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To cite this article: A A Arbatskiy *et al* 2017 *J. Phys.: Conf. Ser.* **891** 012163

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Algorithm of dynamic regulation of a system of duct, for a high accuracy climatic system

A A Arbatskiy¹, G N Afonina¹ and V S Glazov¹

¹ National Research University «MPEI», Russia

arbatsky1985@mail.ru

Abstract. Currently, major part of climatic system, are stationary in projected mode only. At the same time, many modern industrial sites, require constant or periodical changes in technological process. That is 80% of the time, the industrial site is not require ventilation system in projected mode and high precision of climatic parameters must maintain. While that not constantly is in use for climatic systems, which use in parallel for different rooms, we will be have a problem for balance of duct system. For this problem, was created the algorithm for quantity regulation, with minimal changes. Dynamic duct system: Developed of parallel control system of air balance, with high precision of climatic parameters. The Algorithm provide a permanent pressure in main duct, in different a flow of air. Therefore, the ending devises air flow have only one parameter for regulation – flaps open area. Precision of regulation increase and the climatic system provide high precision for temperature and humidity (0,5C for temperature, 5% for relative humidity). Result: The research has been made in CFD-system – PHOENICS. Results for velocity of air in duct, for pressure of air in duct for different operation mode, has been obtained. Equation for air valves positions, with different parameters for climate in room's, has been obtained. Energy saving potential for dynamic duct system, for different types of a rooms, has been calculated.

1. Introduction

Currently, major part of all designed and realized ventilation systems of various buildings, both residential and industrial, are stationary. Which means they are designed for continuous operation in projected mode only, or they have a maximum of 2 modes, one of which does not ensure precise aerodynamic tuning of the system.

At the same time, many modern industrial sites, as well as administrative and residential buildings, require constant or periodical changes in technological process (for administrative buildings, these changes in technological process are changes of the number of people present within the interior).

Thus, there is a need to create an aerodynamic ventilation system, which will maintain the required parameters of the interior at varying characteristics of technological process. At the moment, all available systems are based on adjustment of air flow by direct control of the regulating device (figure 1) with adjustment of ventilation unit according to pressure sensor data.



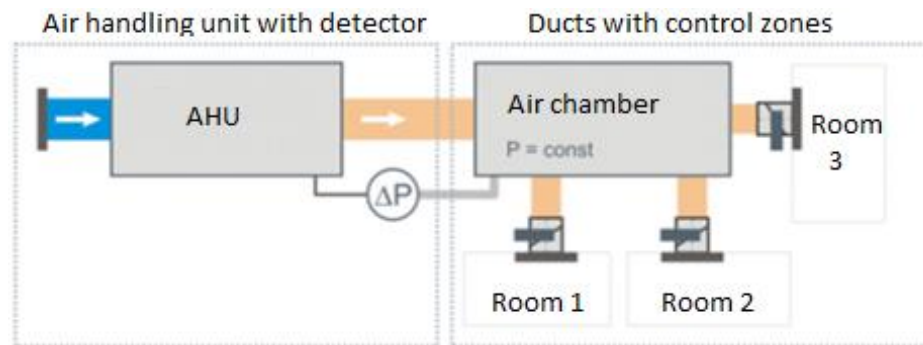


Fig. 1 Basic scheme of system with controllable air flow and static pressure chamber [1]

The main issue with this system is the need to maintain constant pressure in distribution chamber, which severely limits applicability of such systems, because significant volumes are required for the static pressure chamber.

One can also purchase separate regulatory devices equipped with their own pressure sensor and controlled by external signal (figure 2)



Fig. 2 TVR series static flow valve by Trox

The disadvantage of installation of such devices into common ventilation system is the disturbance of balance of the whole system after every movement of any of the units. And because every unit tries to maintain its flow parameters, it results in constantly deregulated system. Also, such system is rather costly, because each valve basically has its own controller and set of pressure sensors.

Both abovementioned kinds of controllable flow systems have severe limitations for system sizes, and the option with valves demonstrated in fig. 2 cannot ensure high precision of maintained climatic parameters.

2. Aerodynamic calculation

In order to work out an alternative solution, one must perform a detailed aerodynamic calculation of air duct network at various modes of operation. A theoretized air duct network in fig. 2 shall be used for illustration:

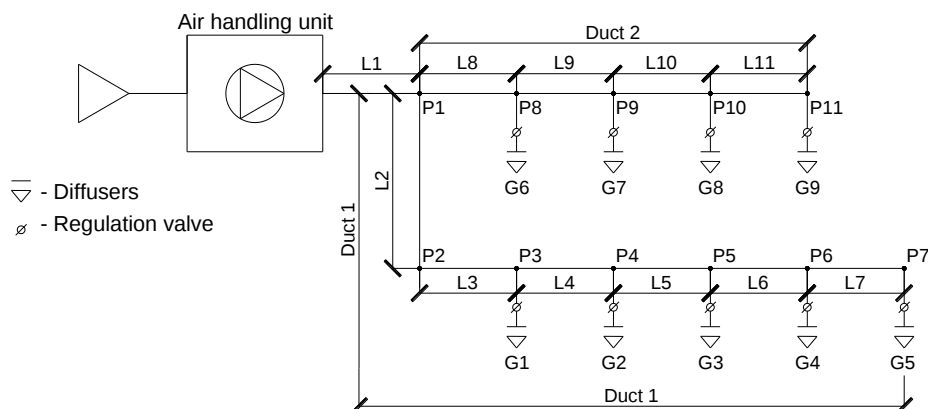


Fig. 3 Basic scheme of theoretical ventilation system
(P1-P11 are reference points for measurements of pressure values,
L1-L11 are section lengths, and G1 – G9 are air flows)

Thus, we can set various air flows, lengths and air duct diameters and perform aerodynamic calculation utilizing the classic method [2]:

$$P_{\text{tot}} = \Delta P_s + P_{\text{req}} \quad (1)$$

Where:

P_{tot} – total excessive pressure, created by the unit;

P_{req} – required pressure at the farthest distributing device;

$$\Delta P_{\text{tot}} = \Delta P_{\text{fr}} + \Delta P_{\text{loc}} \quad (2)$$

Where:

ΔP_{tot} – total losses of air drag;

ΔP_{fr} – losses of air drag due to friction at straight sections;

ΔP_{loc} – losses of air drag due to local friction (turns, shutoff and control valves);

$$\Delta P_{\text{fr}} = \xi_{\text{fr}} \left(\frac{l_{\text{fr}}}{d_{\text{eq}}} \right) \frac{\rho w_x^2}{2} \quad (3)$$

Where:

ξ_{fr} – frictional factor (calculated according to the flow mode):

- For smooth pipes (relative roughness less than 0.001):

$$\xi_{\text{fr}} = 64 / \text{Re}_x \quad \text{- For } \text{Re}_x < 2300; \quad (4)$$

$$\xi_{\text{fr}} = 0.3164 / \text{Re}_x^{0.25} \quad \text{- For } 2300 < \text{Re}_x < 10000; \quad (5)$$

$$\xi_{\text{fr}} = 1 / (1.82 \lg \text{Re}_x)^2 \quad \text{- For } 10000 < \text{Re}_x < 100000; \quad (6)$$

$$\xi_{\text{fr}} = 0.0032 + 0.221 / \text{Re}_x^{0.237} \quad \text{- For } 100000 < \text{Re}_x; \quad (7)$$

- For rough pipes (relative roughness over 0.001):

$$\xi_{\text{fr}} = 0.11 \delta_x^{0.25} \quad \text{- если } \text{Re}_x > 568 * \delta; \quad (8)$$

$$\xi_{\text{fr}} = 0.11 (\delta + 68 / \text{Re}_x)^{0.25} \quad \text{- если } \text{Re}_x < 568 * \delta; \quad (9)$$

Re_x – Reynolds number (turbulence level);

δ – relative roughness;
 d_{eq} – equivalent diameter of pipes (inside diameter);
 l_{fr} – length of calculated section;
 ρ – coolant density;
 w_x – flow speed;

$$\Delta P_{loc} = \sum \xi_{loc} n \frac{\rho w_x^2}{2} \quad (10)$$

Where:

ξ_{loc} – coefficient of local resistance ($\xi_{loc}=2$ -for turns; $\xi_{loc}=1.5$ – for shutoff and control valves; $\xi_{loc}=1$ – for hydraulic separators);

n – number of resistances;

A survey has been conducted for various ratios of lengths, air duct diameters and air flows in different branches. Total pressure values at reference points for various modes have been obtained. The main goal was to determine similar modes with slight differences in absolute pressure along the network with maximum variability of air flows. The results of some calculations demonstrating the correlation of total pressure within the air duct and its length, for duct 1 and duct 2 (according to figure 3) are presented as charts in fig. 4 a-b, initial data for them presented in table 1 a-b.

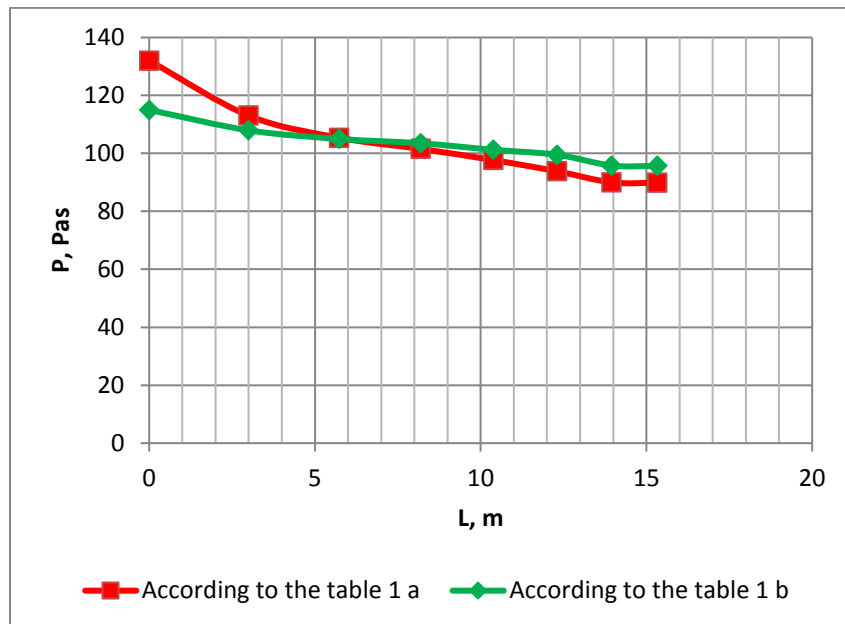
Table 1 a. Parameters of theoretized network (figure 3) in design mode

Section lengths L, m		Air flows G, m ³ /h		w _x , m/s	d _{eq} , m
L1	3	G1	5000	2.5	2.5
L2	2.73	G2	5000	2.5	1.9
L3	2.46	G3	5000	2.5	1.9
L4	2.19	G4	5000	2.5	1.7
L5	1.92	G5	5000	2.5	1.5
L6	1.65	G6	5000	2.5	1.2
L7	1.38	G7	5000	2.5	0.8
L8	1.11	G8	5000	2.5	1.7
L9	0.84	G9	5000	2.5	1.5
L10	0.57	-	-	2.5	1.2
L11	0.3	-	-	2.5	0.8

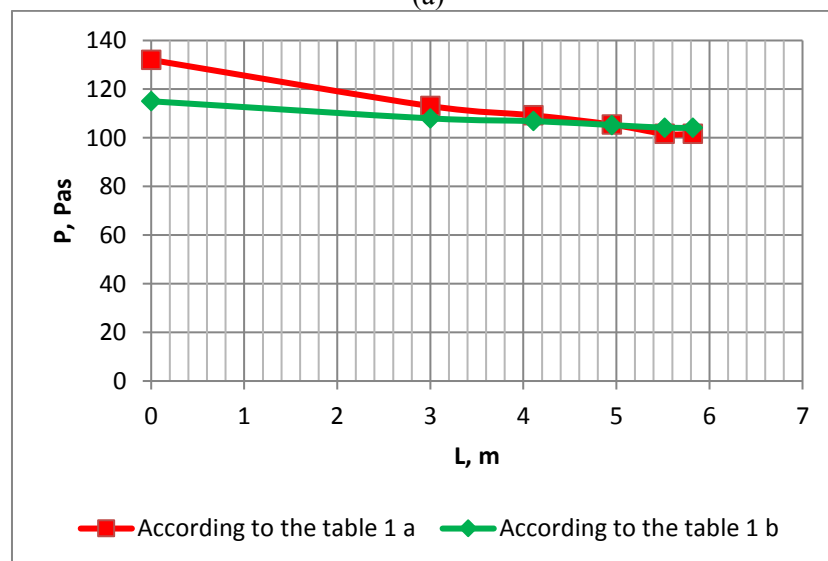
Table 1 b. Parameters of theoretized network (figure 3) in one of free modes

Section lengths L, m		Air flows G, m ³ /h		w _x , m/s	d _{eq} , m
L1	3	G1	300	1.5	2.5
L2	2.73	G2	5000	1.6	1.9
L3	2.46	G3	600	1.6	1.9

L4	2.19	G4	5000	1.9	1.7
L5	1.92	G5	5000	1.7	1.5
L6	1.65	G6	600	2.5	1.2
L7	1.38	G7	5000	2.8	0.8
L8	1.11	G8	5000	1.3	1.7
L9	0.84	G9	400	1.6	1.5
L10	0.57	-	-	1.3	1.2
L11	0.3	-	-	0.2	0.8



(a)



(b)

Fig. 4 Charts of absolute excessive pressure values in reference points of theoritized network from figure 3 in design and free modes.

Pressure created by the unit for design mode is 132 Pas,
for free mode it is 115 Pas. a) – duct 1, b) – duct 2

Thus it was determined that at rates within the range of 2 – 3.5 m/s along the whole network of air ducts, even at significant lengths of some sections (up to 10 m), insignificant deviations (up to 10%) of pressure before each distributing device can be achieved by changing the initial pressure created by the ventilating unit. In practice it can provide for precise adjustment of air flow at every device according to any external sensor.

It was determined for the survey that the unit must maintain such pressure that the pressure before the farthest distributing device will estimate no less than 50 Pas.

3. System adjustment algorithm

After conducted research, the algorithm for adjustment of the system can be fixed for two parameters according to (2) and (9), initially limiting the physical parameters of the system with the following criteria:

- a) Flow rate: 2 – 3.5 m/s;
- b) Geometry: round or rectangular with maximum side ratio 1/2;
- c) Temperature of moving air is 0 - 60 C;

Limitation “a” is due to the results of conducted surveys of aerodynamics of air ducts and possibility of precise fixation of correlation between the diameter and flow rate with application of acceptably precise discrete correction.

Limitation “b” is due to the need to ensure the quality of air flows around the cross-section of the duct, which in turn ensures the correctness of calculation utilizing the classic method [2].

Limitation “c” is due to fixation of air density parameters as a constant value, and kinematic viscosity for application of acceptably precise discrete correction.

Thus, the following correlation can be obtained from equations (1) - (9):

$$P_{\text{tot}} = f(G, L) \quad (11)$$

Where:

G – air flow m^3/h ;

L – length of the longest calculated branch, m;

P_{tot} – total excessive pressure created by the unit, Pas

The conclusion is also made based on the results of aerodynamic calculation, which has shown that adopting limitations “a” leads to the use of correlation (7) only, as Re values are over 100 000 in 100% of cases, and together with limitations “b” and “c” the values of rate, density and viscosity are used as constants with application of acceptably precise discrete corrections. Thus, when applying (7) to (3) we get:

$$\Delta P_{fr} = \frac{0.048L \left[0.25(d\varepsilon_{w1})^{0.237} + 1 \right]}{d^{1.237}} \varepsilon_p \varepsilon_{w2} \quad (12)$$

Where:

d – equivalent diameter of air duct;

ε_{w1} – first correction for deviations of rate;

ε_{w2} – second correction for deviations of rate;

ε_p – correction for temperature;

Now it is needed to derive $d=F(G)$ type correlation, which will vary for round and rectangular ducts. This correlation is also fixed by fixing flow rate as a constant with application of discrete correction. Therefore, for circular air ducts:

$$d_{\text{circ}} = 0.012 \varepsilon_{w3K} G^{0.5} \quad (13)$$

For rectangular air ducts:

$$d_{rec} = 0.0089 \varepsilon_{w3\kappa} G^{0.5141} \quad (14)$$

Where:

ε_{w3} – third correction for deviations of rate;

Thus, by applying (13) and (14) in (12), we get the following for round air ducts:

$$\Delta P_{fr} = \frac{11.43L \left[0.087(G^{0.119}(\varepsilon_{w3}\varepsilon_{w1})^{0.237} + 1) \right]}{G^{0.619} \varepsilon_{w3}^{1.237}} \varepsilon_{\rho} \varepsilon_{w2} \quad (15)$$

For rectangular air ducts:

$$\Delta P_{fr} = \frac{16.55L \left[0.082(G^{0.122}(\varepsilon_{w3}\varepsilon_{w1})^{0.237} + 1) \right]}{G^{0.439} \varepsilon_{w3}^{1.237}} \varepsilon_{\rho} \varepsilon_{w2} \quad (16)$$

Accordingly, correlation of a similar kind can also be obtained for ΔP_{loc} by generalizing the values of local resistances:

$$\Delta P_{loc} = 4.69n \varepsilon_{w4} \varepsilon_{\rho} \quad (17)$$

Where:

n is the total amount of local resistances (turns, offsets, T-bends, etc.);

ε_{w4} – fourth correction for deviations of rate;

Therefore, for every point of network (n section) one can derive a unique dependance of pressure from rate (physical parameters of the network, such as: length and number of resistances, are adopted as constant values for a particular system and each of its sections):

$$P_n(G_n) = P_{n-1}(G_n) - [\Delta P_{loc,n}(G_n) + P_{fr,n}(G_n)] \quad (18)$$

While the flow rate is determined exclusively by the position of the shutoff flap controlled by the sensor in the room, according to the known correlation between the rate of opening of the flap and the rate and difference of pressures:

$$G = F \sqrt{\frac{2\Delta P}{\xi \rho}} \quad (19)$$

Where:

F – flow area of the flap ensuring the required flow rate;

ΔP – pressure difference between the air duct where the air is taken from and the remaining pressure, to overcome network resistance after the flap $\Delta P = P_n - P_{req}$;

ξ – flap resistance coefficient (depending on the flap door type);

ρ – air density;

According to the results of conducted research, a complete description of theoretized algorithm of operation of the system with all required elements can be made (figure 5):

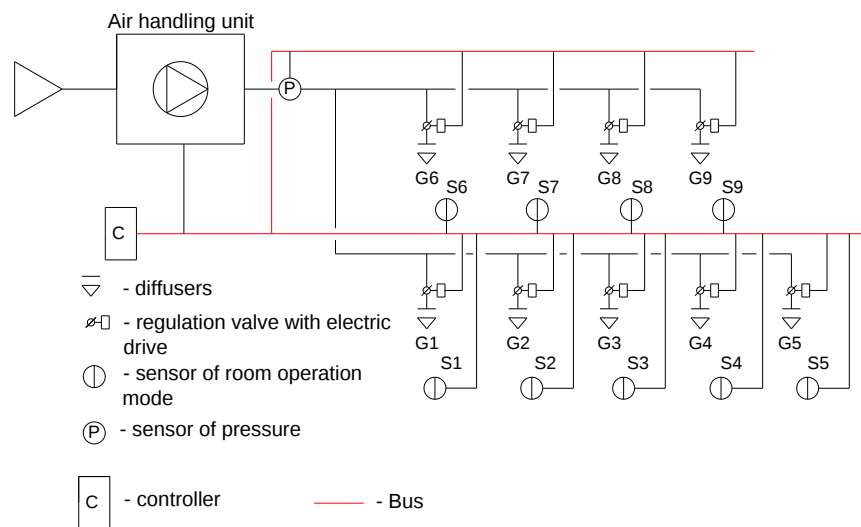


Fig. 5 Basic scheme for automatization of dynamic control

1. One of S_n sensors signals changes in the mode of operation of the room (changes of temperature, CO content, etc.);
2. The flap door for the room, or set of flaps, begin to close according to the address signal from the controller by PID algorithm;
3. Signals are transmitted from the actuators of the flaps all the time while their position is changing;
4. The controller calculates the air flow through the adjusted flaps according to the algorithm (19) and recalculates the overall air flow and accordingly the values of pressure before each flap door according to the algorithm (18) utilizing correlations (15)-(17). While the only changeable parameter is air flow – G . The other parameters are set as constant values determined for every section of the network;
5. Together with changes of pressures along the whole network, the pressure created by the ventilation unit is also being lowered by pressure converter installed right after the ventilation unit in order to maintain the pressures at reference points deviating for no more than 10% from the initially set values;
6. In case several signals are required from a single room or several actuators within a single room to be controlled, local switching units can be utilized with a singular independent algorithm for a particular room;

While that algorithm is in use, only the flaps that adjust the ventilation of that particular room are activated. The consistency of flow rate through other flaps is ensured by maintaining the pressure distribution according to the set algorithm.

4. Ensuring aerodynamic stability

As the present system is intended for operation with a big number of discretely set constant values, which lowers the precision of the applied algorithm to some extent, the criteria for aerodynamic stability of the adjustable system must be set. Partially, the said criteria have been provided in the previous section as limitations for dimensional characteristics of air ducts and air flow rates. However the location of choking flaps also significantly affects the aerodynamics.

A survey in PHOENICS CFD-modelling system has been conducted in order to determine the beginning of stable area after duct offset. The survey included air flow rates in the main duct ranging between 2.5 and 10 m/s at various sizes of rectangular offsets with dimensions ratio over 1/2. The following results have been obtained (Figure 6):

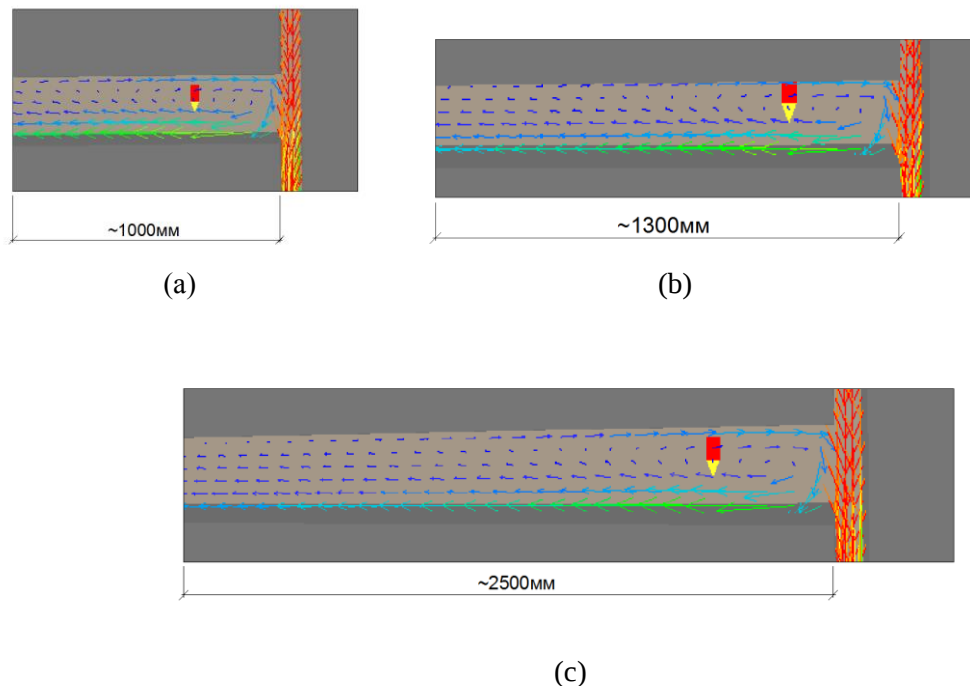
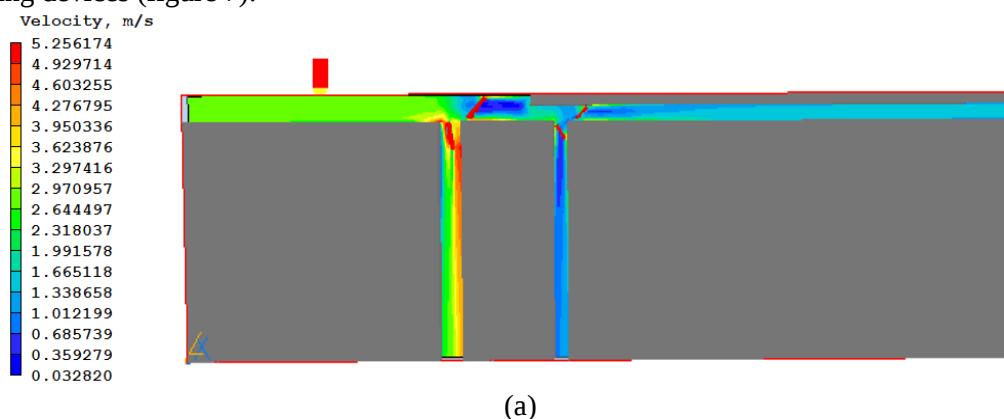


Fig. 6 Turbulent vortex resulting from interaction of air with offset at various flow rates in the main duct
(on the right): a) – 2.5 m/s, b) – 4 m/s, c) – 6.8 m/s

k- ϵ turbulence model [3] was used for calculations, with application exclusively of the equations for aerodynamics. All energy equations were turned off.

Fig. 6 shows that the size of turbulent vortex in all cases estimates 500-800 mm. Monodirectional flow begins approximately after 1000 mm after the offset. Thus, regulating devices in offsets in order to ensure higher quality of control can be placed no closer than 500 mm to the main duct, and in case it is possible, 1000 mm.

These results comply well with the major picture of flattening of flow in air duct when passing regulating devices (figure 7):



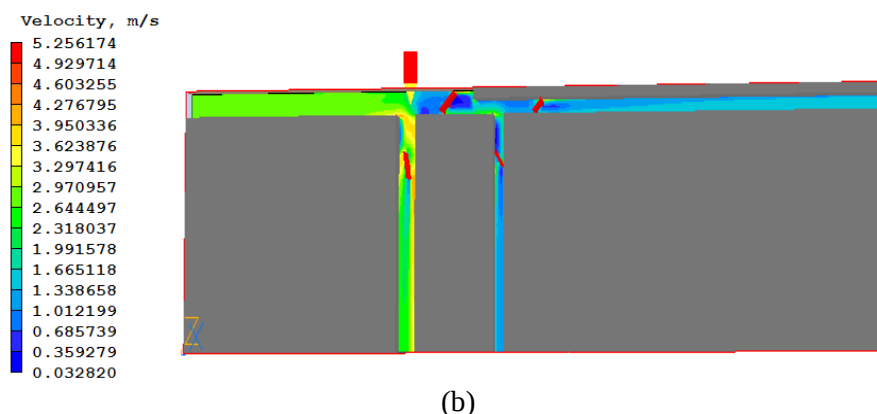


Fig.7 Distribution of air flow rates in the main channel (top) and offsets after adjustment by choking devices

- a) – when the choking devices are located right next to the main flow,
 b) – when choking devices are located 0.8 m away from the main flow

Figure 7 well demonstrates that flattening of air flow when the regulating device is 0.8 m away from the main duct is much faster (in figure 7a the stratification of flow by speed in the lower parts of offsets is much higher than in figure 7b).

5. Energy saving potential

Within the boundaries of the present work, estimates of overall energy saving potential of the present system in various types of buildings have been made. The energy saving potential directly depends on the average load of the building throughout the year. Thus, considering operation practice [4], it can be determined in percents of overall energy consumption of buildings:

- For office buildings: 10-20%;
- For public buildings: 15-25%;
- For residential buildings: up to 60%;
- For industrial buildings: depends on the manufacturing type, can be low-efficient for 3-shift manufacturing with high load factor. The lower the load factor and the smaller the number of shifts at the facility, the more efficient it becomes.

6. Conclusion

1. The algorithm of operation of dynamic air ventilation system has been obtained together with limitations of its use;
2. The general view of dependence of air flow on the position of regulating flap door at constant pressure difference has been obtained;
3. The analysis of conditions ensuring aerodynamic stability of the system ensuring higher precision of adjustment has been conducted;
4. Estimations of the power resource saving potential of the present system have been made.

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