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THE INFLUENCE OF GEOMETRIC CHARACTERISTICS OF THE BUILDINGS FACADES ON THE HEAT TRANSFER TO THE WIND FLOW

Abstract: *This paper presents the results of a numerical study of heat transfer from the external surfaces of freestanding structures in the surface layer of the atmosphere. Numerical models of structures have the same heat transfer area, but different heights and lengths. Numerical modeling of heat transfer from structures in a wind flow in a three-dimensional formulation made it possible to establish some features of convective heat transfer from enclosing structures, depending on the height of the building and the speed of the wind flow. In particular, it is shown that the dependence of the surface-averaged values of the heat flux density on the height of the building has a local minimum, after which the average heat flux density increases insignificantly with an increase in the height of the building.*

Keywords: *CFD modeling, convective heat transfer, heat transfer coefficient, wind flow.*

Introduction

New materials, technologies and architectural solutions in construction can reduce energy consumption during their operation by 50-75% compared to 2000 levels, and the refurbishment of existing residential and industrial installations can still reduce energy consumption by 30% [1]. Together, this will significantly reduce energy costs, make a significant contribution to reducing environmental impact and climate change, and improve indoor climate conditions.

Indeed, energy efficiency can be compared to an untapped clean energy resource with enormous potential. The availability of this resource is associated not so much with technological constraints and existing approaches as with ineffective management.

Decision-making inefficiencies are especially relevant at the early design stage in the case of new construction and at the stage of choosing renovation options in the case of existing buildings. The correct choice of options for architectural solutions for new construction or reconstruction options, as well as effective management after completion of construction can provide modern modeling, in particular, simulation of heat and mass transfer processes in buildings and structures in interaction with the environment.

An important tool in the design and operation of buildings are programs for modeling the energy consumption of buildings [2]. These programs combine many mathematical and empirical models to describe the associated energy flow processes in buildings.

The paper [2] analyzes seven programs for modeling energy consumption of buildings: ESP-r, EnergyPlus, IES, IDA, TAS, TRNSYS and SUNREL. ESP-r is an open software code for building energy simulation developed by the University of Strathclyde (Glasgow – Scotland). ESP-r simulates the thermal, visual and acoustic performance of a building, and estimates the thermal and electrical power of the simulated building.

EnergyPlus software code is a collection of many software modules that estimate the amount of energy required to heat and cool a building using various systems and energy sources.

IDA Indoor Climate and Energy (IDAICE) is a software code for dynamic multi-zone modeling and is intended for a fairly accurate assessment of the thermal indoor climate in individual zones of the structure, as well as the energy consumption of the entire building as a whole.

TasEngineering is designed for dynamic modeling and thermal analysis of buildings and structures.

TRNSYS is widely used to model solar equipment and technological solutions, as well as ordinary buildings and structures.

SUNREL is a software for simulating the energy consumption of small buildings.

These programs combine many fundamental and empirical models to describe a variety of energy flow processes in buildings [1].

This paper examines the process of convective heat transfer between the external surfaces of buildings and the environment. In most cases, the convective heat exchange of building facades with the environment is estimated by calculating the value of convective heat transfer coefficients (CHTC):

$$\alpha_k = \frac{q_s}{T_s - T_a} \tag{1}$$

where:

q_s – the heat flux density on the surface of the surrounding structures;

T_s – temperature of the outer surface of the building;

T_a – ambient temperature.

The more accurately the values of the heat transfer coefficients are determined, the more accurate will be the assessment of the heat taken from the building envelope.

In works [2, 3], an analysis of a significant number of existing empirical models for assessing the CHTC of enclosing structures is carried out. It is shown that all models can be divided into several groups:

Linear equations for convective heat transfer coefficients:

$$\alpha_k = A + B \cdot U \tag{2}$$

where:

A, B – empirical coefficients;

U – wind speed.

Power function of the convective heat transfer coefficient from wind speed:

$$\alpha_k = a + b \cdot U^n \tag{3}$$

where:

a, b, n – empirical coefficients.

Traditional criterion equations:

$$Nu = aRe^{b}Pr^{c} + d \tag{4}$$

In total, these works analyzed and classified 76 dependences of the CHTC for the facades of buildings and structures, and most of these relationships are used in the above software packages for modeling the thermal state of buildings.

The indicated correlation for the convective heat transfer coefficients allow one to take into account a number of factors that determine the convective heat flow from the facades of buildings located in the wind flow:

- wind speed;
- wind direction in relation to the orientation of the facades (angle of attack of the wind);
- orientation of the surface relative to the wind in a qualitative sense (windward, leeward);
- the angle of inclination of the surface in relation to the plane of the earth (in extreme cases, horizontal and vertical);
- terrain type;
- shelter by nearby buildings;
- surface texture;
- difference between surface and air temperatures (Δt);
- surface size and aspect ratio.

At the same time, the type of building (high, medium or low rise) and its geometry are also important factors in assessing convective heat loss. However, these factors are not included in the above list, since none of the models for CHTC described in reviews [2, 3] are able to account for differences in the type and geometry of the building. You can also add that relations (2)-(4) take into account the wind speed and one of the above factors, while CFD modeling makes it possible to take into account in one model almost all parameters affecting the convective heat exchange of buildings with the environment, including the factors listed above.

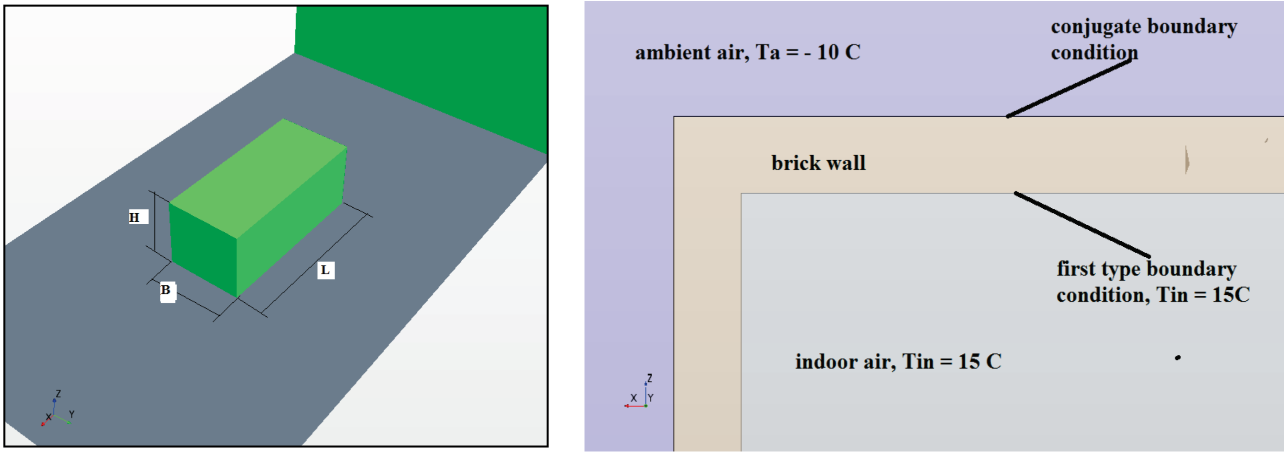
A fairly successful attempt to link the heat transfer of building facades with their geometry was made in [4, 5]. In these studies, 3D CFD modeling of three groups of buildings was carried out. The first group includes buildings, the height of which is $H \le B$ (B is the width of the building) Figure 1, to the second group – buildings with $H \ge B$, and to the third – those with $H = B$. In these works, the building length L remained constant.

As a result, for the windward facades of buildings (in this case, it is a facade $H \times B$), power-law functions (3) of the dependence of CHTC on the wind speed are obtained. In this simulation, the wind speed varied from 1 m/s to 5 m/s at the height of the weather vane, and the temperature difference $T_s - T_a$ (formula (1)) remained constant: T_s = 30°C and T_a = 10°C, which may correspond to the conditions of a cloudless days in the month of April.

In this regard, the main goal of this work is to find out the correlation between the main architectural features of buildings and structures with the boundary convective heat fluxes on the facades of buildings in a wind flow using three-dimensional CFD modeling.

Geometric model

In this paper, models of detached buildings are considered Figure 1. In total, 6 models of buildings were created, interconnected by the condition that the area of the facades of buildings in the environment is the same. The height of buildings H varies, and its length L, the width of buildings B remains constant Figure 1.



a) b)

FIGURE 1. *Geometricmodelofresearchobjects: a) solution domain; b) fragment of a plane vertical section*

Table 1 shows the calculations of the corresponding dimensions in the building models.

TABLE 1. *Calculation of geometric parameters of CFD models*

Width *B*, m	18	18	18	18	18	18
Length *L*, m	60	50	40	30	20	10
Height *H*, m	10	12.79	16.55	21.88	30.00	43.93
Area of facades, m²	2640	2640	2640	2640	2640	2640

It is assumed that the buildings, the dimensions of which are given in Table 1, have brick walls with a thickness of 30 cm (Fig. 1b).

Constraints, boundary and initial conditions

In accordance with the simulation conditions, detached buildings are located in a turbulent wind flow of the surface layer of the atmosphere under conditions of normal air stratification, the thermophysical characteristics of which are constant.

The computational domains were determined in accordance with the recommendations [6]. At the entrance to the solution area, vertical profiles of the average horizontal wind speed U (logarithmic law), turbulent kinetic energy (k – m^2/s^2) and dissipation rate of turbulent kinetic energy (ε – m^2/s^3) are set, according to the $k-\varepsilon$ turbulence model for atmospheric boundary layer [7]. This model is built for a neutral atmospheric boundary layer in which turbulence occurs only due to friction and shear, and not due to thermal stratification.

$$U(z)=\frac{u^*}{k}\ln\left(\frac{z+z_0}{z_0}\right)$$

$$k(z)=u^{*2}/\sqrt{C_\mu} \qquad (5)$$

$$\varepsilon(z)=\frac{u^{*3}}{k(z+z_0)}$$

where:

u^* – the friction velocity of the atmospheric boundary layer, m/s;

k – Karman constant, 0.41;

z – height above the ground, m;

z_0 – height of the aerodynamic roughness (m) of the terrain type.

The friction speed $u*$ is related to the wind speed U_{10} at the height of the weather vane (10 m). In this study: U_{10} = 1, 3, 5 and 10 m/s. The z_0 parameter is 1 m, which corresponds to a city center without sufficiently tall buildings [8]. The wind speed vector is directed perpendicular to the windward surface of the building facade. The incident air temperature is −10°C, which is taken as the incident air temperature T_a in equation (1). The constant temperature assumption over the height of the atmospheric boundary layer is a good enough assumption for neutral air stratification with zero heat flux at the ground and a limited height of the solution region. The temperature on the inner surface of building fences is considered to be set (+15°C). On the outer surfaces of the building fences, the conditions for conjugation of the temperature and heat flux fields are set.

Mesh models

In this CFD study, several mesh models were used: rectangular uniform mesh Figure 2a, rectangular mesh with a seal at the facades surfaces Figure 2b, and mesh with polyhedral cells Figure 2c.

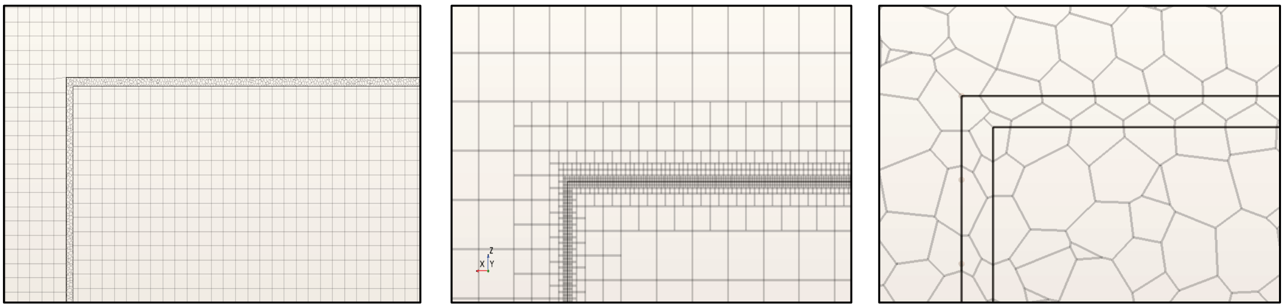

a) b) c)

Figure 2. *Mesh models in numerical study*

The defining size in all mesh models corresponded to 0.5 m, and the number of cells varied from 2400 to 4000 thousand cells. Analysis of the sensitivity of the solution to mesh models and to the number of cells in the models did not give significant deviations. The largest deviation was no more than 3%.

Mathematical model

The system of equations describing hydrodynamics and heat transfer in the system under study consists of:

- ContinuityEquations:

$$\frac{\partial\rho}{\partial\tau}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{6}$$

- Navier-Stokes System of Equations:

$$\begin{gathered}\frac{\partial\rho u}{\partial\tau}+\frac{\partial\left(\rho u^2\right)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=\\=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left[\mu_{ef}\frac{\partial u}{\partial x}\right]+\frac{\partial}{\partial y}\left[\mu_{ef}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu_{ef}\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]\end{gathered} \tag{7}$$

$$\frac{\partial \rho v}{\partial \tau}+\frac{\partial(\rho vu)}{\partial x}+\frac{\partial\left(\rho v^{2}\right)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=$$
$$=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[\mu_{ef}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]+2\frac{\partial}{\partial y}\left[\mu_{ef}\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial z}\left[\mu_{ef}\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right] \tag{8}$$

$$\frac{\partial \rho v}{\partial \tau}+\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial\left(\rho w^{2}\right)}{\partial z}=$$
$$=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[\mu_{ef}\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu_{ef}\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)\right]+2\frac{\partial}{\partial z}\left[\mu_{ef}\frac{\partial w}{\partial z}\right]-\rho g \tag{9}$$

- Energy Equation:

$$\frac{\partial\left(C_{p}\rho T\right)}{\partial \tau}+\frac{\partial\left(C_{p}\rho uT\right)}{\partial x}+\frac{\partial\left(C_{p}\rho vT\right)}{\partial y}+\frac{\partial\left(C_{p}\rho wT\right)}{\partial z}=$$
$$=\frac{\partial}{\partial x}\left[\lambda_{ef}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_{ef}\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[\lambda_{ef}\frac{\partial T}{\partial z}\right] \tag{10}$$

- Ideal gas equation of state:

$$p=\rho RT \tag{11}$$

Air flows in the surface layer of the atmosphere are traditionally modeled by numerically solving the Reynolds-averaged system of Navier-Stokes differential equations, which is closed by two additional equations for the kinetic energy of turbulence (12) and dissipation of the kinetic energy of turbulence (13):

$$\frac{\partial \rho k}{\partial \tau}+\frac{\partial \rho uk}{\partial x}+\frac{\partial \rho vk}{\partial y}+\frac{\partial \rho wk}{\partial z}=$$
$$=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right]+\mu_t S^2-\rho\varepsilon \tag{12}$$

$$\frac{\partial \rho \varepsilon}{\partial \tau}+\frac{\partial \rho u\varepsilon}{\partial x}+\frac{\partial \rho v\varepsilon}{\partial y}+\frac{\partial \rho w\varepsilon}{\partial z}=$$
$$=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right]+C_1\frac{\varepsilon}{k}\mu_t S^2-C_2\rho\frac{\varepsilon^2}{k} \tag{13}$$

where:

$$S=\left[\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2+\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2+2\left(\frac{\partial u}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+2\left(\frac{\partial w}{\partial z}\right)^2\right]^{0.5}$$

It is shown in [9] that in this case, for the problems of turbulent transport in atmospheric flows over the underlying surface, it is advisable to use the following constants for the k – ε model: $C_\mu = 0.033$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$; $C1_\varepsilon = 1.176$; $C2_\varepsilon = 1.92$.

Heat transfer in solids (enclosing structures) is described by the heat conduction equation:

$$C_p \rho_m \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda_m \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda_m \frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda_m \frac{\partial T}{\partial z}\right] \tag{14}$$

In modern CFD packages, such as ANSYS or STAR CCM, the above system of equations is solved numerically according to explicit, implicit or mixed schemes.

Results

Numerical integration of the system of equations (6)-(14) using CFD packages allows calculating all field functions for unambiguous determination of both local and average values of the thermal characteristics of the simulated object.

Figure 3 shows the average values of the boundary heat flux q_s over the surfaces of all facades, depending on the building height H and the wind flow rate U_{10}. The data indicate that with an increase in wind speed, the value of the heat flux increases. In the range of building heights from H = 10 m to H = 16 m, a decrease in the average heat flux with increasing height is observed, and with a further increase in the height H at all wind speeds, a slow increase in q_s is observed.

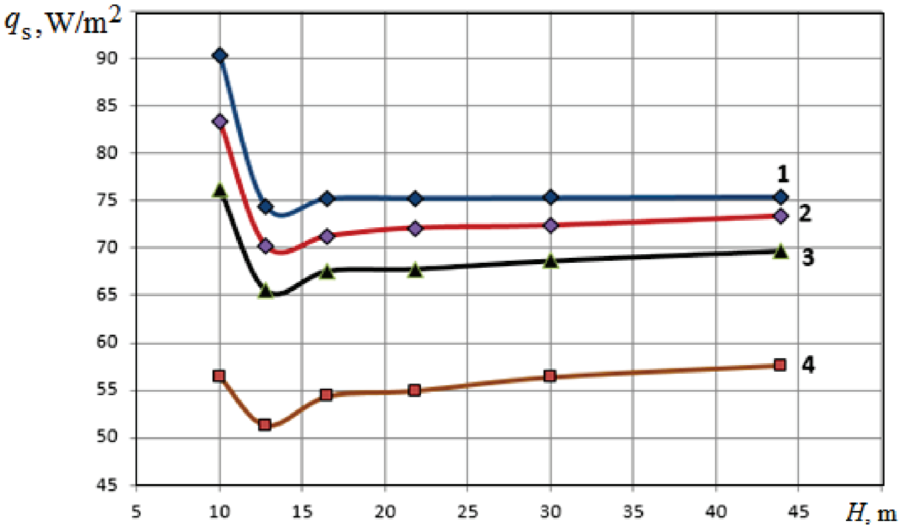


FIGURE 3. *Average heat flux qs on the surface of buildings depending on the height of the building and wind speed: 1 – U_{10} = 10 m/s; 2 – 5 m/sec; 3 – 3 m/s; 4 – 1 m/sec*

The graphs in Figure 3 clearly indicate that the height of the building affects the convective heat transfer of structures.

Heat transfer coefficient

In modern governing documents of architecture and construction, the convective component of the heat flux on the outer surfaces of the enclosing structures is proposed to be estimated by means of the heat transfer coefficients, which are regulated in these documents. Therefore, the authors of most of the works devoted to the thermal characteristics of buildings and structures pay particular attention to this coefficient. CFD modeling allows to numerically determine the fields of velocity, temperature, heat fluxes and other field functions, allowing to calculate both local and average values of heat transfer coefficients on the facades of the buildings under study.

In Figures 4-6 show the local values of the heat transfer coefficients on the outer surfaces of the enclosing facades of the simulated buildings. Local coefficients are calculated along centerlines on roof surfaces, windward and leeward facades.

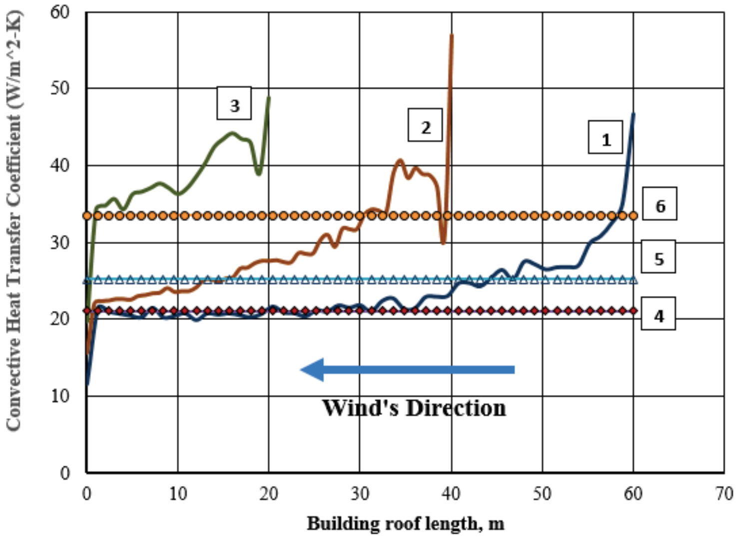


FIGURE 4. *Values of heat transfer coefficients on roofs of buildings of different heights: 1 – corresponds to a building with a height of H = 10 m; 2 – H = 16 m; 3 – H = 30 m; 4 – Frank's model; 5 – McAdams model; 6 – polynomial model*

An increase in the values of local heat transfer coefficients on the roof of buildings with an increase in its height (curves 1, 2, 3 in Figure 4) is due to an increase in the wind flow velocity with an increase in the distance from the ground.

As expected, the local heat transfer coefficients on the windward facade of buildings are rather much higher than the corresponding values on the leeward side Figures 5 and 6. Moreover, the higher the building, the greater the difference. See also Figures 5 and 6 indicate that the values of the heat transfer coefficients on the windward and leeward sides of the building do not actually depend on its height. At the ground, the coefficients coincide, and as the height increases, the coefficients correlate quite well in physical values up to the separation of the wind flow at the edge of the buildings.

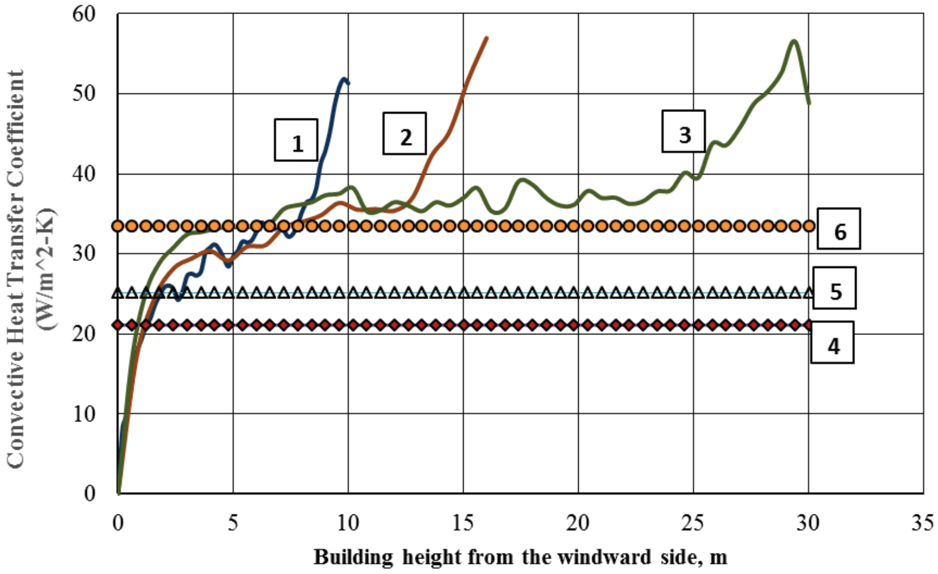


FIGURE 5. *Values of heat transfer coefficients on the windward side of buildings of different heights: 1 – corresponds to a building with a height of H = 10 m; 2 – H = 16 m; 3 – H = 30 m; 4 – Frank's model; 5 – McAdams model; 6 – polynomial model*

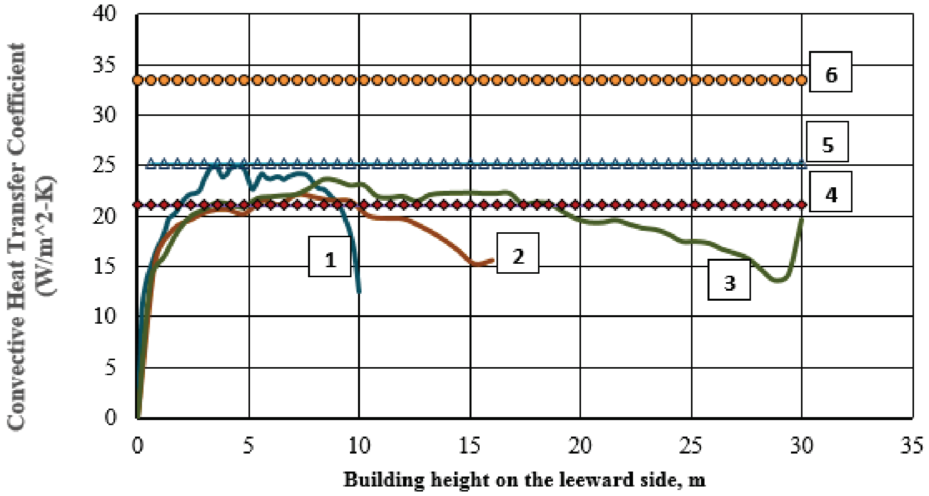


FIGURE 6. Values of heat transfer coefficients on the leeward side of buildings of different heights: 1 – corresponds to a building with a height of H = 10 m; 2 – H = 16 m; 3 – H = 30 m; 4 – Frank's model; 5 – McAdams model; 6 – polynomial model

Comparison of known models for heat transfer coefficients with simulation data

In Figures 4-6 show a comparison of local values of heat transfer coefficients for buildings with different geometries with known calculation models for average values of heat transfer coefficients, which are used in the above-mentioned software packages for calculating the thermal characteristics of new buildings and buildings in need of renovation.

It should be noted that the models below, which are Frank, McAdams and the polynomial model, were chosen almost arbitrarily, since in the works known to us [2, 3, 10], no preference is made for any of them:

Frank's formula [10]:

$$\alpha_k = 7.34U^{0.656} + 3.7e^{-1.97U} \tag{15}$$

The second term on the right-hand side of formula (15) characterizes the amount of heat transfer by natural convection. For the calculated wind speed for winter conditions, the average speed is taken from those points for January, the frequency of which is 16% or more.

McAdams model [2, 3]:

$$\alpha_k = 5.687\left[m + n\left(\frac{U_f}{0.3048}\right)^p\right] \tag{16}$$

where *m, n, p* are roughness parameters for smooth and rough surfaces [2, 3].

Polynomial model [2, 3]:

$$\alpha_k = D + EU_{10} + FU_{10}^2 \tag{17}$$

where:

α_k – combined emissivity and convection coefficient;

D, E, F – roughness coefficients [2, 3].

Comparison of local values of heat transfer coefficients on external surfaces of buildings obtained as a result of this CFD simulation with the data of empirical models for average coefficients indicates that none of the considered empirical models coincides with local calculated data.

However, we can say that Frank's model (curve 4 in Figure 6) more or less corresponds to local CHTC on the roofs of low buildings (no more than 10 m). Other considered models are not suitable for use in assessing convective heat fluxes on the roofs of buildings and structures. The polynomial model fairly closely describes convective heat transfer from the windward side, while the Frank and McAdams models correlate with heat transfer on the leeward side of the models. It is quite possible that other models of convective heat transfer will be more adequate.

Influence the wind flow speed on the value of the heat transfer coefficient on the building facades

In specialized software codes for assessing the thermal state of buildings, which were discussed above, the convective component of heat fluxes is calculated using heat transfer coefficients averaged over the surfaces of the enclosing structures [2, 3]. Also, the average values of the heat transfer coefficients are regulated in the management documents of architecture and construction known to us. In particular, Ukraine has adopted a standard for the convective heat transfer coefficient for the external surfaces of building envelopes, corresponding to a value of 23 W/m²K.

The results of CFD modeling of buildings of different heights with the same heat transfer surface at four values of wind speed are used to obtain a correlation between the value of the average CHTC over the surfaces of buildings and the average speed of the wind flow U_{10} at the height of the weather vane (10 m).

In Figure 7 shows the graphs of the dependences of the CHTC from the height of the buildings and the speed of the wind flow. The graphs unambiguously indicate that the convective component of the heat flow from the external facades of buildings significantly depends from their height and the speed of the wind flow.

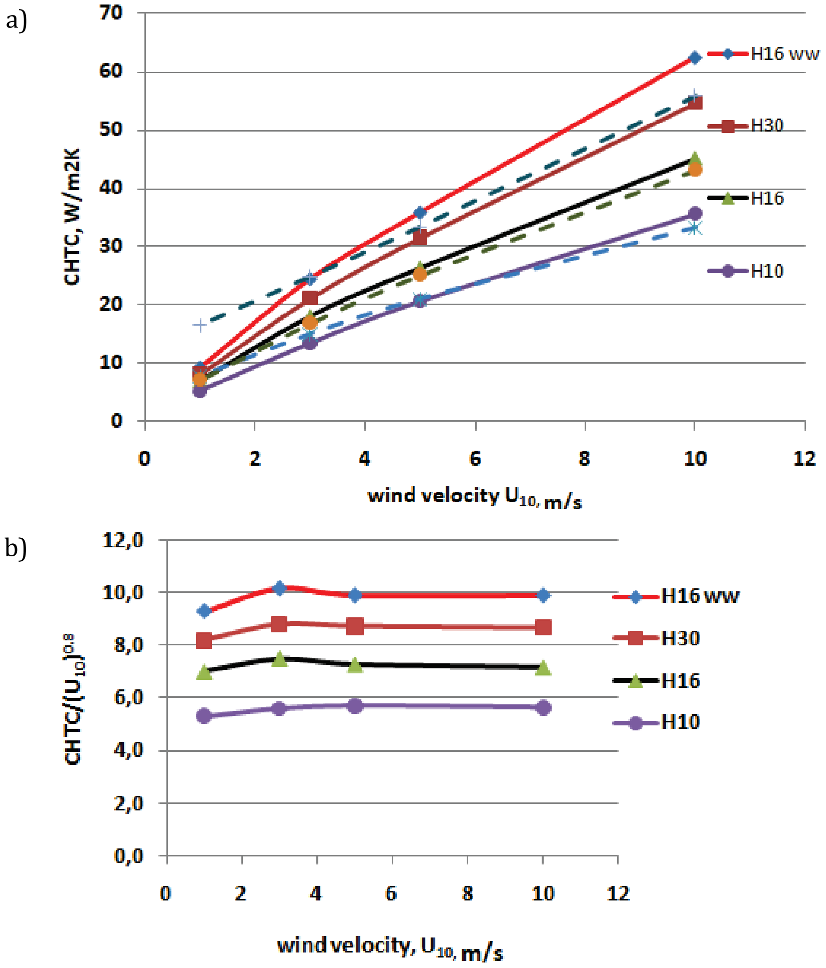


FIGURE 7. Profiles of surface-averaged CHTC (CHTCavg) on the surface of the heat transfer of buildings: H10, H16, H30 – buildings with a height of 10, 16, 30 m; H16ww – corresponds to the windward side of a 16 m high building; 1 – CHTCavg values according to the polynomial model; 2 – according to the McAdams model; 3 – after Frank's model

Taking into account the turbulent nature of air movement in the atmosphere, it is advisable to consider the dependence of the ratio $\alpha_k/(U_{10})^{0.8}$ on the wind speed. These dependences are shown in Figure 7b. The horizontal character of the curves in Figure 7b indicates that the functions $\alpha_k = F(U_{10})$ are fairly accurately approximated by power functions of the form (3). Table 2 shows an explicit view of these functions depending on the height of the building, obtained from the results of CFD modeling.

Table 2*. An explicit form of functions $\alpha_k = F(U_{10})$ depending on the height of the building, obtained from the results of CFD modeling*

Building height	*H* = 10	*H* = 16	*H* = 30	Windward facade of the building *H* = 16 m
CHTCavr	$\alpha_k = 5.6U_{10}^{0.8}$	$\alpha_k = 7.2U_{10}^{0.8}$	$\alpha_k = 8.6U_{10}^{0.8}$	$\alpha_k = 9.8U_{10}^{0.8}$

For comparison, Figure 7a shows the values of the heat transfer coefficients calculated according to known models for estimating α_k. The graphs in Figure 7a show that Frank's model is appropriate for buildings up to 10 m in height, the McAdams model gives good results for buildings up to 16 m in height, and the polynomial model works for buildings 30 m or more.

Conclusion and findings

Based on the results of this study, the following conclusions can be drawn:

Empirical models, such as Frank's formula, designed to assess the convective component on the outer surfaces of the enclosing structures of buildings and structures, take into account only 2, 3 parameters from a large number of factors on which the convective heat exchange of buildings in the wind flow of the atmospheric surface layer depends. Modern CFD modeling packages allow simultaneously taking into account a much larger number of factors affecting convection, including the geometry of buildings and their architectural features. Therefore, when creating sufficiently important objects, it is advisable to use CFD modeling, which is quite convincingly shown by this study.

The results of this numerical simulation clearly indicate that the geometry of buildings and their architectural features affect the convective heat transfer of structures to the environment, which in turn changes the heat balance of buildings as a whole.

Conflicts of Interest: The author declares no conflict of interest.

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