Air movement processes in living rooms with windowsill supply air valves

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Abstract. The main issue highlighted in the given paper is deviation of microclimate parameters from regulatory values due to improper distribution of air flows in living rooms of blocks of flats. The present work is aimed at obtaining a working mathematical model of natural ventilation system operation, and its further studying for optimization or modernization. The analysis of regulatory documents, research works of national and foreign scientists, developments in the field of natural ventilation and ventilation of residential buildings in general, as well as specific field experiments describing or mentioning similar problems has been carried out. The author's mathematical model of air exchange in the living room has been presented and analyzed. The boundary conditions in the mathematical model were set as air flow rate and air temperature, and the temperature on the surface of the heater. The features and patterns of air flow distribution inside the room were determined, obtained as a result of mathematical modeling. The distributions of air velocity in the volume of the room were given. Similar problems were indicated for premises of residential buildings of a different functional purpose. Amendments to the existing standards, as well as technical solutions were proposed. Keywords: air exchange, mathematical modeling, aerodynamics, natural ventilation, residential buildings.

1 Introduction

Air supply devices appeared in blocks of flats due to the increase in building air tightness driven by installation of plastic windows. The need for supply air in order to compensate for the amount removed from kitchens and bathrooms began to manifest itself in the form of increased humidity in the rooms and, as a result, a lot of problems caused by moisture condensation on the inner surfaces of windows, the appearance and growth of mold and fungus in bathrooms [1]. Controlling excess moisture in indoor air is not the only objective of ventilation. Suspended dust particles also have a negative impact on residents and can cause allergic reactions and cardio pneumatic diseases. The regulatory documents specify the relative humidity and air velocity inside the room, also for the purpose of dust control in rooms. However, it is often not possible to ensure the relative humidity and air changeability in the entire volume of a residential building [2]. The formed dead-air spaces inside the buildings can be easily detected by the accumulation of settled dust.

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Air infiltration valves are used to ensure the required air exchange values during the cold period, when ventilation of the room by means of opening windows is undesirable [3]. Moreover, the formation of dust inside the room is particularly intense during the cold season, when moisture content of the outside air is minimal. In this case, the relative humidity of the indoor air becomes lower than the required value [4, 5].

Heating systems like heat insulated flooring help to solve the problem of dust in the air by creating upward air flow due to convection, thus the air in the room is moving actively and mixing and dust particles are removed from the room by the exhaust ventilation system [6, 7]. However, such systems are not used in multi-storey residential buildings for a number of reasons, and their independent alteration is illegal. The use of electricity for floor heating leads to significant operational costs [8].

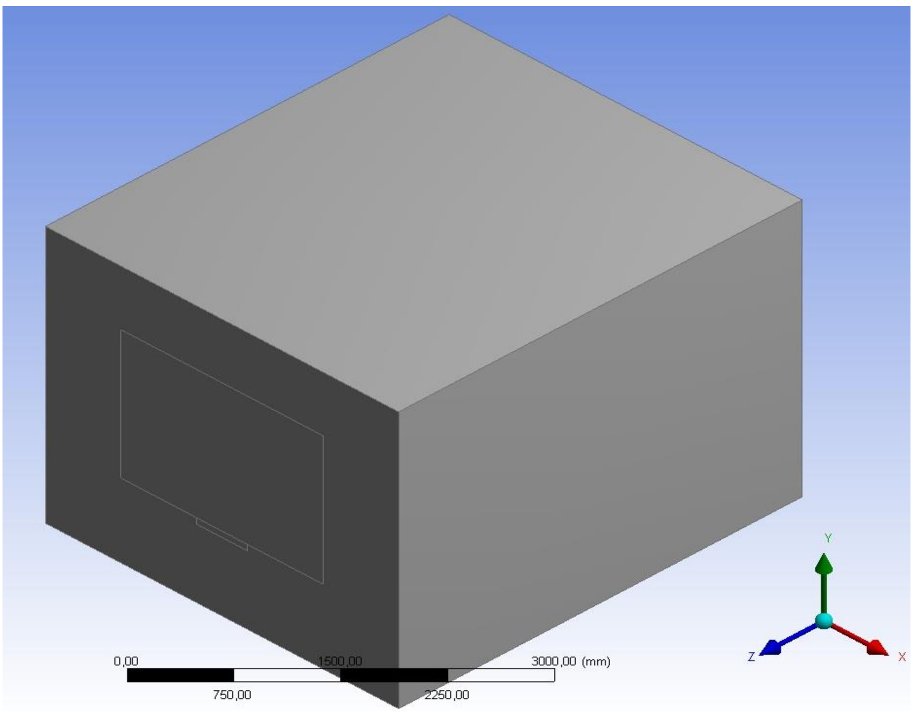

Fig. 1. General 3D-model illustration.

Understanding and analysis of air distribution inside the rooms of residential blocks of flats with windowsill supply air valves requires building a mathematical model.

The given study is aimed to identify the peculiarities of air distribution inside a room with the air supply device during the cold season. A three-dimensional model of a room with a windowsill supply air valve and a working heater has been introduced (Fig. 1).

2 Model Description

Mathematical model of natural ventilation is required for simulation of testing and further system modernization [9]. In fluid and gas dynamics the model of air movement is described by Navier-Stokes equations, convection is described by Boussinesq model. In ANSYS Fluent, the Spalart-Allmaras model (SA model) is used as the equation solver during the process simulation, since it is suitable for the selected mesh quality and low indoor air velocity [10]. When using this linear turbulence model, it is assumed that the so-called generalized Boussinesq's hypothesis [11] and Fourier's law are valid, as well as the values of the molecular components of the stress tensor (Pa), and the heat flux density vector (W/m²):

$$\tau_t = 2\mu_t\left(-\frac{1}{3}\mathrm{I}\nabla\cdot\vec{u}\right)+\frac{2}{3}k\mathrm{I},\ \vec{q}=-\lambda_t\nabla \quad (1)$$

where μt - is turbulent viscosity (Pa·s); S - strain velocity tensor (m/s), k - turbulent kinetic energy (J); λt - turbulent heat conduction (W/(m·K)); I - identity tensor; T - temperature (K); $\vec{u}$ - velocity vector of mean flow (m/s).

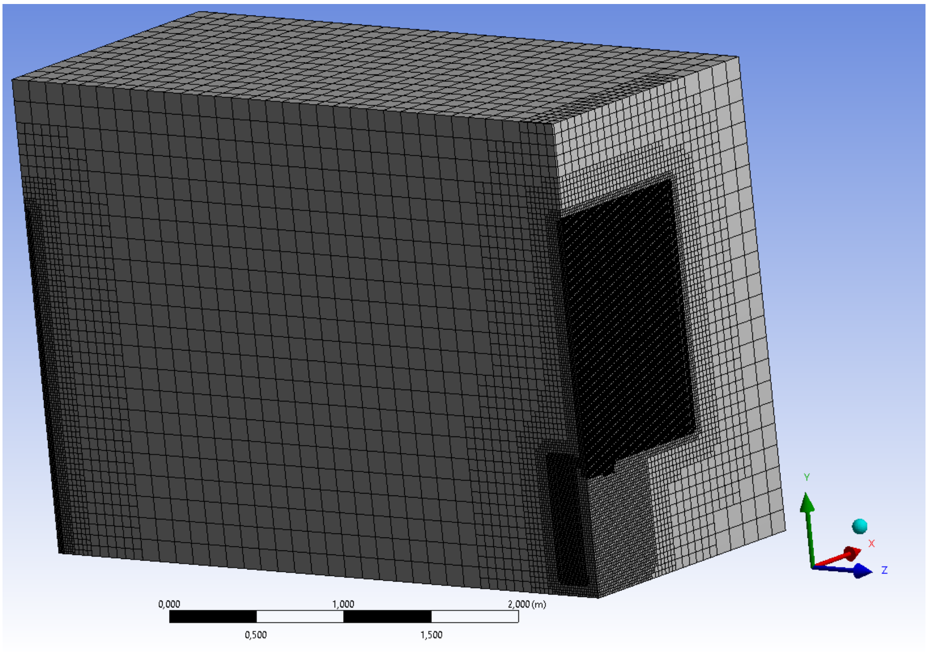

Fig. 2. Density of pace of model spacing.

Turbulent heat conduction is expressed in terms of turbulent viscosity using the ratio:

$$\lambda_t = \frac{C_p\mu_t}{Pr_t}, \quad (2)$$

where Prt - is the turbulent analogue of Prandtl number, Cp - is molecular heat capacity in isobaric process, J/(mol·K).

The properties of the mesh (Fig. 2):
the minimum pace of model spacing – 0.001 m;
the maximum pace of model spacing – 0.13 m;
the number of nodes – 1160744 pcs;
the number of elements – 1039844 pcs.

2.1 Initial Data

Overall dimensions of the building axbxh: 3.5x4.0x2.8 m.

The value of air flow was determined according to the standard air flow value for bedrooms, living rooms, children's rooms at the total floor area of a flat per person of less

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than 20 m2, and it was set as 3 m3/h per 1 m2 of floor area, as specified in the regulatory documents. Thus, following this condition the value of air flow rate is 42 m3/h.

The temperature of inlet (supply) air is accepted as equal to - 10 ºC.

The temperature on the surface of a heater is +60 ºC.

3 Results of Simulation

At the end of simulation of the ventilation system operation, velocity distributions inside the building were obtained (Figs. 3-6).

Velocity distributions in longitudinal section (Fig. 3):

- the maximum speed of air movement was observed along the exterior wall ~0.8 – 0.9 m/s;
- along the plane of the ceiling at the height of from 1.5 to 2.5 m ~0.1 m/s;
- along the plane of the floor at the height of up to 0.2 m ~0.1 – 0.2 m/s;
- in the service area of the room the velocity of air movement, below 1.5 m from the floor ≥0.08;
- the middle floor (the third one) has the minimum air flow rate;
- the lower floors (the first and the second) have the average air flow rate due to great aerodynamic resistance and pressure difference.

Velocity distributions in horizontal planes (Figs. 4, 5) within the boundaries of the service area have the velocities corresponding to the ones in the longitudinal section of the building. Velocity in the corners and next to the walls is minimum.

At the boundary of the service area (0.5 m from the wall) by the exterior wall (Fig. 6) the air movement velocity is ~0.08 – 0.15 m/s.

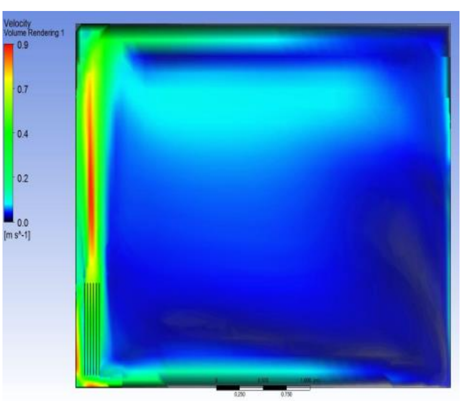

Fig. 3. Velocity distributions in section through the center of the building from the supply valve to the door.

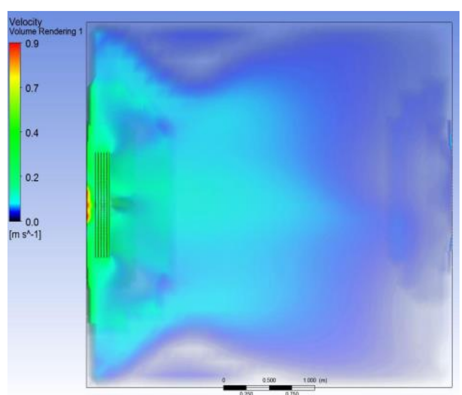

Fig. 4. Velocity distributions at the height of 0.2 m from the floor.

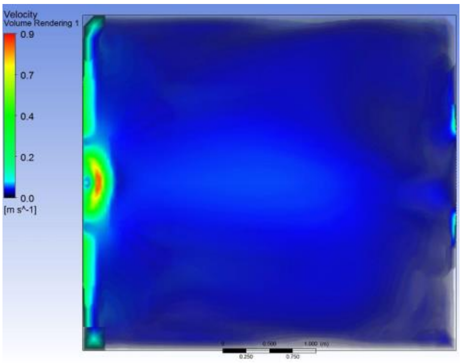

Fig. 5. Velocity distributions at the height of 1.2 m from the floor.

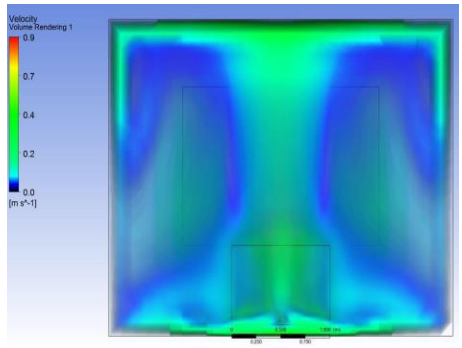

Fig. 6. Velocity distributions along the wall with the supply valve at the distance of 0.5 m.

4 Results

The results of study correspond to the actual distributions of velocities in the volume of the building; dead-air spaces, distributions of velocities along the height, the location of convective flows near the operating heating device confirm the objectivity of the obtained mathematical model.

The data on the minimum air flow rate in the human breathing zone given in foreign regulatory documents (see Table1) have values which are several times less than the Russian ones [12, 13]. These data take into account the sanitary and epidemiological aspects of the issue, including also relative humidity, however, at such air flow rate, it is impossible to ensure the necessary conditions in the entire space of the room. Russian standards meet sanitary norms to a greater extent, but, as the model shows, the conditions for the necessary air exchange are not maintained throughout the entire space of the room. None of the currently existing standards takes into account the placement of furniture, which affects both the volume and the distribution of airflows in the space of the room. Thus, the optimal solution will be to divide the living space into functional zones and reduce the regulated minimum air consumption, which will lead to a directly proportional reduction in heat consumption for heating the supply air.

Table 1. Regulatory values of air exchange in different countries.

Country	**Regulatory value of air exchange in residential buildings**
Russia	3 m^3/h per 1 m^2 of living floor area
	30 m^3/h per person, but not less than 0.35 h^{-1}
The USA [12]	The minimum value (in the breathing area) 2.5 l/s per person (9 m^3/h) or 0.3 l/s per 1m^2 (1.08 m^3/h)
	For private single-family and blocks of flats 0.35 h^{-1}, but not less than 7.5 l/s (27 m^3/h) per person
European countries [13]	Standard 0.3 l/s per 1 m^2 (1.08 m^3/h) Comfort 0.4 l/s per 1 m^2 (1.08 m^3/h)

Most people choose the space close to the window as their working space since it has the best natural lighting. Considering this fact, it is possible to divide the room into functional zones, one of which, the closest to the window, will be a living zone, while the rest of the room can be used for placement of furniture, household appliances and other needs [14].

Along with that, the reduced air consumption will enable to increase the heat transfer coefficient of the inner surface of the exterior wall by reducing the velocity of air movement. Thus it will reduce heat losses.

Less air flow rate with low moisture content enables us to reach the regulatory values by means of water exhalation with people's breathing and other processes.

Regarding the supply devices, the optimal solution would be to use a valve built into the design of the window frame, which has a suitable, adjustable airflow and a jet directed into the room [15]. They are cheaper and easier to maintain and install.

In the future, it is also necessary to study the distribution of airflows in flats in general, especially in bathrooms and kitchens, where the concentration of harmful substances of pathogenic bacteria and microorganisms in dead-air spaces or under improper air movement can lead to diseases and deterioration of well-being of residents. An example of improper distribution of airflows can be the placement of a single exhaust ventilation grill in a combined bathroom in the wet zone of a bath or a shower, and not close to the toilet. In this case, all air pollutants from the bathroom and corridor reach maximum concentration in the zone of maximum temperature and humidity.

5 Conclusions

Resulting from mathematical simulation and analysis of velocity distributions the following conclusions can be drawn:

- when designing supply ventilation system in residential buildings the energy-efficient solution will be conventional division of space into functional zones considering the placement and sizes of the furniture;
- updating of the current regulatory documents is required, along with the reduction of the regulated values of air exchange up to the minimum level as set in the world practice;
- reduction of air supply rate will enable to increase the relative humidity up to the regulatory values.

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