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Assessment of Factors Affecting the Energy Efficiency of High-Rise Buildings in Modern Cities

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Abstract. The problem of energy consumption of modern high-rise buildings is becoming increasingly important. The growing number of high-rise buildings and the development of urban infrastructure have resulted in the increased energy consumption. Modern high-rise building construction affects the density of urban space and significantly changes local climatic conditions. The development of local climatic factors in thigh-rise building construction and their impact on the energy efficiency of buildings is a relevant and insufficiently studied problem. The article analyzes the influence of modern urban development on the climatic and aerodynamic conditions of the terrain. The assessment of climatic factors influencing heat losses of a high-rise building is carried out. High-rise buildings in the city of Moscow are considered; calculations are made and qualitative and quantitative parameters of the variation in the main climatic factors are given with reference to the architecture of the building. Using the example of the Evolution Tower, calculations have been made and dependency graphs of the temperature and wind speed on the height of the building are presented. The results of the research can be used to assess the influence of climatic factors on the energy costs of high-rise buildings, and can be taken into account in the design of modern energy-efficient buildings.

1. Introduction

Being one of the main problems of modern society, lack of free space in big cities leads to an increase in the demand for residential, public, administrative and commercial spaces, and an increase in the number of cars. Architects seek for solutions for the maximum use of space, its multifunctionality and accessibility. In this regard, high-rise multifunctional buildings are of great interest. On the one hand, an increased area of the foundation is beneficial, but on the other hand, the high cost of designing and constructing high-rise buildings results in higher maintenance costs. It is noteworthy that the higher the building is, the more expensive it is to operate.

It is known that buildings are affected by external climatic factors, such as outside air temperature, wind, solar radiation. The intensity of the impacts of these factors depends on both the climatic zone where the building is located, and the architectural forms and orientations of the building. It is obvious that the natural and climatic factors influence the choice of architectural forms of buildings and the structure of urban development [14].

Another urgent problem of the modern world is that the cost of energy is increasing, while its reserves are decreasing from year to year. Consequently, the issue of reducing the energy consumption of modern high-rise buildings is becoming increasingly important.

It has been found that the energy consumption of all civil buildings is greater than the energy costs of all industrial facilities, including factories, plants, metallurgical plants and energy spent on transport with all its cars, trains and ships (Fig. 1) [4].

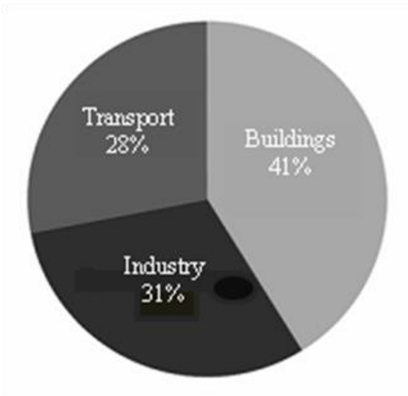

Figure 1. Distribution of energy consumption in Europe

Distribution of energy consumption in different countries can depend on the natural and climatic factors, the pace of development of industry and cities, the introduction of energy-saving technologies, etc.

The city, as a rule, includes an industrial area, a residential area, a public and a natural area. With the rapid pace of development of countries' economies, and the increasing density of population, it has become necessary to improve big cities by developing their transport and engineering infrastructure. The increasing density of population in modern big cities significantly affects the density of residential and public areas [6]. As a result, many multifunctional high-rise buildings are changing the architecture of these areas, which significantly affects the consumption of energy resources. Skyscraper architecture, transforming the aerodynamics of the terrain, affects the heat and wind conditions of residential and public areas [11]. The modern construction industry is characterized by the density of urban development, well-developed infrastructure, and transport networks. Rapid development of cities and the growth of modern high-rise buildings change the natural landscape of the area and significantly affect the existing climate conditions. Thus, modern cities are subject to constant changes, increasing the demand for energy resources. In big cities, the problems of finding ways to save energy, creating multifunctional energy-efficient high-rise buildings and developing technologies are quite acute today.

A high-rise building is a building taller than 75 m or more than 25 floors. For the rational use of areas, high-rise buildings are designed to be multifunctional. According to the famous Russian architect and urban planner A A Tsvetkov, buildings and structures up to 120 m high (30-35 floors and below) belong to the class of high-rise buildings, and buildings of 120 m high (40 floors) and higher belong to skyscrapers. The 120 m boundary is chosen because the lowest clouds float precisely at this altitude. Maintenance of high-rise buildings and skyscrapers requires considerable energy costs. In this regard, the problem of constructing energy-efficient high-rise buildings to reduce their operating costs is one of the most important tasks. To solve this problem, it is necessary to identify the main factors affecting the energy efficiency of modern high-rise buildings.

2. Methods

Obviously, the main factors affecting the energy efficiency of buildings are natural climatic factors (Fig. 2).

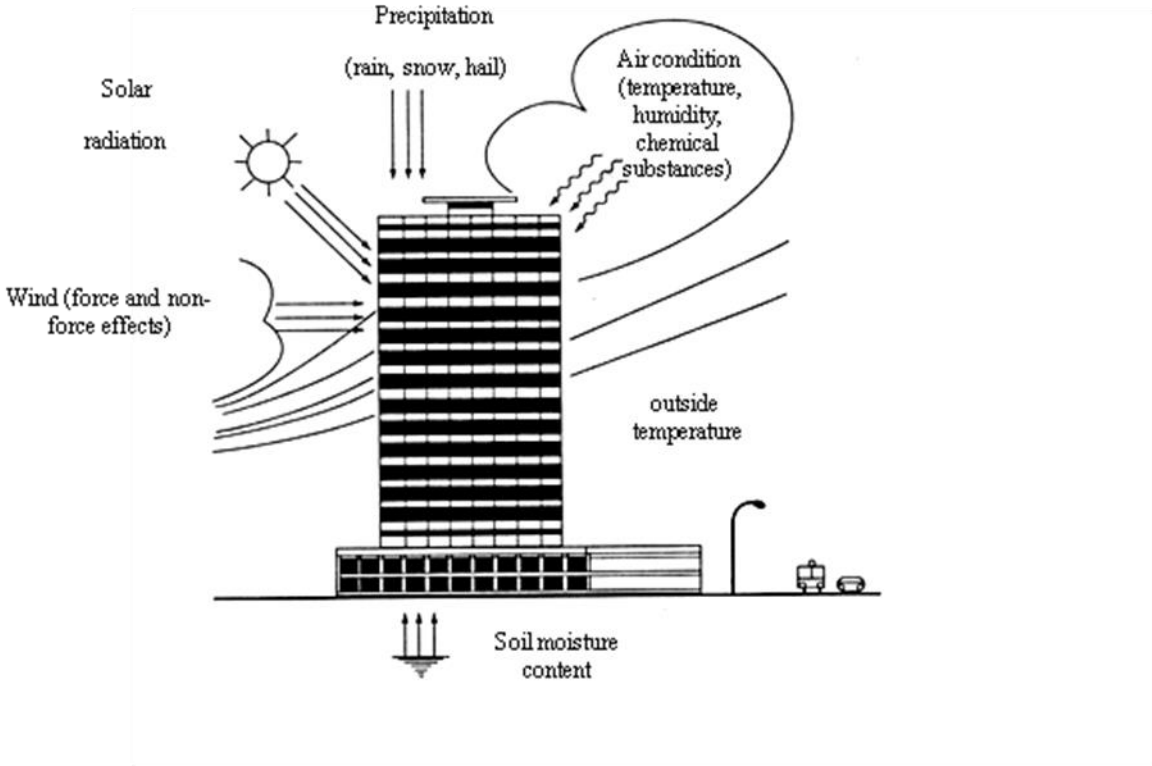

Figure 2. Climatic factors of external effects on buildings

Natural and climatic factors, being an important quality of the urban environment, are subject to significant changes with the development of modern buildings. Such factors as the temperature of the outside air and the wind speed might change along the height of the building. In addition, solar radiation affects the insolated facades and causes the formation of upward convective currents, modifying the aerodynamics of the urban environment. The processes of absorption and emission of radiation, evaporation and heat transfer on different surfaces of the urban environment form various microclimate conditions in a geographic area with the same type of climate. Thus, local climatic parameters are formed due to the heterogeneity of urban development and the underlying surface [5,14].

Obviously, solar radiation changes the microclimate of the adjacent territory of modern urban development and has a significant impact on the energy efficiency of high-rise buildings. In turn, the intensity of solar radiation depends on the transparency of the urban atmosphere. About 20% of the solar radiation can be lost due to the turbidity of the atmosphere in conditions of big industrial cities with high-density construction. In the summer, differences in the intensity of direct solar radiation in residential and industrial areas of the city reach 20-22%. There intensity of direct solar radiation in a radius of up to 3 km in close proximity to big industrial enterprises is weakening, and it can reach 35-40% [1,2]. Similar phenomena coupled with the violation of the aerodynamic conditions of the area lead to the formation of the urban heat island. The urban heat island is a phenomenon, in which the temperature of urban space is higher than the temperature of surrounding rural areas. The intensive development of modern high-rise buildings promotes the intensive operation of engineering and transport networks and the formation of anthropogenic factors causing the emergence of the heat island [3].

As a result, it should be noted that with the development of high-rise buildings, the natural and climatic factors affecting the microclimate of the urban environment are experiencing significant changes.

Changes in the main parameters of climatic factors were investigated using the example of Evolution Tower. Based on the calculations performed, graphs are plotted for the change in outdoor air temperature and wind speed, depending on the height of the building. Obviously, the change in external climatic parameters has an effect on the heat and air conditions at different floors of a high-rise building.

The change of the outside air temperature and atmospheric pressure depending on the height of the building can be calculated by the following formulas [7]:

$$t_h = t_0 - 0.0065 \times h, {}^0C \quad (1)$$

$$p_h = p_0 (1 - 2.25577 \times 10^{-5} \times h)^{5.2559}, Pa \quad (2)$$

where t_h, p_h is temperature, °C, and pressure, Pa, at a height h, m, respectively.

t_0, p_0 is temperature, °C, and pressure, Pa, near the ground surface, respectively.

Estimated climatic parameters according to [4] were for the city of Moscow.
Using the data obtained, the dependence graphs of the outside air temperature along the height of the building were constructed (Fig. 3).

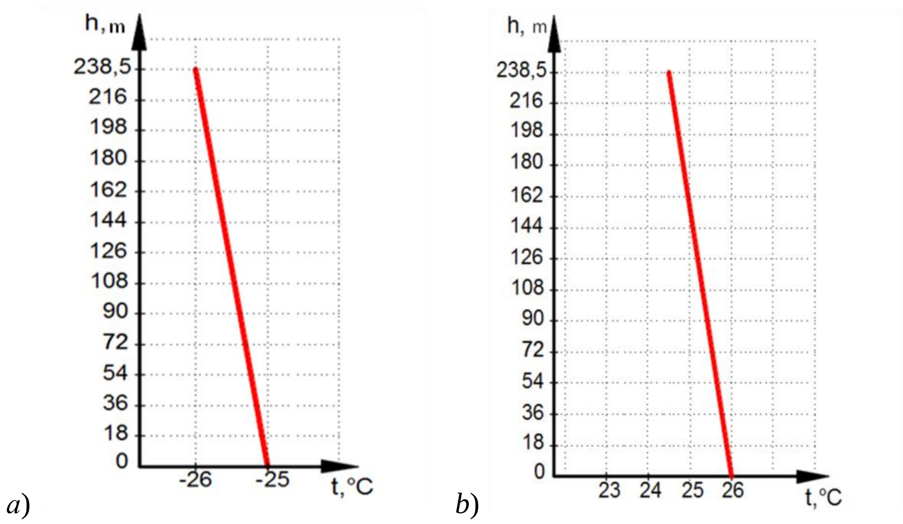

Figure 3. Variation of outside air temperature along the height of the Evolution Tower in the city of Moscow: *a*- for the coldest 5-day period; *b*- for the warm period.

Various models are used to estimate the change in wind speed by height: the Ekman spiral, the logarithmic law, the power law. [5,6] These models are used to estimate the wind speed V at a height h if the wind speed V_0 is known at a height h_0.

The power law of variation of the wind speed with respect to height has the form [8,9]:

$$V_h = V_o (h/h_o)^{\alpha}, m/s \qquad (3)$$

where V_h is wind speed, m/s, at a height h, m;

V_0 is wind speed, m/s measured at a height h_0, m (the wind speed is measured at a height of 10-15 m, therefore h_0 = 10—15 m);

α is an exponent that depends on the terrain type and is found experimentally; it is recommended for centers of big cities α = 0.33, for suburban areas α = 0.22 and for open space α = 0.14 [9].

Based on the results of the calculation, a graph of the change in wind speed along the height of the building was constructed (Fig.4)

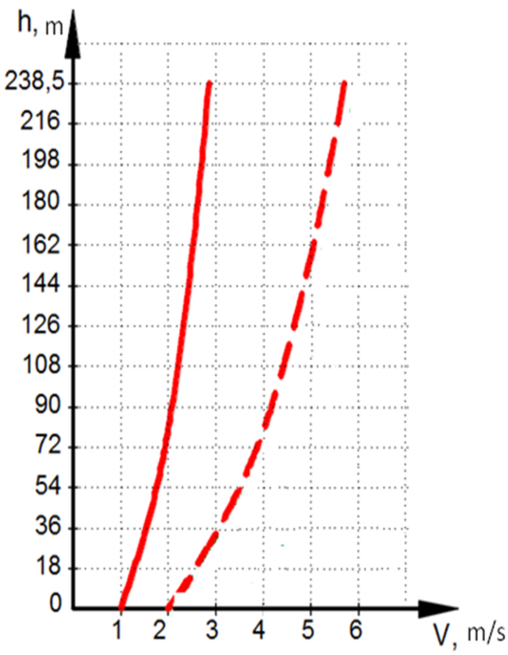

Figure 4. Variation of the wind speed along the height of the Evolution Tower in the city of Moscow

As can be seen from Fig. 4, with an increase in the height of the building, the wind speed increases, and in urban development areas this occurs more intensively.

3. Results of the study

Using the example of the Evolution Tower, the calculation of the heat losses of the multi-storey buildings for the city of Moscow was carried out.

The heat loss of the room due to heat transfer through the outer walls is determined by summing the heat losses through each external wall, which are calculated according to the formula [10]:

$$Q_{mn_i} = k_i \times F_i (t_i - t_o^x) n \times (1 + \sum \beta_i), W \qquad (4)$$

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where: $k_i \times F_i(t_i - t_o^x)n$ are main heat losses;

k_i is coefficient of heat transfer of the wall, W/ºC×m^2;

F_i is outer wall surface area, m^2.

t_i is design temperature inside the building

t_o^x is outside temperature at a height h^x;

β is tolerance for the main heat losses depending on the orientation of the vertical wall in the cardinal directions.

n_i is coefficient taken depending on the position of the outer surface of the enclosing structure with respect to the outside air, i.e. coefficient reducing the temperature difference (t_i– t_o) for walls that do not contact with the outside air.

Using the calculation of heat losses in the building, a graph was constructed (Fig. 5)

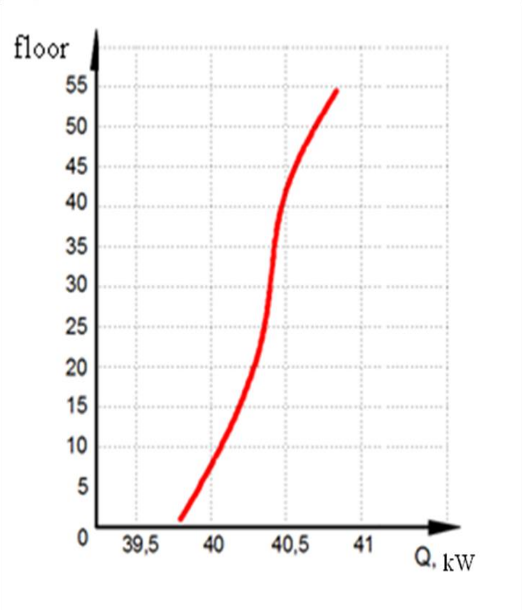

Figure 5. Heat losses at different floors of the Evolution Tower for the city of Moscow.

The power of the ventilation system is calculated by the formula:

$$Q^V = L \times \rho \times (t_i - t_o^x) \times C / 3.6, \text{ kW} \quad (5)$$

L is air consumption, m^3/h;

ρ is air density, $\rho = 1.2 kg/m^3$

C is air heat capacity, $C = 1.005 kg/kg^0C$

Based on the calculation of the ventilation capacity of the building, a graph was constructed (Fig. 6).

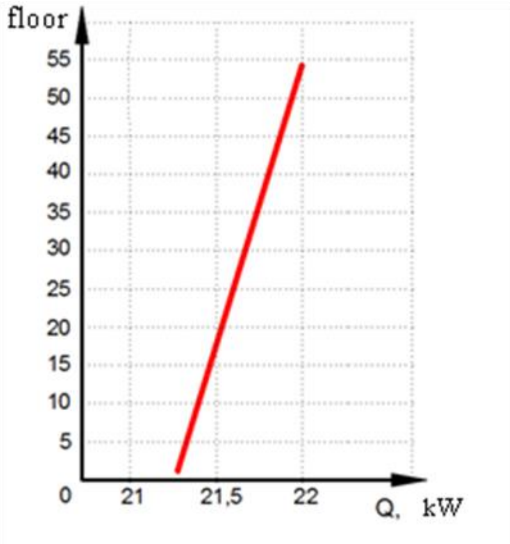

Figure 6. Ventilation capacity at different floors of the Evolution Tower for the city of Moscow.

The change in external climatic parameters affects the heat and air conditions at different floors of a high-rise building. As can be seen from Fig, 5 and 6, the heat loss of rooms and the capacity of the ventilation system increases with the height of the room location.

4. Conclusions

1. With the increasing building height, the outside air temperature and atmospheric pressure decrease, while the air pressure difference between the upper and lower floors increases. This can lead to a significant flow of air masses from the lower floors to the upper ones, to the violation of the estimated air balances, to a decrease in the winter air temperature on the lower floors.

2. Due to the irradiation of the external surfaces of the building by solar radiation during the warm period of the year, their temperature increases sharply and differs significantly from the outside air temperature. As a result of the temperature difference, a convective heat flow directed upwards of the building is formed, and there is a so-called near-surface (boundary) layer of heated air, which is of great importance for designing air intake devices and determining the air permeability of the enclosing structures because of the changing values of the air flow velocity at the outer surface of buildings.

3. The increase in wind speed with the height of the building during the cold period of the year influences the heat transfer coefficient of the outer surface of the enclosing structure. It will increase slightly, while reducing the heat transfer resistance of the external enclosing structure and reducing the overall resistance to heat transfer of the enclosing structures.

4. The decrease in the air temperature with the height affects the value of the surface density of the heat flow passing through the outer enclosing structures, which leads to an increase in the heat losses of rooms located at different floors.

5. Decrease in the outside temperature with the increasing height of the building affects the capacity of the ventilation system.

When solving problems of city planning and constructing high-rise buildings at the stage of development of design documentation, it is necessary to take into account the specifics of climatic factors that affect the heat and wind conditions of the environment and the energy efficiency of buildings.

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