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Original Article

Smoke Ventilation Differential Pressure System

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Abstract *- This article reviews the basic principles of differential pressure system operation. The initial data, geometric characteristics, and parameters of the smoke ventilation systems are based on a modern residential building, based on which the calculation was made. The study resulted in the conclusions of the main provisions for the calculation and design of the differential pressure system, which is necessary for the safe opening of doors by people of different groups at the fire starting point. The article clearly shows the principle of drawing up a communication diagram and displays important aspects in calculating and selecting parameters for the fan. The calculations are based on the calculations of European colleagues who have already highlighted the problem in 2020. The entire methodology has been worked out and adapted to Russian design standards. A typical development atypical to European construction is given as an example. Materials, comments, and corrections were obtained as a result of joint work with the specialists of the "AVOK" organization.*

Keywords *- Calculation methodology, Construction, Parameters for the fanfire, Safety, Smoke ventilation.*

1. Introduction

The study's main purpose is to provide the safest possible conditions for evacuating people at the fire starting point [1-5]. In addition to determining the necessary parameters for selecting a fan, it is necessary to calculate the pressure, taking into account the geometric features of the door. The closer on it should be enough so that people of different groups (children, the elderly, pregnant women) can easily get into the fireproof zone, vestibule gateway, and staircase cage without the risk of being in a fire puff of smoke [6-11].

First, it is necessary to determine the procedure for making calculations. Therefore, one should start by choosing the defining door. Depending on the layout of the building, this can be a door that connects the inter-apartment corridor and the fireproof area, a door between the vestibule and the staircase, and many other variants that depend only on the layout [12-15]. The criterion for choosing a door is the most unfavorable conditions during the evacuation of people: air pressure between rooms, which can significantly affect the force applied to open the door [16-19]. In this case, it should be a door that connects the inter-apartment corridor and the fire-safe zone (Fig. 1, a door highlighted in a red circle).

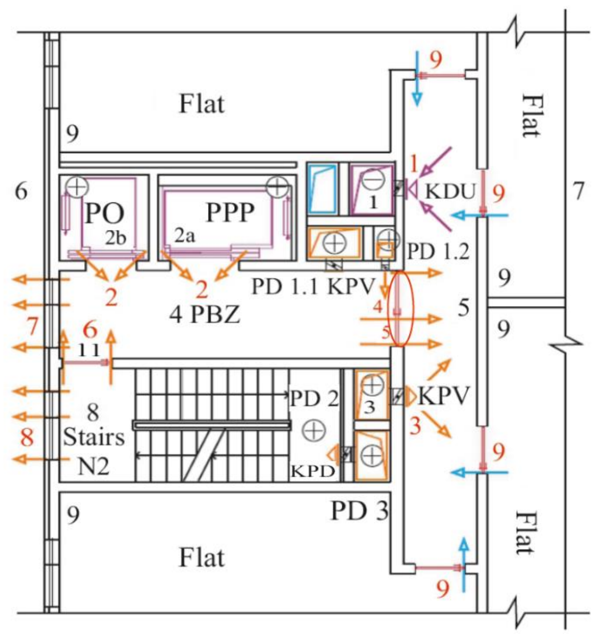

Fig. 1 An example of the layout of a typical residential building

The arrows in Figure 1 indicate the direction of air movement: leaks and air supply by the compensation system and air removal by the exhaust smoke ventilation system. That is why it is necessary to choose a communication scheme, which is drawn up based on the building layout before starting the calculation after choosing the design door [20].

After the settlement door has been selected, a communication diagram has been drawn up, and all the necessary data has been obtained, it is worth starting the calculations. Many formulas are taken from MP to SP 7.13130.2013 [21]. The value of specific gas permeability is taken under the requirements of SP 7.13130.2013 [17], and the principle of operation and air distribution in the network are taken from Manual 14.91 to SNiP 2.04.05-91[22].

2. Calculation Methods

First, it is necessary to compose the communication systems (Fig. 2, 3).

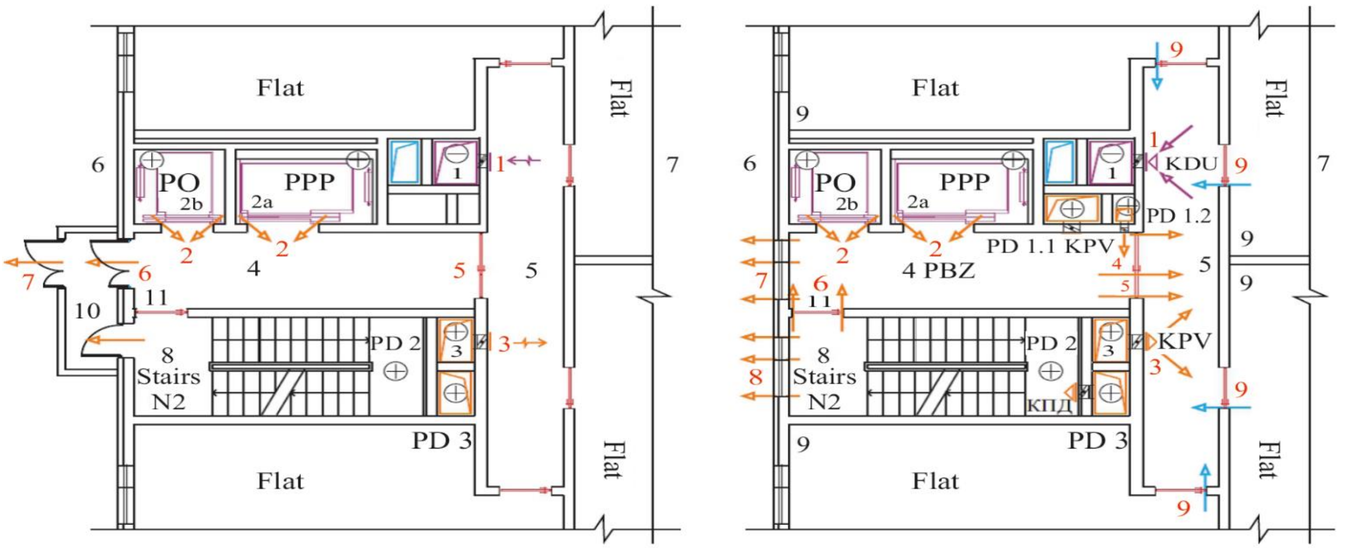

Fig. 2 The first and typical floor of the building

1 – smoke extraction shaft; 2 – elevator shaft; 3 – facewall shaft; 4 – elevator hall / fireproof zone; corridor; 6 – leeward facade; 7 – windward facade; 8 – staircase; 9 – flats; 10 – vestibule; 11– the door from the staircase to the elevator hall

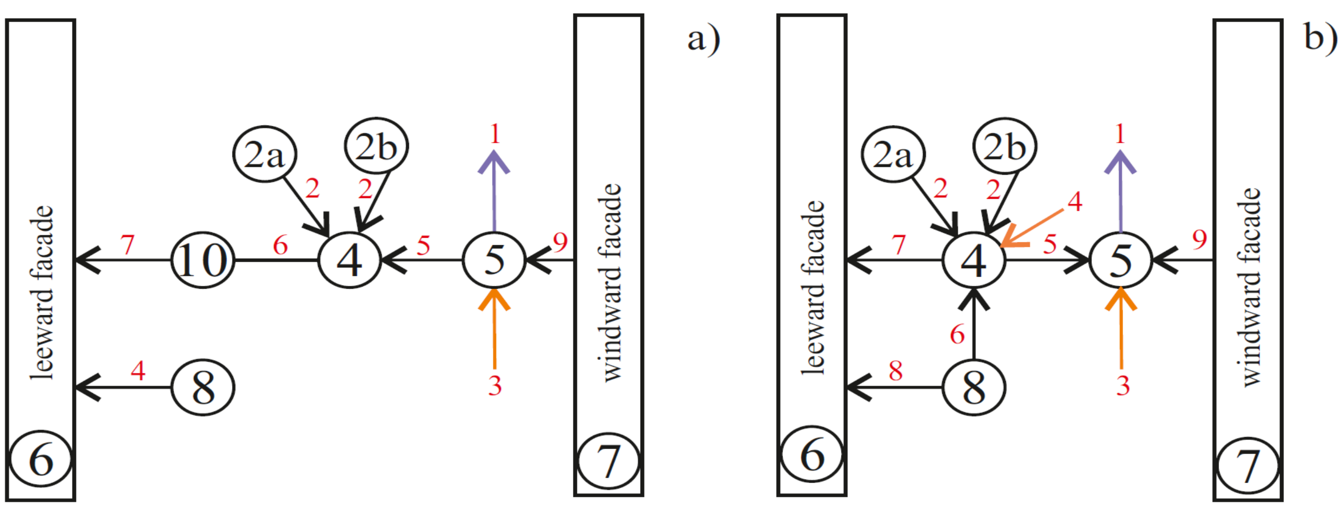

Fig. 3 Communication schemes for the first and typical floors

(a): 1 – closed smoke exhaust valve (draught); 2 – the open door of the elevator shafts (discharge);
3 – closed valve of compensation air supply (leak); 4 - the open door from the staircase to the vestibule to the street (leak); 5 - the closed door from the elevator hall to the corridor; 6 - the open door from the elevator hall to the vestibule to the street (leak); 7 - open the door to the outside (leak)
(b): 1 – open the smoke exhaust valve; 2 - close the closed door of the elevator shafts (leak);
3 - open valve for compensating air supply (supply); 4 - compensating air supply in the fireproof zone to the closed door; 5 - the closed door from the elevator hall to the corridor (draught); 6 - the closed door from the staircase to the elevator hall / fireproof zone; 7 - elevator hall windows (leak); 8 - staircase windows (leak); 9 - apartment doors

Fig. 2 shows the layouts of the first and typical floors. In this case, all ventilation equipment is located on the roof of the building. The worst option for starting a fire in the hearth on the second floor. On the first floor, from the staircase, two doors are sequentially opened to the street, and the elevator cabs are on the first floor [23]. Under the circles with black numbers in Figure 3, which are specific rooms of this building, all incoming or outgoing air flows (*draught* and leak) can be added to the diagram. It is important to consider the influence of the leeward and windward facade of the building. This value will affect the resulting differential configurations without a specified differential pressure. It is possible to proceed to the calculation when the rooms are arranged on the communication diagram under the layout, the direction of air movement is determined depending on the system operating in this room, and the types of *draught* and leak are indicated by the red numbers on the arrows of the diagram.

The following five types of doors are of interest:

- a door from the apartment to the inter-apartment corridor;
- a door connecting the inter-apartment corridor and the fire-safe zone (calculated);
- a door from the fireproof area to the staircase [17]; elevator doors [24];
- a door from the staircase to the street [23].

They can be open and close. If the door is open, and the air is supplied to this room at a certain speed to prevent smoke from bursting from the protected space [25], then the formula is used (1).

$$Q_{DO} = v\, A_{DOOR}, \qquad (1)$$

where Q_{DO} is a volumetric airflow through an open door from a protected space to unprotected space, m³/s;

v is a required airflow speed (1.3 or 1.5), m/s;

A_{DOOR} is a fully open door area, m².

If it is necessary to know how much air will pass through an open door, formula (2) is used.

$$Q_{OPENING} = C_V A_{OPENING} \sqrt{\frac{2}{\rho}} (\Delta P)^{1/R}\ , \qquad (2)$$

where $Q_{OPENING}$ is airflow through the corresponding hole, m³/s;

C_V is a coefficient (0.6 ÷ 0.9);

$A_{OPENING}$ is a hole area, m^2;

ΔP is a differential pressure on both sides of the hole, Pa;

ρ is an air density of 1.2 kg/m³;

R is a flow rate.

The flow rate can vary depending on various parameters, for example, the hole's shape and the air intake's location in the sealed space. It usually ranges from 0.60 to 0.95. In the absence of additional data, 0.64 should be used in calculations.

For wide holes, such as gaps around doors and large openings, an R-value can be assumed to be 2.0, but for narrow leak distances created by gaps around windows, a more appropriate R-value is 1.6 (laminar flow) [20].

Formulas similar in physical meaning can be found in Guidelines for mass air flow "Smoke ventilation systems for residential and public buildings," published by AVOK in 2021.

$$G_d = V_d \rho_d B_d H_d, \qquad (3)$$

where V_d is an airspeed in an open doorway, sufficient to prevent the release of combustion products into the staircase, m/s; V_d = 1.3 m/s - for residential buildings; V_d = 1.5 m/s - for public buildings;

ρ_d is an intake air density, kg/m³;

B_d, H_d are width and height of the doorway, respectively, m.

$$G_{en} = (\mu f)_{en} [2\rho_d (P_{s1} - P_{en})]^{1/2}\ , \qquad (4)$$

where $(\mu f)_{en}$ is an equivalent hydraulic area of building entrance doors, m^2;

ρ_d – is an intake air density, kg/m³;

P_{s1} is a pressure in the staircase at the level of the first floor, Pa;

P_{en} is a pressure at the level of the lower border of the entrance door on the leeward facade, Pa.

At this stage, the first disagreements appear. GOST R 53307-2009 [24] regulates testing with closed doors of residential apartments at the time of operation of smoke removal and compensation systems. At the same time, calculations show that when an air temperature is 20 °C, and a door is opened, the load on the fan will be higher than with closed doors. Therefore, the choice of formulas and door positions for various calculation options is still open. In the study, the door from the apartment with the fire source to the inter-apartment corridor was opened in all cases. Other doors of residential apartments were closed, and draughts were taken into account according to formula (5).

$$G_{di} = \left(\frac{\Delta P}{S_d}\right)^{1/2}\ , \qquad (5)$$

where ΔP is a differential pressure between rooms, Pa;
d is a characteristic of resistance to gas permeation of doors, 1/(kg·m).

It is also true to use formula (6).

$$Q_{DC} = 0{,}83 A_D (\Delta P)^{1/2}\,, \quad (6)$$

where Q_{DC} is an air leak through all closed doors, m³/s.
A_D is a total leakage area of a closed door, m²;
ΔP is a differential pressure on a closed door, Pa.

Formula (6) does not use the value of the specific gas permeability but uses the reference value of the total leakage area through doors for various purposes. To calculate the leakage through the slots of the elevator doors, formula (6) is also used, but with different values for the total leakage area through different doors.

To pressurize air at a pressure of 20-150 Pa [17], it is necessary to consider air leaks through walls and ceilings. These leaks can be neglected in other areas, especially those with low air mobility and unknown differential pressure. Leaks through the walls are determined by the formula (7), and leaks through the floor or ceiling are determined by the formula (8).

$$Q_{WALL} = 0{,}83 A_{LW} (\Delta P)^{1/1{,}6}\,, \quad (7)$$

where Q_{WALL} is air leakage through all walls and shafts, m³/s;
A_{LW} is a total wall/shaft leakage area, m²;
ΔP is a differential pressure on the wall, Pa.

$$Q_{FLOOR} = 0{,}83 A_{LF} (\Delta P)^{1/1{,}6}\,, \quad (8)$$

where Q_{FLOOR} is air leakage through all floors, m³/s.
A_{LF} is a total floor leakage area, m²;
ΔP is a total differential pressure across the overlap, Pa.

There may be window openings in staircases, through which there may also be leaks, which are determined by the formula (9).
Leakage through window openings is determined by the formula (9).

$$Q_{WC} = 0{,}83 A_W (\Delta P)^{1/1{,}6}\,, \quad (9)$$

where Q_{WC} is air leakage through all closed windows, m³/s.
A_w is a total leakage area of a closed window, m²;
ΔP is a differential pressure on a closed window, Pa.

Almost all calculation formulas are based on (1) and (2). Derivation of different values from available flows and pressure drops comes down to finding the resulting airflow [26], which creates a pressure drop across the closed door, considered calculated.

$$\Delta P_{FLOOR} = \frac{\rho}{2}\left(\frac{Q_{VERT}}{A_{eff}}\right)^2, \text{Pa}, \quad (10)$$

where Q_{VERT} is a vertical volumetric flow up the stairs to the floor, m³/s;
ρ is an air density, kg/m³;
A_{eff} is an effective area (empirical - 1.8 ÷ 3.8 for the general geometry of stairs), m².

The resulting difference with the value of the effort at which a person can open the door based on the condition of applying a force of no more than 100 N was compared. It is determined by the formula (11).

$$\Delta P_{100N} = \frac{(100N - F_{dc})\, 2\, (W - a)}{W^2 H}, \text{Pa}, \quad (11)$$

where F_{dc} is a door opening force without pressure drop, H;
W is a door width, m;
H is a door height, m;
a is a door handle distance, m;
$\Delta P_{100N}$is differential pressure corresponding to an opening force of 100 N, Pa.

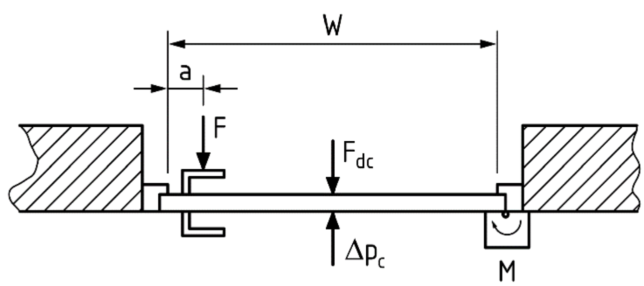

Fig. 4 Door opening force parameters
a – adjusted distance; F, F_{dc} – door opening force; M – door closer closing moment; W – door width; Δp_c – differential pressure

The pressure drop on each floor, obtained by formula (10), will be compared with the value obtained by formula (11), and, if the value is exceeded, will be changed the geometric characteristics of the door or the force of the closer. In the Guidelines "Smoke ventilation systems for residential and public buildings," all possible options for the state of doors with a given layout are considered in detail; and this article discusses the basic principles of operation of differential pressure systems, drawing up communication schemes and demonstrating the design features of the smoke ventilation system.

3. Results

Table 1. The total values of the calculation of a 10-storey building

Storey	Air amount in fireproof zone	Flow leakage per floor	Pressure loss on the floor	Pressure distribution profile
	Q_{SDx}	Q_{TDC}	ΔP_{FLOOR}	
	m³/s	m³/s	[Pa]	[Pa]
10	34.975	3.498	5.25	30
9	31.48	3.498	4.72	35.25
8	27.98	3.498	4.20	39.97
7	24.48	3.498	3.67	44.16
6	20.99	3.498	3.15	47.84
5	17.49	3.498	2.62	50.99
4	13.99	3.498	2.10	53.61
3	10.49	3.498	1.57	55.71
2	7.00	3.498	1.05	57.28
1	3.50	3.498	0.52	58.33
In total	34.98	34.98		

$$\Delta \boldsymbol{P_{100N}} = (\mathbf{100}\ \boldsymbol{N} - \boldsymbol{F_{DC}})\mathbf{2}(\boldsymbol{W} - \boldsymbol{a})/(\boldsymbol{W^2 H}).$$

With a door height of 2.0 m, a door width of 1.0 m, a distance between the door handles of 0.1 m, and a door closing force of 38 N, the pressure drop will be 55.8 Pa.

$$\Delta \boldsymbol{P_{100N}} = (\mathbf{100} - \mathbf{38}) \cdot \mathbf{2} \cdot (\mathbf{1} - \mathbf{0,1})/(\mathbf{1^2} \cdot \mathbf{2}).$$

ΔP_{100N}=55,8 Pa.

4. Conclusion

Based on the obtained values of the air consumption in the building, considering all draughts and leaks, the differential pressure on each floor, and the door opening force, the following conclusions can be drawn.

It is necessary to calculate the differential pressure system and clarify it on each floor, comparing a drop with the permissible value of the door opening force (according to the example, the differential value exceeds the permissible 55.8 Pa on the first and second floors).

Suppose the obtained value does not correspond to the limit one. In that case, selecting a door with different geometric characteristics or a door closer with a lower value of the door opening force is necessary.

The communication diagram must be followed closely since missed values of suction, and air leakage from different rooms can significantly affect the shift in the pressure drop value up or down throughout the building.

The condition of the limit value of the door opening force should not be neglected.

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