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DESIGN OF NATURAL VENTILATION SYSTEM TO ENSURE STANDARD AIR CONSUMPTION

Abstract. Total losses of aerodynamic pressure in an exhaust ventilation system have been determined in two ways: by calculation of the air regime of the building as a whole, together with the ventilation systems serving the building, and the aerodynamic calculation of a system isolated from the building. The calculation of the building air mode has been carried out by the iterative method of solving the system of equations of air balances of all premises of the building and units of all ventilation systems. Ventilation systems that provide standard air consumption for all systems on all floors of the building have been subject to an analysis. The found relations between aerodynamic resistances of the floor branch of such an exhaust ventilation system from the exhaust grate to the common trunk and the trunk itself from the floor branch to the mouth of the exhaust shaft allowed us to assert that an increase in the air rate to the upper normative permissible air boundaries is possible, since despite the increased aerodynamic resistance in the trunk of the system, pressure losses in the floor branches of the upper floors are reduced due to ejection. The article provides an analysis of the natural ventilation system with the external air inflow through the swing-flap window and the supply valves. The calculations have shown the feasibility of using a supply opening, the aerodynamic resistance of which is close to zero in the calculated external ventilation conditions. In addition, the supply device must be adjustable, so that when the outside air temperature lowers and, consequently, the available pressure of the ventilation system increases, its cross-section may be reduced to avoid an unnecessarily big flow of the supply air. An example of such a supply device can be a swivel-flap window with adjustable opening. Aerodynamic calculations of natural ventilation systems, which are isolated from the building, may be provided only at an almost zero inflow aerodynamic resistance to the sufficient air flow in the ventilation design external conditions.

Keywords: the air balance of the room, the system of equations, pressure loss, air rate in the ducts, the supply opening, the cross section of the ducts

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КОНСТРУИРОВАНИЕ СИСТЕМЫ ЕСТЕСТВЕННОЙ ВЕНТИЛЯЦИИ ДЛЯ ОБЕСПЕЧЕНИЯ НОРМАТИВНЫХ РАСХОДОВ ВОЗДУХА

Аннотация. Суммарные потери аэродинамического давления в вытяжной системе вентиляции определены двумя способами: расчетом воздушного режима здания в целом вместе с системами вентиляции, обслуживающими дом, и аэродинамическим расчетом изолированной от здания системы. Расчет воздушного режима здания выполнен итерационным методом решения системы уравнений воздушных балансов всех помещений здания и узлов всех систем вентиляции. Рассматривались системы вентиляции, обеспечивающие нормативные расходы воздуха по всем системам на всех этажах здания. Найденные соотношения между аэродинамическими сопротивлениями поэтажного ответвления такой системы вытяжной вентиляции от вытяжной решетки до общего ствола и самого ствола от поэтажного ответвления до устья вытяжной шахты позволили утверждать, что увеличение скорости движения воздуха до верхних допустимых нормами границ возможно, так как при этом, несмотря на повышенные аэродинамические сопротивления в стволе системы, снижаются потери давления в поэтажных ответвлениях верхних этажей за счет эжекции. В статье рассматривается система естественной вентиляции с притоком наружного воздуха через поворотно-откидную створку окна и через приточные клапаны. Расчеты показали целесообразность применения приточного отверстия, аэродинамическое сопротивление которого в расчетных для вентиляции наружных условиях приближается к нулю. Кроме того, приточное устройство должно быть регулируемым, чтобы при понижении температуры наружного воздуха и, следовательно, увеличении располагаемого давления для системы вентиляции уменьшить свое сечение для недопущения излишне большого расхода приточного воздуха. Примером такого приточного устройства может служить поворотно-откидная створка окна с регулируемым открытием. Аэродинамический расчет изолированных от здания систем естественной вентиляции допустим только при практически нулевом аэродинамическом сопротивлении притоку достаточного расхода воздуха в расчетных для вентиляции наружных условиях.

Ключевые слова: воздушный баланс помещения, система уравнений, потери давления, скорость воздуха в воздуховодах, приточное отверстие, поперечное сечение воздуховодов

Relevance of the research subject

The most important task of aerodynamic calculations of natural supply and exhaust ventilation systems is the choice of cross sections of ventilation ducts [1].

An exhaust system is the main part of natural ventilation systems of residential buildings. Till the 2000s, when "tight" windows made the greatest part in this country, aerodynamic calculations of such systems were carried out on the assumption that there is no aerodynamic resistance between the external supply air compensating the exhaust and the exhaust grille [2]. The available pressure from the grill to the mouth of the exhaust shaft was compared with the pressure losses just within this particular tract. Since at that time the windows were sufficiently breathable that, as it had been believed, it was possible to neglect their aerodynamic resistance to the supply air, this resistance was not taken into account [3].

With the advent of "tight" windows, it became clear that the aerodynamic resistance of the supply openings can play a significant role in the formation of the exhaust air consumption through a natural ventilation exhaust system. Therefore, both the design recommendations [4] and the research papers [5, 6] started to include the losses for the air passage through a supply opening in the aerodynamic pressure losses taken into account. Moreover, the supply opening has been considered as the beginning part of the ventilation supply and exhaust pipelines.

The problem study level

There are many works that considered the composition of a natural exhaust ventilation system as a part of the overall air regime of the building. It took into account all air flows therein: through windows and supply valves, the air migration flows between the rooms, including stairwells and elevator shafts, the air flows complicated by passage through tees and crosses, in the ventilation tract of the exhaust system itself [7–23]. In all these works, the authors used their calculation programs developed on PC or hydraulic integrator. The analysis of the problem statement in the listed works shows clearly that the supply opening is not a direct continuation of the ventilation pipeline. Along with other breathable elements of the room, the air inlet serves as one of the sources (or drains) of the air flow participating in the air balance of the room and forming the pressure inside the room. It is from this pressure that the available pressure acting on the exhaust grill of the aforementioned room depends.

In all of the above works, the tasks set in them were successfully solved, but we do not know any comparison of the ventilation pipeline air flow consumptions to be got by calculation programs and an engineering analysis.

The purpose of the article is to solve two problems. First, it is necessary to determine the ratio between the aerodynamic resistances of the floor branches and sections of the trunk from the place of tapping into it of each branch to the mouth of the exhaust shaft, removed through each exhaust grate, providing normative air consumption. Secondly, it is necessary to assess the impact of failure to take into account the pressures in the premises in the aerodynamic calculation of the exhaust system.

Method of the room air mode calculation

Calculations of the room air exchange in a multi-storey building can be performed only taking into account the topology of the building, because the premises are connected by the air permeability of structures between them, as well as ventilation systems or stair and elevator halls [7–16]. A building is a complex aerodynamic pipeline work. The room air exchange in the building occurs under the influence of the difference of full excess pressures formed on each air-penetrable element (hole) between the rooms, including the elements of ventilation systems. The calculation of the total overpressure formed under certain weather conditions in each room in the general case is a solution of a system of the air balance equations of each room and each node of ventilation systems. The number of equations of the system under calculations is equal to the number of rooms in the building in sum with the number of nodes of ventilation systems. Moreover, when describing the air balance of each room or node of the ventilation system, use is made of two types of equations [7–16]. The first of them is the Kirchhoff's first law, which states that the sum of the air consumption through all air-permeable elements of the room or node in question must be zero. The second is the Bernoulli equation, which is a form of the energy conservation law and describes the dependence of pressure losses on the consumption of air passing through the air-penetrable element.

As boundary conditions, the outdoor air pressures are set for each air-permeable element connecting any room with the outdoor environment: windows, entrance doors, etc. The external pressure consists of the gravitational pressure, which decreases with increasing height of the hole above the ground, and the wind pressure, which depends on the wind rate, increasing with height, as well as the wind direction, forming the windward, leeward and side facades of the building [16]. In addition, at it has been suggested by V.V. Baturin [8], for buildings with approximately the same temperature in all rooms, a variable gravitational component of the internal pressure is applied to the external pressure with a minus sign. The external pressure P_{ext}, Pa, thus takes the form of:

$$P_{ext} = g(H - h)\rho_{ext} + (C - C_3)\rho_{ext}\, k \cdot V^2/2, \qquad (1)$$

where: g — gravitational acceleration, m²/s; H — the height of the building from the ground to the top point, m; h — height above ground of the center of an air-permeable element, m; ρ_{ext} is the outdoor air density (subject to the air temperature within the considered time period), kg/m³; C, C_3 — aerodynamic coefficients the design air-permeable element at the design façade and on the leeward side; k — the coefficient accounting for changes in wind pressure depending on the height above ground and the type of the terrain; V — wind rate, m/s.

As a result of the specified methodical pattern, i.e. removal of the indoor pressure variable part to the external one, the pressure of each room P_{int}, Pa, has a constant value by height that facilitates the solution of the system of equations. As a usual, a point model of the building rooms is subject to consideration, where the full overpressure of each room is applied in the centre of the room.

In addition to the meteorological factors, in the Bernoulli equation it is required to specify the air permeability of the elements, which is described by the resistance characteristics S, Pa/(kg/h)² of the elements. The S values are constant values for most openings and depend on the air consumption only for tees of ventilation systems.

Object of research

For a fragment of the plan of the building under investigation see Fig. 1. On each residential floor (starting from the 2nd) there are three apartments: two 2-room flats: one with one-way orientation (apartment 1), and the other with two-way orientation (apartment 2), as well as one 3-room flat with the windows overlooking two opposite facades (apartment 3). The section has a lift hall with passenger elevators, from which on each floor there is an exit to the balcony for passage to an isolated evacuation smoke-free staircase and an inter-apartment corridor. The doors of the three apartments and the stair-

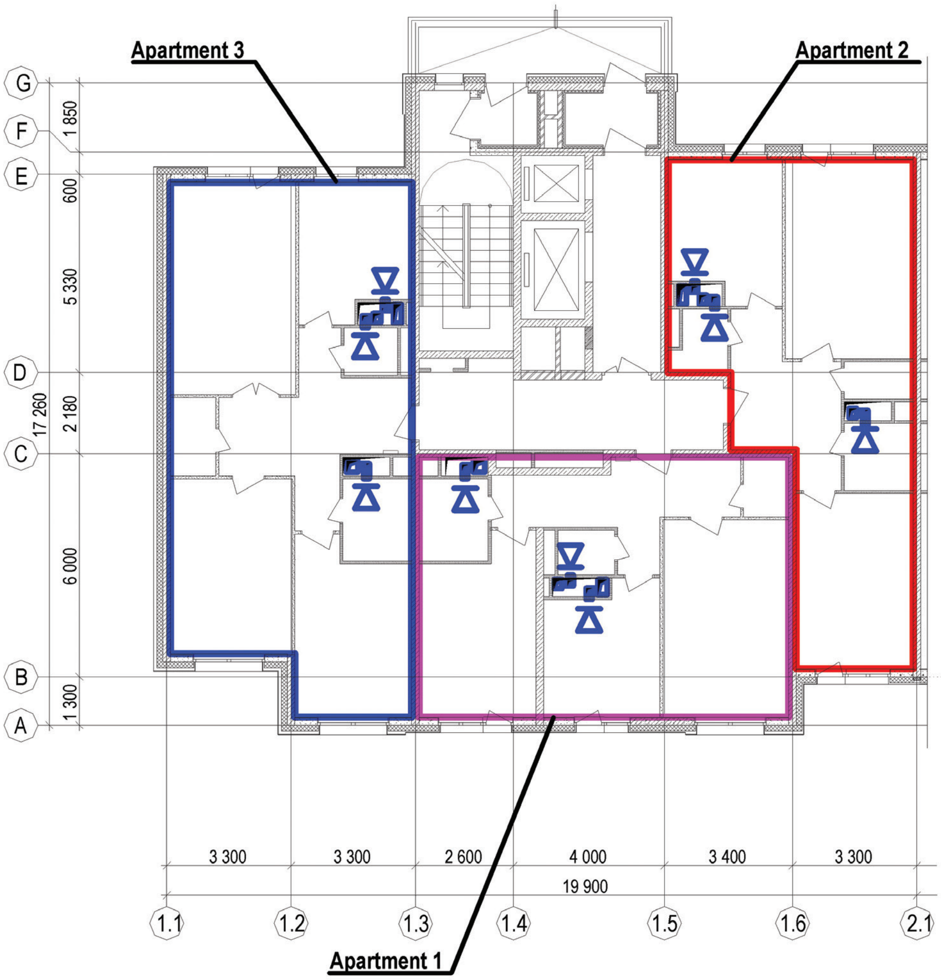

Fig. 1. Fragment of the plan of a typical floor in a multi-storey residential building

case-lift hall on each floor open into the mentioned one common corridor.

The house provides a natural system of supply and exhaust ventilation, which is made in the form of three independent systems that remove exhaust air from kitchens, toilet and bathrooms. Each of the three systems is designed as a prefabricated channel (trunk) and floor branches (satellites). Additional aerodynamic drags have been enables by inserts to the exhaust grilles. At the same time, the resistance characteristics of the floor branches, together with the exhaust grids, decreased from the first floor to the last one.

The houses have an unheated attic, 3 m high, which transits insulated exhaust shafts, increasing the available pressure for all floors of the building, including the upper floors. Moreover, the upper two floors have floor-by-floor channels, brought into the atmosphere independently without joining the common trunk. The construction shafts, in which vertical prefabricated channels are located, are brought above the level of the roof under a hood.

First, let's define the tasks of a ventilation system. There are two approaches to the problem solution. There are those, who think that in a residential building the required air exchange should be provided at closed supply openings. These requirements refer us to the windows that were used up to the 2000s. Such windows do not allow to regulate the fresh air consumption during the periods, when the apartment inhabitants, for example, are absent in this apartment. It makes impossible the power saving when heating the "extra" supply air.

This article supports the point of view, that provision of a standard air exchange of an apartment or its separate rooms is obligatory only during the time when the consumer considers it necessary. At all other times, the supply openings should be closed, and the air penetration through them should be minimized. In this case, the tightness of the supply holes in the closed state should not be absolute, that is, they should not be sealed. The slits in the supply openings are designed to provide the minimal air exchange, eliminating the air stagnation in the apartment, when its inhabitants are absent for a long period of time. The apartment shall be ventilated through the open flaps of the supply openings.

This study has considered the buildings with the air inflow through the opening swing-flap windows and the air supply valves. In addition, the study has been made of the apartment air exchange with closed windows.

First of all, the attention shall be paid to the area of the supply holes. The AERECO valves have an area of 0.0036 m^2 and are installed in each living room. When a swivel-hinged window sash is open at an opening angle of 30 degrees, the area of the open part makes 0.231 m^2 and when a swivel-hinged window sash is open at an opening angle of 3 degrees, the area of the open part makes 0.024 m^2. But, if the apartment airing through the opening sashes enables the change of the supply opening area during the year, in a case of the valves a greater inflow area is possible only after having established additional valves in advance.

The following requirements have been respected when selecting cross-sections of the ducts: the aerodynamic resistance of the floor branched offsets should exceed the aerodynamic resistance in the collecting channel; the air rate in the exhaust ducts on the flow way is increasing; in the final sections of the network the rate does not exceed 2 m/s.

The configuration of natural ventilation systems has been selected taking into account the existing recommendations in such a way, that under the ventilation design conditions (the outdoor temperature +5 °C and the windless weather) in all apartments, the air exchange deviated from the design rule by no more than 1 m^3/h. In accordance with the normative documents 60 m^3/h of air should be removed from the kitchen and 25 m^3/h from the bathroom and the toilet.

Since in 19-storey houses with the air supply through the opening window sashes provision can be made of a larger inflow area than through the supply valves, to perform the investigation task the calculations of the buildings with the windows have enabled the find of smaller cross-sections of the air ducts than of the buildings with valves. Steel exhaust ventilation ducts have rectangular sections, gradually increasing from the lower floors from 200×250 mm to 350×400 mm on the 9^{th} to 17^{th} floors for the trunk serving the kitchens. The cross-sections of the trunks, which serve the toilets and the bathrooms, increase from 200×200 mm to 200×350 mm. The floor-to-floor branches of all systems have the same 150×150 mm section on all floors and adjustable exhaust grilles. In the building with the valves it turned to be impossible to provide such sections of air ducts to enable the standard normative air exchange of the apartments above the 10^{th} floor

This is despite the fact that the cross-sections of the ducts are much wider than in the house with opening windows: the cross-sections gradually increase from the lower floors from 400×500 mm to 800×800 mm on the floors from the 9^{th} to the 17^{th} for the trunk serving the kitchens. The cross-sections of the trunks serving the toilets and the bathrooms increase from 200×250 mm to 550×600 mm. The floor branches of the systems serving the kitchens have the same 150×150 mm cross-sections on all floors and adjustable exhaust grilles. The branches of systems for toilet rooms up to the 10^{th} floor have the sections of 100×150 mm, above — 150×150 mm.

Analysis of the got results

To identify the appropriate ratio of aerodynamic resistances of the floor branch and the prefabricated collecting ventilation channel from the tie-in of the branches to the mouth of the shaft, multivariate calculations were performed for buildings of different number of floors. Cross-sections of all floor branches were taken the same 150×150 mm. The tendency of the ratio changes with increasing the building floor number has been revealed. The variants of design of an exhaust ventilation system, in which the exhaust air consumption is close to standard values on all floors of the building, have been considered. First, the ratio of these values in one building decrease from the lower floors to the upper ones. The decrease is the more, the higher the building. Secondly, while the exhaust air rate is the same in the trunk on the upper floors in the buildings of different number of storeys, the ratio of the above values increases with increasing number of the storey. At higher air rates in the trunk on the upper floors the ratio values decrease, keeping the tendency to decrease from the lower floors to the upper ones. For confirmation of the described trends see the Table 1.

It is interesting that with fully closed windows of the apartment, in which the inflow in the ventilation mode is provided through the open sashes, through the windows with a total area of 8.4 m^2 in the apartment with a resistance to air permeability of the window of 0.9 $m^2 \cdot h/kg$ at $\Delta P = 10$ Pa in the ventilation design outdoor conditions, the flow rate varies from 21.1 m^3/h on the ground floor to 9.5 m^3/h. Under the design heating outdoor conditions, these consumptions are respectively equal to: 44.1 m^3/h and 19.9 m^3/h. It should be noted that there are no norms for the air exchange in an apartment in the absence of residents there. The AVOK rules for the standardized air exchange [24] provide minimum requirements for kitchens and sanitary units when they are not in use. However, these standards are rather aimed at removing residual odors in the apartment and therefore seem to have too high values for the case of a long-term absence of the residents.

Through the supply holes the supply air flows into the apartment and is then removed through all exhaust systems. The inflow holes of the smaller area create higher aerodynamic inflow drags. Thus, the windows sashes, being open at 30 degrees at standard air consumption in the calculated outdoor ventilation conditions create the aerodynamic resistance close to 0.01 Pa, while the aerodynamic resistance of the supply valve at standard consumptions is from 21.5 Pa on the lower floors to 4.5 Pa on the upper floors. As a result, the available pressure is expended to overcome this resistance and it is necessary to provide larger sections of air ducts. But even the above sections of the ducts do not provide the normative exhaust consumptions on the floors above the 10th, which by the 17th floor fall to 14 m^3/h in the toilet systems and to 39.5 m^3/h in the kitchen systems.

The assessment of the impact of the refusal to take into account the room pressures in aerodynamic calculations of the natural ventilation exhaust system has been performed by comparing the results of multivariate analysis of the building air mode on a computer and the manual calculation. The PC calculation analysis has been performed according to the program developed by us [25–27], and the manual aerodynamic calculations have been performed according to the generally recognized method of the building isolated system [3]. The options with the inflow through the opening rotary sash of a window and through the inflow valve have been considered. The calculations have been performed for design outdoor ventilation as well as heating conditions. For some calculation results see the Table 2. The data of the Table 2 refer to the design outdoor ventilation conditions. The ventilation system, which removes air from the toilets and bathrooms, is located in an apartment with a two-way orientation, in one room of which one swivel-fold window is open at 30 degrees.

Since the nominal pressure at the mouth of the shaft is 0, the formed pressure in the apartment should be considered the available pressure for losses from the grid to the shaft mouth. The discrepancy between the values specified in columns 2 and 3 of Table 2 is explained by the accuracy of the PC air flow calculations in 1 kg/h. The discrepancy of the data given in the Table is within 3–9 %, which is an estimate of the accuracy of PC calculations.

Table 1

The Ratio of pressure losses in floor-to-floor branches and the exhaust system collecting duct of multi-storey residential buildings

Value denomination	Number of floors in the building			
	8 floors	12 floors	16 floors	18 floors
Exhaust system of the Toilet and Bath rooms				
Ratio of pressure losses in a branch and the trunk of the system	2.91–2.04	3.70–2.25	5.11–2.26	4.12–1.59
Exhaust air rate in the trunk upper part, m/s	1.4	1.39	1.39	1.58
Exhaust system of Kitchens				
Ratio of pressure losses in a branch and the trunk of the system	1.78–1.57	3.1–2.07	3.04–1.1	2.52–0.69
Exhaust air rate in the trunk upper part, m/s	1.6	1.36	1.67	1.9

Table 2

Floor-to-floor distribution of the aerodynamic pressure summary losses in the ventilation and pressure systems of the apartments

Floor	PC calculations of the air mode of the whole building		Manual calculations of an isolated system of natural exhaust ventilation		
	Summary pressure loss from the grille to the shaft mouth, Pa	Indoor pressure in the apartment, Pa	Available pressure, Pa	Summary pressure loss from the grille to the shaft mouth, Pa	Summary pressure loss from the outdoor environment to the shaft mouth, Pa
8-storey building					
1	19.60	18.59	17.43	17.24	17.25
2	17.70	16.59	15.43	15.33	15.34
3	15.58	14.59	13.43	13.44	13.45
4	13.54	12.59	11.43	11.38	11.39
5	11.42	10.58	9.42	9.47	9.47
6	9.30	8.58	7.42	7.46	7.46
7	6.39	6.57	5.42		
8	4.44	4.57	3.42		
12-storey building					
1	27.65	26.61	25.44	25.23	25.23
2	25.64	24.60	23.44	23.31	23.32
3	23.66	22.60	21.44	21.42	21.43
4	21.59	20.60	19.43	19.37	19.37
5	19.58	18.60	17.43	17.38	17.39
6	17.52	16.59	15.43	15.45	15.46
7	15.50	14.59	13.43	13.41	13.42
8	13.43	12.59	11.43	11.48	11.48
9	11.33	10.58	9.42	9.48	9.49
10	9.21	8.58	7.42	7.46	7.46
11	6.39	6.58	5.42		
12	4.45	4.58	3.42		
18-storey building					
1	39.91	38.62	37.45	38.15	38.15
2	37.97	36.62	35.45	36.47	36.48
3	35.99	34.62	33.45	34.20	34.21
4	33.98	32.61	31.45	32.48	32.49
5	32.07	30.61	29.44	30.53	30.53
6	30.04	28.61	27.44	28.56	28.57
7	28.06	26.61	25.44	26.59	26.60
8	26.07	24.60	23.44	24.63	24.64
9	24.03	22.60	21.44	22.66	22.67
10	21.99	20.60	19.43	20.67	20.68
11	19.95	18.60	17.43	18.66	18.66
12	17.88	16.59	15.43	16.61	16.62
13	15.82	14.59	13.43	14.67	14.68
14	13.72	12.59	11.43	12.66	12.67
15	11.59	10.58	9.42	9.43	9.44
16	9.43	8.58	7.42	7.44	7.45
17	6.39	6.58	5.42		
18	4.45	4.58	3.42		

The mismatch of the system available pressure in manual calculations and the apartment internal pressure in PC calculations can serve as an estimate of the accuracy of the isolated problem statement in manual calculations. Within the absolute value the above discrepancies make 1.2 Pa for all floors of houses of different storeys. However, since the magnitude of the losses themselves from the grid to the mouth of the shaft falls from the lower to the upper floors, the relative error increases from 3–6 % to 25.5 %. And the smaller relative differences on the lower floors belong to the taller buildings.

If we compare the total pressure losses got during PC and manual calculations, the differences of these values are within 1–2.5 Pa. The relative size of the discrepancy varies: in a 8-storey building — from 12 to 20 %, in a 12-storey building — from 8.7 to 19 %, in a 18-storey building — from 4.4 to 21 %. The smaller relative differences relate to the lower floors, and the larger ones to the upper floors.

It should be noted, that approximately the same estimates have been got by us in the calculations of other buildings and systems. Based on these results, it can be stated, that the approach adopted in the design practice to the aerodynamic calculation of natural ventilation systems, assuming an isolated position of the system from the building, is quite acceptable.

Conclusions

1. When the slits in the windows did not create significant resistance to the air inflow, the isolated aerodynamic calculation was justified. But even in those days there were many complaints about the ventilation of the upper floors of buildings. A major disadvantage of the old windows was the inability to reduce the infiltration of outside air when the inflow was excessive or not required at all. When equipping the buildings with tight windows, the question arose about the necessary aerodynamic resistance of adjustable supply devices. The article answers this question by stating the need to have a supply opening, the aerodynamic resistance of which in the calculated external conditions for ventilation approaches zero while ensuring the standard air consumption. With a decrease in the outside air temperature and, consequently, an increase in the available pressure for the ventilation system, the supply opening should be able to reduce its cross-section to prevent an unnecessarily large consumption of supply air. An example of such a supply device can serve as a swivel-flap window with adjustable opening.
2. The performed researches allow to assert that the isolated aerodynamic calculation of separate systems of natural ventilation is admissible only at practically zero aerodynamic resistance to the inflow of a sufficient air consumption.
3. Currently used supply valves, as a rule, do not have a sufficiently large live section for the passage of supply air. Their aerodynamic resistance should be taken into account in the aerodynamic calculation. When selecting a valve for installation, preference should be given to valves with as large a live section as possible. When equipping the building with supply valves, household fans should be equipped with exhaust ventilation systems on at least 4 upper floors.
4. When designing the ventilation piping work, it should be borne in mind that high speeds within the permissible operating range not only lead to an undesirable increase in the aerodynamic resistance of the system trunk, but also to the air ejection (suction) from the floor-to-floor branches, which improves the ventilation of the upper floors. This suction is evidenced by small values of the ratio of pressure losses in the floor branch to the pressure losses in the trunk from the branch and above on the upper floors of the building. In the future it is necessary to calculate values of ratios of the specified aerodynamic resistances at various exhaust air rates in an exhaust system trunk on the top floors of the building at various number of storeys of buildings and at observance of various standard air exchange at the design outdoor conditions.
5. The windows to be provided for the buildings, when closed, must enable the air permeability, which is sufficient to prevent the air stagnation in the apartment if its residents are absent for a long period of time. In the future, it is necessary to determine the apartment air exchange norms for such a case.

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