Consideration of Climatic Parameters Changes in the Design of Ventilation Systems for High-Rise Buildings

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Abstract. Capacity of heating system is determined by transmission heat losses through external enclosures and heating of infiltration air. Airflow rate of infiltration air depends on external pressures in the center of air-permeable openings. A major component of this parameter is wind force pressure, which value depends on its speed changing with the height of a building. In previous research works was made a compromising analysis of existing calculation methods of wind speed changes on the height of high-rise buildings. Based on the obtained review, two calculation methods have been chosen in the present article: method, based on speed change coefficient and power-law method. The article presents the results of air mode calculation for high-rise building in Moscow. Results of calculations based on method of speed change coefficient provides higher values of supply airflow rate than in case of excluding the impact of wind speed changes along the height of a building and using power-law method.

1. Introduction

High-rise buildings play a significant role in housing stock. The international experience shows that widely developed system of public and recreation institutions in multi-storey residential buildings is a modern trend of urban development [1].

Natural ventilation is regarded as one of the most energy-efficient ways of providing requirement microclimate parameters in building [2]. Several studies have been carried out to analyze possibilities of natural ventilation systems in high-rise buildings [3-6], but most of them are considered on hot and humid climate. Implementation of natural ventilation systems in high-rise buildings in countries with cold climate has not been sufficiently studied. Such systems are traditionally used in residential buildings in Russia. Designing natural ventilation systems in high-rise buildings represents a real challenge for engineers. Increasing the height of a building leads to need of designing hermetic external enclosures to reduce infiltration heat losses. The appropriate thermal protection of the buildings should be solved not only depending on the climate of the construction area, but also both on the mode of operation and the indoor heat access into the premises [7]. On the other hand, it is necessary to ensure required rate of ventilation air.

According to building code SP 253.1325800.2016 “High-rise buildings utilities”, air mode calculation for high-rise buildings should take into account temperature and wind speed changes along the height of a building:

1. Reduction of outdoor air temperature for 1 °C every 100 meters. In mega-cities, such as Moscow, the intensity of heat islands provides a major impact on air temperature distribution. Vertical
proliferation of heat island thermal impact is manifested up to 500 meters in daytime and 100 meters in nighttime [8]. Monograph [9] contains the results of comparison climate parameters in mega-cities and suburban areas: in a cold period of a year air temperature differences at an altitude of about 150 meters exceed 1°C. In view of the above, reduction of outdoor temperature in calculation of air mode was not taken into account in this article.

2. Estimated wind speed should be determined taking into account the speed change coefficient, \( \xi \), according to the height of the building (Table 1).

| Building height | 2         | 2.5       | 3         | 4         | 5         | 6         | 7         | 8         | 10        |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 10              | 1.0       | 1.0       | 1.0       | 1.0       | 1.0       | 1.0       | 1.0       | 1.0       | 1.0       |
| 50              | 2.3       | 1.8       | 1.8       | 1.5       | 1.4       | 1.4       | 1.3       | 1.2       | 1.2       |
| 100             | 2.8       | 2.4       | 2.2       | 1.9       | 1.8       | 1.7       | 1.5       | 1.4       | 1.2       |
| 150             | 3.2       | 2.8       | 2.5       | 2.1       | 2.0       | 1.8       | 1.7       | 1.6       | 1.4       |
| 200             | 3.5       | 3.0       | 2.7       | 2.4       | 2.1       | 2.0       | 1.8       | 1.7       | 1.4       |
| 250             | 3.8       | 3.2       | 2.8       | 2.5       | 2.3       | 2.1       | 1.9       | 1.8       | 1.5       |
| 300             | 3.8       | 3.4       | 3.0       | 2.6       | 2.4       | 2.2       | 2.0       | 1.9       | 1.6       |
| 350             | 4.0       | 3.4       | 3.0       | 2.6       | 2.4       | 2.3       | 2.1       | 2.0       | 1.7       |
| 400             | 4.0       | 3.4       | 3.2       | 2.8       | 2.5       | 2.3       | 2.1       | 2.1       | 1.8       |
| 450             | 4.0       | 3.6       | 3.2       | 2.9       | 2.6       | 2.4       | 2.2       | 2.2       | 1.8       |
| 500 and higher  | 4.0       | 3.6       | 3.2       | 2.9       | 2.6       | 2.5       | 2.3       | 2.2       | 1.9       |

However, numerous studies presented different calculation methodology, namely power-law distribution [10-12]:

\[
\bar{v}_z = \left( \frac{z}{h} \right)^m \quad (1)
\]

\( \bar{v}_z \) – average wind speed at the altitude considered (\( z \)), m/s;
\( \bar{v}_h \) – average wind speed, m/s.
\( m \) – power index, which is a complex function of climatic characteristics and terrain.

To indentify the impact of wind pressure changing on the infiltration rate and air exchange in dwelling, air mode of a high-rise building has been calculated.

2. Calculation methods

Research covered section of 26-storey residential building (25 floors with dwellings) with height 81.2 meters and natural ventilation system. There are three apartments on each floor. Supply of outdoor ventilation air is carried out through turning-flap window opening with cross-section 0.231 m from one living room. The exhaust air is removed through ventilation grids by vertical duct from each apartment, connected to the main ventilation channel. Apartments on 25 and 26 floors are ventilated by separate ventilation systems with individual ducts.
Calculations were made for a cold period of a year (heating season): outdoor air temperature – 25°C and wind speed 2 m/s. Taking into account the fact, that the most of the time windows are closed and aeration lasts for a few minutes, it was decided to make calculation for different modes: with opened and closed ventilation openings.

Air mode of a building is a combination of several factors, which affect the process of air exchange in separate premises through filtration, posed under wind pressure, temperature difference and operation of ventilation systems. All premises are connected by stairwell, elevator lobby, ventilation systems and air-permeable openings [13-19].

Building is a complex aerodynamic network. Air movement occurs under pressure difference inside the building. There are two main equations for description of air mode of a building [18-20]. One of them is Kirchhoff's First Law: total airflow rate thought air-permeable elements equal to zero. The second is Bernoulli equation, showing dependence of pressure losses on airflow rate thought air-permeable element.

Whole building is separates into a several connected schemes (vertical apartments, main corridor, stairwell and elevator lobby), that are calculated individually. Computation of scheme associated with the other part of a building (vertical of main corridors, stairwell and elevator lobby, for example) is carried out as a last resort. Internal pressures in premises and airflow rate though air-permeable openings (formula 2 and 4) and ventilation systems (formula 5) are determined by equations:

\[ G_o = \left( \frac{|P_o - P_{out}|}{S_o} \right)^{\frac{1}{r}} \cdot \text{sign}(P_{in} - P_{out}) \]  
(2)

\[ P_{out} – \text{total excessive external pressure in the center of air-permeable element, Pa;} \]
\[ P_{in} – \text{indoor pressure, Pa.} \]
\[ r – \text{filtration coefficient (3/2 – for windows, 2 – for doors);} \]
\[ S_o – \text{resistant characteristic of air-permeable opening, Pa/(kg/h)^2:} \]
\[ S_o = 10 \cdot \left( \frac{R_o}{F_o} \right)^{\frac{1}{2}} \]  
(3)

\[ R_o – \text{airflow resistance of air-permeable opening, (m^2·h)/kg, with pressure difference between both sides of air-permeable element equal 10 Pa;} \]
\[ F_o – \text{area of air-permeable opening, m}^2. \]

Air flow rate through the open window:
\[ G_w = 3600 \mu_w A_w \sqrt{2 \rho (P_{out} - P_{in})} \cdot \text{sign}(P_{out} - P_{in}) \]  
(4)

\[ \mu_w – \text{discharge coefficient of air-permeable opening.} \]

Air flow rate in exhaust ventilation systems:
\[ G_i = \left( \frac{|P_e - P_b|}{S_i} \right)^{\frac{1}{2}} \cdot \text{sign}(P_e - P_b) \]  
(5)

\[ P_e, P_b – \text{air pressure in the beginning and the end of calculated part of ventilation network, Pa;} \]
\[ S_i – \text{resistant characteristic of calculated part of ventilation network, Pa/(kg/h)^2:} \]
\[ S = \frac{\lambda \cdot l + \sum \zeta}{2 \cdot f^2 \cdot \rho \cdot 3600} \]  
(6)

\[ \lambda – \text{hydraulic friction coefficient;} \]
\[ d – \text{equivalent diameter of ventilation duct, m;} \]
\[ l – \text{length of ventilation duct, m;} \]
\[ \zeta – \text{local resistance coefficient;} \]
\[ f – \text{cross section area of element, m}^2; \]
\( \rho \) – air density, kg/m\(^3\).

External pressure in the center of air-permeable element, \( P_{\text{tot}}^{\text{out}} \), Pa, includes wind and gravity components, as well as internal gravity pressure, which is put with external pressure [21], because it makes calculations of indoor pressure of premises much easier [13, 22, 23]:

\[
P_{\text{tot}}^{\text{out}} = g(H-h)(\rho_{\text{out}}-\rho_{\text{in}}) + \left( C_d^o - C_a^o \right) \frac{v^2}{2} \rho_{\text{out}} k
\]

\( H \) – distance between suspended zero to earth level, m;
\( h \) – distance between center of air-permeable element to earth level, m;
\( \rho_{\text{out}} \) – external air density, kg/m\(^3\);
\( \rho_{\text{in}} \) – ambient air density, kg/m\(^3\);
\( C_d^o, C_a^o \) – aerodynamic coefficients [21], that means a part of static pressure, formed on each façade of a building because of wind pressure;
\( v \) – wind speed on a building façade [23, 24], m/s;
\( k \) – coefficient, which takes into account the difference of wind pressure on the height of a building.

### 3. Results and discussions

Calculations were conducted for three different options: excluding the impact of wind speed changes along the height of a building (line 1), with power-law method (line 2) and speed change coefficient (line 3). The graph presents the results of air mode calculation for the apartments on the upwind side of a building with opened (left) and closed (right) turning-flap window (Figure 1).

![Figure 1](image)

Figure 1. Supply air flow rate for the apartments on the upwind side of a building with opened (left) and closed (right) turning-flap window.

In the case when the turning-flap window is opened supply air flow rate increasing with the height of a building. This growth is particularly evident in calculations based on speed change coefficient (line 3). The obtained airflow rates through open turning-flap window exceed sanitary requirements. Therefore in case of high-rise buildings it is necessary to use controlled valves for supply ventilation.
When the turning-flap window is closed, supply airflow rate decreases with the height of a building, despite increasing wind speed.

4. Conclusions
Results of calculations based on the method of speed change coefficient provide inflated supply airflow rate incoming thought air-permeable openings thereby contributing to increased energy consumption of heating system. This factor will be a reason of “over-heating” in building, causing deterioration of internal microclimate quality.

Comparing results of calculations using power-law method and excluding the impact of wind speed changes along the height of a building shows that consideration of the impact of changing wind speed with the height of a building is negligible on supply airflow rate for buildings lower than 80 meters.

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