in a uniform airflow parallel to the face (Jürges, 192). However, the structure of the flow around the building is more complicated than the one over a flat face.
- On the whole, the impact of the notable parameters like building roughness, wind direction, and surrounding buildings are considered either partially or not at all. Furthermore, a wide range of these expressions does not include the complicated interaction among these parameters. For instance, the proposed correlation in the CIBS Guide (Institute of Building Service, 1979.): $\text{CHTC} = 4.1 U_{\text{loc}} + 5.8$, where $U_{\text{loc}} = 2/3 U_R$.
- In this correlation, U_{loc} is the wind speed at a certain distance from the building facade and a certain height from the ground, and U_R is the wind speed at a certain height from the roof surface. The precision of these semi-empirical or empirical expressions, so-called secondary sources, is dependent on the precision and availability of the above-mentioned so-called primary sources, i.e., CFD simulations and wind-tunnel experiments or on-site.

Table 1 shows a summary of the experiments of wind-tunnel and the CFD simulations of convective heat transfer which are performed on-wall-mounted rectangular prisms. It can be seen that:

- The CHTC data is dependent on the Reynolds numbers (wind speed). Thus, it is required to investigate Re or wind in every generalized CHTC expression. On the other hand, none of the presented correlations are affected by the roughness of the surface
- The joint impact of diverse parameters on CHTC has been considered in a small number of studies. Blocken et al. (Blocken, B., Defraeye, T., Derome, D., et al., 2009), Emmel et al. (Marcelo, G.E., Marc, O.A., Nathan M., 2007), and Natarajan and Chyu (Natarajan, V., Chyu, M.K., (1994)), studied the combined effect of wind direction and Re and presented CHTC expressions as a function of Re for diverse incoming directions of the wind. Montazeri and Blocken (Montazeri, H., Blocken, B., 2017) and Montazeri et al. (Montazeri, H., Blocken, B., Derome, D., 2015) studied the joint effect of building dimensions and Re. The obtained results of the latter studies have resulted in new generalized expressions surface-averaged CHTC for diverse building surfaces as a function of reference, wind speed, wind direction, and surface roughness of the windward, top (roof) façade, and temperature difference.

Natural and forced convection, in the real-world condition, occur concurrently and the direction of the wind changes constantly concerning the building. This emphasizes the significance of a mixed heat transfer-based model which takes into account the direction of the wind. Therefore, taking the mixed heat transfer into account, the effect of the direction of the wind, the speed of the wind, the roughness of the surface, and temperature difference on CHTC is investigated in the numerical form in this study. As the Reynolds range is $6.85\text{E}+05$ to $3.42\text{E}+06$, the Richardson number differs from 0.1 to 10, taking the specified temperature and velocity range into account for the studied cases. The experiments were conducted in a wind tunnel laboratory and then the changes in the surface

temperature were juxtaposed with the numerical results, to guarantee the precision of the numerical solution ad to select the most suitable solution.

2. EXPERIMENTAL CASE

In this paper, a wind tunnel measuring $0.42 \times 0.42 \times 2$ (m³) is used to derive the experimental results so that a square cube ($5 \times 5 \times 5$ cm³) is arranged in this wind tunnel so that the front face of the cube is 0.675 (m) and the back face of the cube is about 2 (m) from the channel outlet (Figure 1). The fiberglass cube is 1 mm thick and all of its inner surfaces are held at a constant temperature by a dissipating source. During the experiment, the temperature was kept constant on the internal surfaces (60 °C). A copper helical heater was used to heat the faces. Copper coils have electrical resistance and by connecting 12V DC to the two ends of the copper coil, the passing current causes heat loss, and the faces are heated.

Also, temperature-sensitive resistors made of semiconductor materials (thermistors) have been used to measure the temperature of the inner surfaces of the cube. The thermistors are divided into two groups: NTC (Negative Temperature Coefficient) and PTC (Positive Temperature Coefficient). This article uses the NTC type. During the test, these thermistors are connected to the Arduino board and temperature values were recorded in the Arduino board. The Arduino board and microcontroller used were UNO and ATMEGA328, respectively. The Arduino board was responsible for measuring the temperature (through thermistors) and switching on and off the fiberglass faces. The TIP41 transistors were used to transmit 12V voltage to the fiberglass boards, as the control signals come from the Arduino board to the transistors, and the transistors act as electronic switches to connect or disconnect the voltage of the fiberglass faces to keep the surface temperature constant. The specifications of the material used for fiberglass are specified in Table 2.

In the wind tunnel, a variable speed motor is used to generate steady airflow. The YK-2004AH Hot wire anemometer was used to measure the velocity and temperature of the air flowing through this channel. In the test, the air temperature was 18 °C at a constant speed of 20 m/s. Finally, for validation, the temperature of the points from the outer surfaces of the cube visible in Figure 1c was measured. A laser thermometer (TES 1327K Infrared) was used for this purpose. Due to the importance of the accuracy of the equipment used, Table 3 reports the accuracy of the equipment according to their catalog.

Table 1 Overview of studies on convective heat transfer at wall-mounted rectangular prisms based on wind tunnel or CFD.

Reference	Investigation type		Convection Type		parameters						
	WT	CFD	Forced	Natural	Re	Nu	θ	W	H	λ_p	R _f
(Chyu, M.K., Natarajan, V., 1991)	*		*		*						
(V. Natarajan, M.K. Chyu, 1994)	*		*		*		*				
(Meinders, E.R., Van Der Meer, T.H., Hanjalic, K., 1998)	*		*		*						
(Nakamura, H., Igarashi, T., Tsutsui, T., 2001)	*		*		*		*				
(Nakamura, H., Igarashi, T., Tsutsui, T., 2003)	*		*		*						
(Wang, K.-C., Chiou, R.-T., 2006)	*		*		*						
(Marcelo, G.E., Marc, O.A., Nathan M., 2007)		*	*		*		*				
(Blocken, B., Defraeye, T., Derome, D., et al.,		*	*		*		*				

2009)											
(Defraeye, T., Blocken, B., Carmeliet, J., 2010)		*	*		*						
(Allegrini, J., Dorer, V., Carmeliet, J., 2012)		*	*	*	*						
(Liu, J., Heidarinejad, M., Gracik, S., 2015)		*	*	*	*					*	
(Montazeri, H., Blocken, B., Derome, D., 2015)		*	*		*						
(Montazeri, H., Blocken, B., 2017)		*	*		*						
(H. Montazeri, B. Blocken., 2018)		*	*		*		*	*	*		
(Ze-X., Gui-X., Cu, iZhao-Shun Z.,, 2018)		*	*	*	*	*					

Table 2. The thermal properties of fiberglass

Density (kg/m ³)	Specific heat (j/kg-k)	Thermal conductivity
700	1240	0.046

Table 3. Accuracy of used experimental equipment

Equipment	Type	Accuracy
Hotwire anemometer	YK-2004AH	$\pm (5\% + a)$ reading or $\pm (1\% + a)$ full-scale
laser thermometer	TES 1327K Infrared	$\pm 2\%$
Thermistors	NTC	$\pm 0.1\text{ }^{\circ}\text{C}$

Figure 1 Experimental units

- a. The wind tunnel used in experiment *b*. Points on external surfaces for temperature measurement *c*. Placement of the cube

2.1 CFD validation by experimental data

In this step, using the numerical solution, the experimental model described in the preceding section was simulated accurately and quite similarly. An unstructured triangular mesh is used to compute the computational domain. Also, due to the high sensitivity of the results around the cubes, the grids around the cubic surfaces are finer. An overview of the geometry of the problem geometry can be seen in Figure 3. Due to the importance of results' independence from the number of grids and finding the optimal number of grids for economizing time and accuracy of the solution, the computational domain was generated with three numbers 952252, 1270449, 1525929 grid and then temperature changes were reported on one line. The length of this line is 60 cm and its distance from the top of the cube is 1 cm.

The results show that when the computational space was generated with 1270449 grids, there was no significant change in the results and it could be concluded that the optimum network number was this value and the numerical analysis was independent of the number of networks.

To determine the most appropriate turbulence model, simulations with different types of K-epsilon turbulence models including Standard, RNG, Realizable were performed. A SIMPLE algorithm was used to correlate pressure-velocity equations. Second-order discretization schemes were used for both the convection terms and the viscous terms of the governing equations.

The results of the surface temperature changes obtained from the experimental case simulation and comparison with the measured values are shown in Figure 4. The results showed that the K-epsilon type turbulence model had a better performance than the other models in predicting the results of the measured points in the experimental model.

During the preliminary measurement of the exterior surface temperature on the point, ten values were measured repeatedly. Table 4 reports and standard uncertainty calculation of an estimated Standard deviation based on measured data.

Figure 2 Meshed geometry of the numerical modeling of the empirical case include a) full-scale view from above
b) the magnified of the cube around

Figure 3 Temperature variations along the line for different mesh sizes

a

b

Figure 4 Temperature distribution along the line **a)** windward surface **b)** leeward surface

Table 4 reports of uncertainty from a measurement in the experiment

Measured temperature										estimated Standard deviation	standard uncertainty
305.1	305.8	303.9	304.7	305.3	305.2	304.5	304.7	305.6	304.9	0.55	0.58

3. GOVERNING EQUATION

A Reynold-average-based approach is adopted to analyze a three-dimensional steady-state incompressible flow. Continuity, momentum, and energy equations can be expressed as:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial (U_j U_i)}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \nu \nabla^2 U_i + \frac{\partial}{\partial x_i} (-\overline{u_i u_j}) + \rho g_i \beta (T_{ref} - T) \quad (3)$$

$$\frac{\partial (U_j T)}{\partial x_j} = \alpha \nabla^2 T + \frac{\partial}{\partial x_j} (-\overline{u_j T}) \quad (4)$$

Where $u_i u_j$ and $u_j T$ signify Reynolds stresses and turbulent heat fluxes, respectively. The turbulence model selection is dependent on the problem under consideration. In this study, two important factors, i.e., the ground-induced anisotropy on Reynolds stresses and the flow separation around the building, are taken into account [44].

$$\frac{\partial(\rho k)}{\partial t} + \text{div}(\rho k U) = \text{div}\left[\frac{\mu_t}{\partial_k} \text{grad } k\right] + 2\mu_t E_{ij} E_{ij} - \rho \epsilon \quad (5)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \text{div}(\rho \epsilon U) = \text{div}\left[\frac{\mu_t}{\partial_\epsilon} \text{grad } \epsilon\right] + \frac{C_{1\epsilon} \epsilon}{k} 2\mu_t E_{ij} E_{ij} - C_{2\epsilon} \rho \left(\frac{\epsilon^2}{k}\right) \quad (6)$$

Where: k is turbulent kinetic energy, ϵ is the kinetic energy dissipation rate, E_{ij} is the component of the rate of deformation, μ_t is eddy viscosity and can be expressed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (7)$$

C_μ , σ_k , σ_ϵ , $C_{1\epsilon}$, and $C_{2\epsilon}$ are adjustable constants which are required for the software. The values are as follows: $C_\mu = 0.09$, $\sigma_k = 1.00$, $\sigma_\epsilon = 1.30$, $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.92$.

4. NUMERICAL SIMULATION

The computational domain was sized by best practice guidelines reported by (Tominaga, Y., Mochida, A., Murakami, S., Sawaki, S., 2008) and (Franke, J., Hellsten, A., Schlünzen, H., Carissimo, B., 2007). The domain height was set to 5H, where H is cube height. The domain upstream and downstream distances were taken to 5H and 15H, respectively. By applying the surface grid extrusion method, a high-resolution hybrid mesh with approximately 1.8×10^6 hexahedral and prismatic cells was produced. A neutral atmospheric boundary layer was assigned at the domain inlet. Eq. 5, 6, and 7 express the layer inflow profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate, respectively. (Richards, P.J., Hoxey, R.P., 1993)

$$U(z) = \frac{u_{ABL}^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (5)$$

$$k(z) = (3.3 u_{ABL}^*)^2 \quad (6)$$

$$\epsilon(z) = \frac{u_{ABL}^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (7)$$

Where u_{ABL}^* is the friction velocity. The aerodynamic roughness length of the terrain (z_0) is 0.03m [48]. At the top and lateral surfaces, symmetry conditions, and at the outlet, zero static pressure are imposed. Because of the incapability to determine surface roughness, a no-slip wall condition was specified for the ground surface [14]. Figure 5 indicates the velocity profile that is calculated based on mentioned equations.

The solver settings are like those which were presented in section 2.1. The 3D steady N-S equation with a standard k-epsilon turbulence model is used. Boussinesq approximation was also adopted for density estimation, as a mixed heat transfer was studied.

In this study, four parameters such as wind speed, surface temperature difference, and air temperature, and wind direction, or in other words, the angle of the building relative to the wind direction and roughness of the building surfaces, are investigated. The selected values are visible for each of the parameters listed in Table 5. Also, in the simulated models, the Reynolds number ranged from 6.58×10^5 to 3.42×10^6 , the Grashoff number from 1.56×10^{12} to 4.68×10^{12} , and the Richardson number between 0.1 and 10 based on building height. Given that most of the year, the displacements are in the mixed form in the walls of the building, in this paper different parameters were defined in such a way that in all modes, heat transfer is in the mixed form.

To test the grid independence, three meshes with different sizes were generated. A line at a distance of 50cm from over the top surface was studied, and pressure coefficient variations along the line for the three meshes were compared in Figure 6. Smaller meshes were used near walls due to the sensitivity of the results in this region. Figure 6 confirmed the independence of the results from grid size since no significant changes were observed in the pressure coefficient. The Grid Convergence Index (GCI) is used better to evaluate the independence of the results from the grid size. The average CTC of the windward face of the cube is investigated by this method. Roache developed this method for extensive applications in computational fluid dynamics. (Celik, I., Ghia, U., Roache, P.J., Freitas, C.J., Coloman, H., Raad, P. E., 2008)

$$h = \left[\frac{1}{N} \sum_{i=1}^N \Delta V_i \right]^{\frac{1}{3}} \quad (8)$$

$$r = \frac{h_{coarse}}{h_{fine}} \quad (9)$$

$$P = \frac{\ln\left(\frac{\epsilon_{32}}{\epsilon_{21}}\right)}{\ln(r)} \quad (10)$$

$$\epsilon_{32} = \phi_3 - \phi_2 \quad (11)$$

$$\epsilon_{21} = \phi_2 - \phi_1 \quad (12)$$

$$e_a^{21} = \left| \frac{\phi_2 - \phi_1}{\phi_1} \right| \quad (13)$$

$$GCI_{fine}^{21} = \frac{1.25e_a^{21}}{r^p - 1} \quad (14)$$

Where ΔV_i is the volume, N is the total number of cells, h is grid size, ϕ is a parameter of results (in this paper is CHTC), e_a^{21} is extrapolated relative error, and GCI_{fine}^{21} is the fine-grid convergence index. Table 4 illustrates this calculation procedure for the mentioned grids. The amount of GCI_{fine}^{21} shows that numerical results are independent of grid size.

Table 4. Results of GCI test

N_1, N_2, N_3	$r(\text{constant})$	P	ϕ_1	ϕ_2	ϕ_3	e_a^{21}	GCI_{fine}^{21}
1417442, 1866444, 2310592	1.5	3.52	23.81	23.11	22.94	2.9 %	1.14%

Table 5. The considered parameters and their values

Parameters (unit)	Value
Wind speed at an altitude of 10 m (m/s)	1,3,5
Temperature difference (°C)	10, 20, 30
Building orientation or wind direction (°)	0, 22.5, 45, 67.5
The surface temperature of the building (°C)	20
Building surface roughness (m)	0, 0.0015, 0.003

Figure 5 inlet velocity profile

Figure 6 Pressure coefficient variations along the line located at a distance of 50cm from the top surface

5. RESULTS

To determine the significance of each parameter's significance, the effect of each parameter on the CHTC was examined and then the comparison of their significance was presented.

5.1 Investigating the impact of wind speed on CHTC

Studies show that wind speed is the most important parameter among the investigated cases. As can be seen in Table 1, there is a wind speed factor in all formulas presented for CHTC. Due to the difference and importance of checking the two faces against the flow and the top cube, the results for all parameters were presented separately for both mentioned faces. Figure 7 shows the effect of wind speed on the CHTC. It was observed that on both faces the CHTC increased significantly as the wind speed increased.

For example, at roughness altitude of 0.0015 m, wind angle and front face 22.5° and temperature difference of 20°C with increasing speed from 1 m/s to 5 m/s, CHTC for upper and front face changed from 9.01 and 6.31 to 29.5 and $28.1(\text{w}/\text{m}^2\text{K})$. The important point about Figure 7 is the data compression at the investigated speeds. It is clear that for the front face of a cube or building, this compression is greater than the top face. This compactness and multiplicity of data at these speeds indicated the influence of various other parameters investigated in this study.

As can be seen from Figure 7, at the same speed the effect of other parameters on the front face was greater than the top face. Also, at both faces at lower speeds, the effect of other parameters was less than high speeds. In the upper face of the cube, the highest compression was at 1 m/s and had the lowest compression in the upper face at 5 m/s. This indicated the less significance of the effect of other parameters on the upper face in lower speeds, and the more significant of the effect of the other parameters on the front face in higher speeds.

Figure 7 surface CHTCave versus wind speed a) windward face b) top face

5.2 Investigating the Impact of the angle of wind and building on CHTC

Another parameter considered by other researchers is the angle of wind flow with the building. Therefore, to understand correctly the effect of this parameter in this study, the angle of the building with the direction of the flow was changed by changing the location of the building and were simulated at different speeds, temperatures, and roughnesses. As shown in Figure 8, this study ranged from zero to 67.5° . Figure 9 illustrates the results of the CHTC from different angles. The results showed that the overall CHTC decreased with decreasing wind and building angle. But the slope of this decrease was lower for the upper face than the front face, indicating that this parameter had a greater effect on the front face. For example, at speeds of 3 m/s, the difference of temperature was 10°C and the coefficient of height was 0.003 m when the angle was changed from 0° to 67.5° , CHTC varied from 21.37 to $15.83 \text{ w}/\text{m}^2\text{K}$ for the front face, while for the upper face it changed from 19.02 to $18.24 \text{ w}/\text{m}^2\text{K}$ (Figure 9). The results also showed that by increasing the rate of change, it was possible to say more precisely in this range of variation for the wind and building angle, there was a decline for the top and front faces on average about 6 and 30 percent, respectively.

Figure 8. A different angle of wind direction and building a) 0°, b) 22.5°, c) 45°, d) 67.5°

Figure 9 surface CHTC_{ave} versus angle of wind direction and building front face a) windward face b) top face

5-3 Investigating the effect of the surface temperature difference and wind flow on CHTC

In the heat transfer debate, the temperature difference is one of the most vital parameters affecting the rate and manner of heat transfer. In this study, the simulated models were ranged in a way to determine the full effect of this parameter on the CHTC on the front and top cubic faces. It should be noted that since the purpose of this research was to investigate the parameters in the combined displacement, the temperature range considered for this research was from 10° to 30° so that according to the range of velocity and Reynolds range based on building height, the Richardson number be always between 0.1 and 10, resulting in heat transfer in the form of combined displacement. Figure 10 illustrates the effect of the temperature difference parameter on the CHTC in different models. The results show that, like the two parameters discussed in the previous section, the effect of the temperature difference parameter on the face versus current flow is greater than the upper face. It was also found that as the temperature difference increased, the amount of CHTC increased as well. But considering the range studied in this study, it was found that in this range of velocity and temperature, the effect of this parameter was far less than other parameters such as velocity, angle, and roughness height. Specifically, for the 5 m/s velocities, 0° angle, 0 m height, and 10 °C temperature difference, the CHTC values for face versus flow and top face were 26.5 and 25.18 w/m²K, respectively. However, with all the parameters constant and increasing the temperature difference to 30 °C, the CHTC values for the front and top faces will be 28.64 and 25.8 w/m²K, respectively (Figure 10). Considering all the models studied, the results showed that by increasing the temperature difference from 10 °C to 30 °C for the top face and the face against the flow, the average increase of CHTC was 2.5 and 8%, respectively.

Figure 10 surface CHTC_{ave} versus Temperature difference a) windward face b) top face

5-4 Investigating the effect of roughness height on CHTC

according to the literature review, a small number of studies have been conducted on the effect of roughness height on the amount of combined heat transfer from the building surfaces. On one hand, the amount of roughness affects the amount of heat transfer. Therefore, in this study, this parameter was examined along with other parameters mentioned to provide a relationship for the estimation of CHTC value, this important parameter is present as well. Specifically, in this study, different models of roughness height in three modes of 0.003, 0.0015, 0 m were investigated. The results of Figure 11 clearly illustrate the influence of roughness height on the amount of CHTC. For example, increasing the roughness height from 0 to 0.003 m in a model that has a velocity of 3 m/s, an angle of 67.5 ° and a temperature difference of 20 °C increased the CHTC value for the front and upper cubic faces from 14.12 to 16.62 w/m²K and 16.06 to 18.43 w/m²K respectively. The overall analysis of the simulated results also showed that on average the variation in the range expressed for the roughness height, the CHTC for the top face, and the face against the flow were about 14 and 17%, respectively.

Figure 11 surface $CHTC_{ave}$ versus Roughness height a) windward face b) top face

5-5 Comparison of the effect of different parameters on CHTC

Considering the different parameters on CHTC, it is necessary to compare the effect of these parameters and conclude on the importance of each parameter. For this purpose, the Pareto chart was used to present this report. The absolute values of the standardized effects are indicated by the Pareto chart, from the largest effect to the smallest effect. The standardized effects are t-statistics that test the null hypothesis that the effect is 0. The chart also plots a reference line to indicate which effects are statistically significant.

For the front and top face of the cube, the Pareto chart is visible in Figure 12. It was observed that in both faces the wind speed and temperature difference had the most and the least effect on the upstream and downstream planes, respectively. It was also found that in the front panel the angle effect was greater than the roughness, whereas in the upper plane the roughness height had more influence on the CHTC.

When all the impacts were 0, the normal probability plot of the effects indicated standardized effects relative to a distribution fit line for the case. The standardized effects are defined as the t-statistics that test the null hypothesis that the effect is 0. Positive effects rise the response when the settings vary from the low value of the factor to the high value. Negative effects decline the response when the settings vary from the low value of the factor to the high value. Effects higher than 0 on the x-axis have a higher magnitude. Effects further from 0 are more statistically significant. Figure 13 shows the normal plot of the effects diagram for the front and top face of the cube, all conclusions are visible when examining the influence of different parameters on the diagram. This chart also specifies the effect of each parameter. According to the figure it can be seen that by increasing all parameters except the angle, the CHTC increased but with increasing wind angle the CHTC value decreased.

The graph also clearly determined that the parameters on the page were more effective than the flow and were more important. The important point of the graph is the less significance of the temperature difference on the top face and the high importance of each velocity on both sides of the building. It should be noted, however, that the selected temperature range in this study is the conventional range of heat transfer of buildings and the results should be examined separately in different temperature ranges.

Figure 12 Pareto chart of the standardized effect a) windward face b) top face

Figure 15 CHTC contour at different temperature differences

Figure 16 CHTC contour at different building angle

Figure 17 CHTC contour at different roughness height

6. CORRELATION EXTRACTING

In this study, it was found that the parameters investigated in the mentioned range all affect the CHTC. Therefore, a relationship for CHTC based on these parameters should be expressed to increase the accuracy of CHTC calculation in building energy analyzer software. EnergyPlus software is one of the most reputable building energy analysis software. Tables 6 and 7 summarize and present the correlations in Energy Plus software. Due to the importance of the relationship in this paper, two methods were used to extract the relationship.

Table 6 Existing correlation in EnergyPlus software for smooth windward building's exterior surface [50]

Model name	Correlation
1 Simple combined	$h = 10.22 + 3.1V$
2 TARP	$h = 2.8161\left(\frac{PV}{A}\right)^{1/2} + 1.31(\Delta T)^{1/3}$
3 MoWiTT (1994)	$h = \sqrt{[0.84(\Delta T)^{1/3}]^2 + [3.26V^{0.89}]^2}$
4 DOE-2	$h = (-0.1441)(\Delta T)^{1/3} + \sqrt{[0.84(\Delta T)^{1/3}]^2 + [3.26V^{0.89}]^2}$
5 Sparrow	$h = 2.8161\left(\frac{PV}{A}\right)^{1/2}$
6 MoWiTT (2012)	$h = \sqrt{[0.84(\Delta T)^{1/3}]^2 + [2.38V^{0.89}]^2}$
7 Blocken	$h = 4.6V^{0.89} : \theta \leq 11.25$ $h = 5V^{0.80} : 11.5 < \theta \leq 33.75$ $h = 4.6V^{0.84} : 33.75 < \theta \leq 56.25$ $h = 4.5V^{0.81} : 56.25 < \theta \leq 100$
8 Emmel	$h = 5.15V^{0.81} : \theta \leq 22.5$ $h = 3.34V^{0.84} : 22.5 < \theta \leq 67.5$ $h = 4.78V^{0.71} : 67.5 < \theta \leq 112.5$ $h = 4.05V^{0.77} : 112.5 < \theta \leq 157.5$

		$h = 3.54V^{0.76} : 157.5 < \theta \leq 180$
9	Nusselt Jurges	$h = 5.8 + 3.94V$
10	McAdams	$h = 5.7 + 3.84V$
11	Mitchell	$h = \frac{8.6V^{0.6}}{L}$

Table 7 Existing correlation in EnergyPlus software for smooth roof building's exterior surface (EnergyPlus™ Version 8.9.0 Documentation Engineering Reference, 2018)

Model name		Correlation
1	Simple combined	$h = 10.22 + 3.1V$
2	TARP	$h = 2.8161(\frac{PV}{A})^{1/2} + 0.76(\Delta T)^{\frac{1}{3}}$
3	MoWiTT (1994)	$h = \sqrt{[0.84(\Delta T)^{\frac{1}{3}}]^2 + [3.26V^{0.89}]^2}$
4	DOE-2	$h = (-0.1441)(\Delta T)^{\frac{1}{3}} + \sqrt{[0.84(\Delta T)^{\frac{1}{3}}]^2 + [3.26V^{0.89}]^2}$
5	Sparrow	$h = 2.8161(\frac{PV}{A})^{1/2}$
6	MoWiTT (2012)	$h = \sqrt{[0.84(\Delta T)^{\frac{1}{3}}]^2 + [2.38V^{0.89}]^2}$
7	Blocken	$h = 4.6V^{0.89} : \theta \leq 11.25$ $h = 5V^{0.80} : 11.5 < \theta \leq 33.75$ $h = 4.6V^{0.84} : 33.75 < \theta \leq 56.25$ $h = 4.5V^{0.81} : 56.25 < \theta \leq 100$
8	Emmel	$h = 5.11V^{0.78} : \theta \leq 22.5$ $h = 4.60V^{0.79} : 22.5 < \theta \leq 67.5$ $h = 3.67V^{0.85} : 67.5 < \theta \leq 90$
9	Nusselt Jurges	$h = 5.8 + 3.94V$
10	McAdams	$h = 5.7 + 3.84V$
11	Mitchell	$h = \frac{8.6V^{0.6}}{L}$

6-1 Extraction of Correlation Based on Mathematical Formula

In the first method, using quadratic regression and considering all the parameters, the formula is derived using mathematical calculation software. On the other hand, the important thing about each formula is the accuracy formula. The extracted formulas along with their related parameters for each of the front and top cubes faces are presented in Table 8.

As in this table, S indicates the standard deviation of the distance between the fitted values and data values. The measurement of s is in the units of the response. R2 refers to the proportion of variation in the response presented by the model explanation. It is calculated as 1 minus the ratio of the error sum of squares (which is the variation that is not explained by the model) to the total sum of squares (which is the total variation in the model). Adjusted R2 is the percentage of the variation in the response that is explained by the model, adjusted for the number of predictors in the model relative to the number of observations. Adjusted R2 is calculated as 1 minus the ratio of the mean square error (MSE) to the mean square total (MS Total). Predicted R2 is calculated with a formula that is equivalent to systematically removing each observation from the data set, estimating the regression correlation, and determining how well the model predicts the removed observation. The value of the predicted R2 ranges between 0% and 100%.

Also, in the presented formulas V represents the wind speed in meters per second, A denotes the angle between the building and the direction of wind flow in degrees, R denotes the height of the roughness of the building surfaces in meters, and ΔT denotes the difference between surface and wind temperatures.

It is considered that the presented results are very accurate for the results of this research and, considering the validation of the results in the initial section with the results of the laboratory work, it can be claimed that using this relationship in building energy analyzer software is very useful for CHTC calculation. It can increase the

accuracy of these software in calculating building energy and related parameters such as estimation of heat transfer from the exterior surfaces of the building.

Table 8. The mathematical formulation of obtained results

Face	Correlation	S	R-sq	R-sq(adj)	R-sq(pred)
Front	$CHTC = 2.879 + 0.0626 \times \Delta T - 0.0389 \times A + 5.090 \times V + 905 \times R + 0.00039 \times \Delta T^2 + 0.000423 \times A^2 - 0.0677 \times V^2 - 261605 \times R^2 - 0.000656 \times \Delta T \times A + 0.00153 \times \Delta T \times V - 0.50 \times \Delta T \times R - 0.01895 \times A \times V - 6.54 \times A \times R + 384.2 \times V \times R$	0.58663	99.55%	99.49%	99.40%
Top	$CHTC = 0.784 + 0.0091 \times \Delta T - 0.02036 \times A + 5.446 \times V + 515 \times R + 0.000078 \times \Delta T^2 + 0.000284 \times A^2 - 0.1209 \times V^2 - 251420 \times R^2 + 0.000077 \times \Delta T \times A + 0.00315 \times \Delta T \times V - 3.62 \times \Delta T \times R - 0.00404 \times A \times V + 0.37 \times A \times R + 406.1 \times V \times R$	0.43922	99.78%	99.75%	99.70%

6-2 Design Neural Networks base on numerical results

In the developed neural network, 5 rows of input data have been used (the input data include wind speed, temperature difference, angle, roughness height, and face type). For the first layer, 8 neurons were used. The choice of this number is aimed at reducing the complexity of the neural network structure due to its larger size and increasing the accuracy of the simulation results based on the input data. The first layer uses the sigmoid conversion function. The total output of the first layer results in the weighted coefficients with the input data is entered into the second layer. The use of the input data in the second layer with the weighting coefficients is due to the high accuracy of the network output in predicting the peak values of the output data. A linear function was used to extract the data from the second layer. (Figure 18)

70% of the data is used to train the neural network. The rest of the data is used equally for neural network verification and testing. The back-propagation error Levenberg-Marquat method was used for training, which in 26 epochs (repeated weight updating based on error reduction) the root mean square error of the error was less than 0.13296. And this is the point where the neural network's optimal accuracy is made. The error reduction process with the weights being updated is shown in Figure 19.

As shown in Figure 20, the gradient rate in the 32 epochs reached 0.03434, indicating that repeating the weight updating step would not significantly increase the accuracy of the neural network. Meanwhile, the jump rate in the 32 Epochs has reached 0.0001.

Figure 18 The neural network structure developed for the data row

Figure 19 Neural network error rate based on weights update in each epoch

Figure 20 Gradient rate, Mutation and Validation Test in 32 Training Epochs

7. CONCLUSION

Various studies have shown that the most important and influential factors in estimating building energy

consumption in building energy simulator software are accurate and correct CHTC calculations. Therefore, extensive research has been done on the influence of different parameters on CHTC. According to the studies, it was found that the most influential parameters were the wind speed, wind, and building angle, and temperature difference. At the same time, the roughness of the building surfaces also affects the amount of CHTC. On the other hand, no relationship to the CHTC has been presented so far in which there is a combination of wind speed, wind and building angle, temperature difference, and roughness of the building surfaces. Due to the errors in numerical analysis, in this study first, an experimental model similar to the building in wind tunnel space was tested. The experimental model tested in numerical simulation software was simulated and the results of the numerical analysis were compared with laboratory results. After ensuring the accuracy of the modeling method and the numerical modeling, in real computational space for a single building, the influence of wind speed, angle, temperature difference, and roughness height parameters on the CHTC of the top faces and against the flow of the building were investigated. The results indicated that almost all parameters affected CHTC levels in both faces. The effect of these parameters is one of the most important factors in the results of such investigations. The results of the comparison of the effect of parameters showed that for both the front and the top of the cubic face, in both faces the wind velocity and temperature difference had the highest and the lowest effect on the top and opposite faces, respectively. It was also found that in the front face, the angle effect was greater than the roughness, whereas in the upper face the roughness height had more influence on the CHTC. Finally, for the obtained results and considering the amount and manner of the impact of the investigated parameters, using two methods, a relationship has been extracted to calculate CHTC for the top and front face. Comparison of reported correlations with the relationships in Energy Plus software showed the accuracy of the correlation is more and can be used in building energy simulator software. Also, using the analyzed results, the neural network design was performed. it was found that using this neural network, the CHTC of building surfaces can be calculated with high accuracy.

8. Declarations

8-1 Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

8-2 Competing interests

The authors declare that they have no competing interests

8-3 Funding

All costs of this research were provided by the author in charge of the article

8-4 Authors' contributions

Study concept, design, analysis and interpretation of data: **H.Agabalaiefakhim.**, and **K.Zamzamian.**; drafting of the manuscript: **H.Agabalaiefakhim.**; critical revision of the manuscript for important intellectual content **H.Agabalaiefakhim.**, **K.Zamzamian.**, and **M.Hanifi.**

8-5 Acknowledgements

The authors would like to acknowledge the Department of Mechanical Engineering, University of Islamic Azad University of Tabriz , and the Tabriz University laboratory, for their support and contribution to this study.

REFERENCES

Bibliography

- Institute of Building Service. (1979.). *Guide Book A, Section A3, Chartered Institute of Building Services (CIBS), CIBS*. London.
- Allegrini, J., Dorer, V., Carmeliet, J. (2012). Analysis of convective heat transfer at building facades in street canyons and its influence on the predictions of space cooling demand in buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 464-473. doi:https://doi.org/10.1016/j.jweia.2012.02.003
- Allegrini, J., Dorer, V., Carmeliet, J. (2013). Wind tunnel measurements of buoyant flows in street canyons. *Building and Environment*, 59, 315-326. doi:https://doi.org/10.1016/j.buildenv.2012.08.029
- Beausoleil-Morrison. (2001). An algorithm for calculating convection coefficients for internal building surfaces for the case of mixed flow in rooms. *Energy and Buildings*, 33, 351-361.
- Blocken, B., Defraeye, T., Derome, D., et al. (2009). High-resolution CFD simulations for forced convective heat transfer coefficients at the facade of a low-rise building. *Building and Environment*, 44(12), 2396-2412. doi:https://doi.org/10.1016/j.buildenv.2009.04.004
- Celik, I., Ghia, U., Roache, P.J., Freitas, C.J., Coloman, H., Raad, P. E. (2008). Procedure of Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications. *Journal of Fluids Engineering*, 130(7), 078-001. doi:https://doi.org/10.1115/1.2960953
- Chandra.R, Goel.V.K., Raychaudhuri.B.C. (1983). Universal curves for natural convection heat transfer coefficients in flat-plate solar-energy collectors. *Applied Energy*, 13(2), 101-107. doi:https://doi.org/10.1016/0306-2619(83)90003-X
- Chyu, M.K., Natarajan, V. (1991). Local heat mass-transfer distributions on the surface of a wall-mounted cube. *journal of Heat Transfer ASME*, 113, 851–857. doi:https://doi.org/10.1115/1.2911213
- Cooper, P. (1981). The effect of inclination on the heat loss from flat-plate solar collectors. *Solar Energy*, 27(5), 413-420. doi:https://doi.org/10.1016/0038-092X%2881%2990006-2
- Defraeye, T., Blocken, B., Carmeliet, J. (2010). CFD analysis of convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer. *International Journal of Heat and Fluid Flow*, 53, 297–308. doi:https://doi.org/10.1016/j.ijheatmasstransfer.2009.09.029
- EnergyPlus™ Version 8.9.0 Documentation Engineering Reference*. (2018). U.S. Department of Energy.
- Fisher DE, Pedersen CO. (1997). Convective heat transfer in building energy and thermal load calculations. *ASHRAE Transactions*, 103, 137-148.
- Franke, J., Hellsten, A., Schlünzen, H., Carissimo, B. (2007). *Best practice guideline for the CFD simulation of flows in the urban environment. COSTaction 732: quality assurance and improvement of microscale meteorological models*.
- H. Montazeri, B. Blocken., (2018). Extension of generalized forced convective heat transfer coefficient expressions for isolated buildings taking into account oblique wind directions. *Building and Environment*, 140, 194–208. doi:https://doi.org/10.1016/j.buildenv.2018.05.027
- Hagishima, A., Tanimoto, J. (2003). Field measurements for estimating the convective heat transfer coefficient at building surfaces. *Building and Environment*, 38(7), 873-881. doi:https://doi.org/10.1016/S0360-1323(03)00033-7
- Iacovides, H., Launder, B.E. (1995). Computational fluid dynamics applied to internal gas-turbine blade cooling: a review. *International Journal of Heat and Fluid Flow*, 16(6), 454-470. doi:https://doi.org/10.1016/0142-727X(95)00072-X
- Jürges, W. (192). *Der Wärmeübergang an einer ebenen Wand*. 4Oldenbourg: Druck und Verlag von R.

- Karava, P., Jubayer, C.M., Savory, E. (2012). Effect of incident flow conditions on convective heat transfer from the inclined windward roof of a low-rise building with application to photovoltaic-thermal systems. *Journal of Wind Engineering and Industrial Aerodynamics*, 104-106, 428-438. doi:https://doi.org/10.1016/j.jweia.2012.03.026
- Liu, J., Heidarinejad, M., Gracik, S., (2015). The impact of exterior surface convective heat transfer coefficients on the building energy consumption in urban neighborhoods with different plan area densities. *Energy and Buildings*, 86, 449-463. doi:https://doi.org/10.1016/j.enbuild.2014.10.062
- Liu, J., Srebric, J., Yu, N. (2013). Numerical simulation of convective heat transfer coefficients at the external surfaces of building arrays immersed in a turbulent boundary layer. *International Journal of Heat and Mass Transfer*, 61, 209-225. doi:https://doi.org/10.1016/j.ijheatmasstransfer.2013.02.005
- Liu, Y., Harris, D.J. (2007). Full-scale measurements of convective coefficient on external surface of a low-rise building in sheltered conditions. *Building and Environment*, 42(7), 2718-2736. doi:https://doi.org/10.1016/j.buildenv.2006.07.013
- Marcelo, G.E., Marc, O.A., Nathan M. (2007). New external convective heat transfer coefficient correlations for isolated low-rise buildings. *Energy and Buildings*, 39(3), 335-345. doi:https://doi.org/10.1016/j.enbuild.2006.08.001
- McAdams, W. (1954). *Heat Transmission* (third ed. ed.). New York-London: M C Graw Hill N. Y.
- Meinders, E.R., Van Der Meer, T.H., Hanjalic, K., (1998). Local convective heat transfer from an array of wall-mounted cubes. *International Journal of Heat and Mass Transfer*, 41(2), 335-346. doi:https://doi.org/10.1016/S0017-9310(97)00148-8
- Mirsadeghi, M., Cóstola, D., Blocken, B., Hensen, J.L.M. (2013). Review of external convective heat transfer coefficient models in building energy simulation programs: Implementation and uncertainty. *Applied Thermal Engineering*, 56(1-2), 134-151. doi:https://doi.org/10.1016/j.applthermaleng.2013.03.003
- Montazeri, H., Blocken, B. (2017). New generalized expressions for forced convective heat transfer coefficients at building facades and roofs. *Building and Environment*, 119, 153-168. doi:https://doi.org/10.1016/j.buildenv.2017.04.012
- Montazeri, H., Blocken, B., Derome, D. (2015). CFD analysis of forced convective heat transfer coefficients at windward building facades: Influence of building geometry. *Journal of Wind Engineering and Industrial Aerodynamics*, 146(2015), 102-116. doi:https://doi.org/10.1016/j.jweia.2015.07.007
- Morrison, B. (2000). *The adaptive coupling of heat and air flow modeling within dynamic whole-building simulations*. Glasgow, UK: University of Strathclyde.
- Nakamura, H., Igarashi, T., Tsutsui, T. (2001). Local heat transfer around a wall-mounted cube in the turbulent boundary layer. *International Journal of Heat and Mass Transfer*, 44, 3385-3395. doi:http://dx.doi.org/10.1016/S0017-9310(01)00009-6
- Nakamura, H., Igarashi, T., Tsutsui, T. (2003). Local heat transfer around a wall-mounted cube at 45 to flow in a turbulent boundary layer. *International Journal of Heat and Fluid Flow*, 24, 807-815. doi:https://doi.org/10.1016/S0142-727X(03)00087-0
- Natarajan, V., Chyu, M.K. ((1994)). Effect of flow angle-of-attack on the local heat/mass transfer from a wall-mounted cube, *Trans. ASME Journal of Heat Transfer*, 116, 552-560. doi:https://doi.org/10.1115/1.2910906
- Palyvos, J.A. ((2008)). A survey of wind convection coefficient correlations for building envelope energy systems' modeling. *Applied Thermal Engineering*, 28, 801-808. doi:https://doi.org/10.1016/j.applthermaleng.2007.12.005
- Richards, P.J., Hoxey, R.P. (1993). Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model. *Journal of Wind Engineering and Industrial Aerodynamics*, 46-47, 145-153. doi:https://doi.org/10.1016/0167-6105(93)90124-7

- Shao, J., Liu, J., Zhao, J. (2010). Field measurement of the convective heat transfer coefficient on vertical external building surfaces using naphthalene sublimation method. *Journal of Building Physics*, 33(4), 307-326. doi:http://dx.doi.org/10.1177/1744259109357585
- Spittle, J.D., Pedersen, C.O., Fisher, D.E., (1991). Interior convective heat transfer in buildings with large Ventilative Flow Rates. *ASHRAE Transactions*, 97, 505-515.
- Tominaga, Y., Mochida, A., Murakami, S., Sawaki, S. (2008). Comparison of various revised k- ϵ models and LES applied to flow around a high-rise building model with 1:1:2 shape placed within the surface boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(4), 389-411. doi:https://doi.org/10.1016/j.jweia.2008.01.004
- V. Natarajan, M.K. Chyu. (1994). Effect of flow angle-of-attack on the local heat/mass transfer from a wall-mounted cube. *Journals Publications - Journal of Heat Transfer - ASME*, 116, 552-560.
- Wang, K.-C., Chiou, R.-T. . (2006). Local mass/heat transfer from a wall-mounted block in rectangular channel flow. *Heat and Mass Transfer*, 42, 660-670. doi:http://dx.doi.org/10.1007/s00231-005-0038-x
- Y. Liu, D.J. Harris. (2007). Full-scale measurements of convective coefficient on external surface of a low-rise building in sheltered conditions. *Building and Environment*, 42, 2718-2736.
- Yazdani, M., Klems, J.H. . (1994). Measurement of the exterior convective film coefficient for Window in low-rise buildings. *ASHRAE Transact.*, 100 (Part 1), 1087-1096.
- Ze-X., Gui-X., Cu, Zhao-Shun Z., (2018). Numerical study of mixed convective heat transfer coefficients for building cluster. *Journal of Wind Engineering and Industrial Aerodynamics*, 172, 170-180. doi:https://doi.org/10.1016/j.jweia.2017.10.025
- Zhai, Z.Q., Chen, Q.Y., Haves, P., Klems, J.H., (2002). On approaches to couple energy simulation and computational fluid dynamics programs. *Building and Environment*, 37, 857-864. doi:https://doi.org/10.1016/S0360-1323(02)00054-9
- Zhang, R., Lam, K.P., Yao, S.C., Zhang, Y.J. (2013). Coupled EnergyPlus and computational fluid dynamics simulation for natural ventilation. *Building and Environment*, 68, 100-113. doi:https://doi.org/10.1016/j.buildenv.2013.04.002