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DEVELOPMENT OF THE UNIVERSAL AIR COLLECTOR DESIGN FOR MEASURING THE FLOW RATE OF SWIRLING AIR FLOW USING AN INTEGRAL THERMOANEMOMETER

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Measurement of the swirling air flow rate and average speed of air at air distribution units of ventilation systems is a rather difficult task due to the fact that the air flow enters the measuring device at different angles. As a result, significant measurement errors can occur when using point thermoanemometers or other flow meters. The use of integral anemometers facilitates the measurement process. However, it is necessary to eliminate the errors associated with changes in the angle of the air flow to the sensing element of the measuring device. To do this, it is necessary to ensure a rectilinear structure of the air flow using a transitional air collector and rectifier. The aim of this paper is to develop a design of an air collector device that will allow to measure the flow rate of a swirling air flow. The objectives of the paper are to optimize the geometrical parameters of the air collector to ensure a rectilinear flow, minimize its dimensions and aerodynamic drag. The correctness of the air collector design was evaluated by matching the calibration characteristic of the probe of an integral thermoanemometer in the presence of a vortex diffuser in front of the air collector and in its absence. The proposed device has a rectangular shape and consists of a receiver, a rectifying grid, a chamber, an accelerating and stabilizing section, at the outlet of which a thermoanemometer probe is installed. The receiver and the accelerating section are tapered along their length, while the chamber and the stabilizing section have a constant cross-section. The rectifying grid is installed inside the chamber and has a square-shaped honeycomb structure. Several options of the air collector design with different geometrical parameters were studied using computer modelling. The dependence of aerodynamic drag on air flow was plotted. The optimal design of the air collector was chosen, for which a life-size physical model was created. The calibration characteristics of the measuring probe with an air collector were experimentally obtained when a swirling air flow was applied. The developed universal air collector allows the air flow rate measurement at the outlets of almost any air distribution devices of ventilation systems of buildings.

Keywords: *air collector, thermoanemometer, air flow rate measurement, swirling air flow.*

Introduction

To adjust the ventilation systems of buildings, air flow measurements are carried out on air distribution devices: ventilation grids, anemostats, vortex diffusers. Their design can be different. The air flow, passing through them, changes its flow structure [1–5]. However, if the air flow at the outlet of the air distribution devices has a rectilinear structure, then measurement problems usually do not arise. When it is necessary to measure the flow rate of air swirled by a fan or a vortex diffuser, the process becomes complicated and time-consuming, and the error can be significant. To increase the accuracy of air flow rate measurements, it is necessary to transform the structure of the air flow in such a way that a rectilinear flow passes through the probe of the flowmeter.

An air collector with a built-in rectifier is used as an air flow rectifier. The receiver of the air collector has a trapezoidal shape. This is how the testo 420 device from the well-known manufacturer of measuring equipment Testo [6] is arranged. Its disadvantage is low sensitivity at low air flow speeds (below 5 m/s).

There are flowmeters with a cone-shaped air collector, at the outlet of which an impeller is installed [7]. They allow to measure air flow rates at the outlets of anemostats with a diameter of slightly more than 200 mm. The impeller is an integrating device and correctly measures the flow rate even in turbulent air flow with uneven speed distribution, but it cannot correctly measure the flow rate of the swirling air flow.

Another device designed to measure the average speed or air flow rate in air ducts is an integral acoustic anemometer [8]. Its disadvantages include the impossibility of use on air distribution devices.

There are also other types of anemometers that make it possible to make point measurements of air speed with the subsequent averaging of the results over a section: diffmanometers [9], thermoanemometers with a string [10] or thermal film [11]. All of them are point sensors and require preliminary preparation of the air flow. To obtain reliable results, it is necessary to conduct multiple measurements at different points of the section.

It is much easier to measure air flow rates at the outlet of a fan or air distribution devices using a highly sensitive integral thermoanemometer based on a heating cable [12], developed by the authors of the paper [13]. This device can be used in a wide range of changes in the speed (rate) of the air flow and, most importantly, allows to obtain its average value. A special air collector was developed to measure the air flow rate using an integral thermal anemometer on air distribution devices during its rectilinear flow [14].

However, if the structure of the air flow at the outlet of the air distribution devices or the fan is not rectilinear, but swirled, then it is necessary to minimize the influence of the swirling angles on the sensitive element of the thermoanemometer with the help of a transitional air collector and a rectifier. Their design should have minimal aerodynamic drag and ensure the rectifying of the swirling air flow.

Development of the design of the air collector for the air flow rate measurement at the outlet of vortex diffusers

From the experience of building wind tunnels [15], it is known that if a rectifying grid and a set of wire meshes are installed in the flow part of the nozzle, it is possible to turn the swirling flow into a rectilinear flow with a degree of turbulence of about 0.2%. By analogy with the nozzle of a wind tunnel, the design of the air collector should repeat its shape and have, at least, two compressions of the flow, followed by two rectilinear sections with a constant cross-sectional area. An important characteristic of the nozzle is the uniformity of the field of flow speeds at the outlet. Irregularity can be caused by two main reasons: the presence of a boundary layer on the inner surface of the nozzle, formed due to viscous forces in the gas and frictional forces between the gas and the nozzle surface, and the presence of small vortices, which leads to a change in the flow speed at different points on the section nozzle.

In the developed air collector, the air flow after the first narrowing enters a chamber with a grid designed to break up vortices and form a plane-parallel flow. The design of the grid is a honeycomb with square-shaped honeycombs, the sides of which will be denoted as S. To equalize the air flow in the direction of the flow, the honeycomb depth L was chosen taking into account the presence of at least five gauges from the minimum cell size $L \geq 5 \cdot S$ (according to [16]). The second narrowing increases the air flow speed along the nozzle, and the vortices crushed by the grid weaken due to their interaction with each other. After the second narrowing, the nozzle of the air collector has a rectilinear section, where the final rectifying of the flow takes place in front of the sensitive element of the thermoanemometer probe, for which the flow with an angle of attack of at least 75° is required. The turbulence of the flow must be reduced to the level of sensitivity of the thermoanemometer probe, since it has thermal inertia, which will smooth out the presence of fluctuations in the flow.

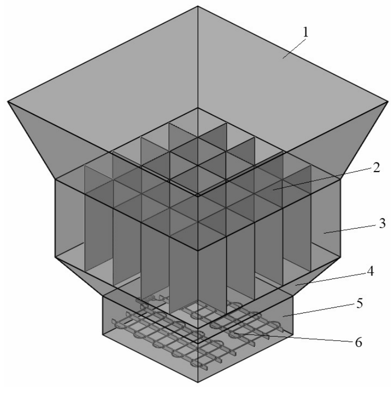


Fig. 1. Model of the air collector:
1 – receiver, 2 – rectifying grid,
3 – chamber, 4 – accelerating section,
5 – stabilizing section,
6 – probe of the integral thermoanemometer

The design of the air collector is shown in Fig. 1.

The source of the flow turbulence is its vortex-like movement, which is created by the guide lamellas of the diffuser, the instability of the angular rotation speed of the fan, as well as the roughness of the inner surface of the air collector and structural elements located in the air flow. The presence of small vortices interacting with each other and the mass of air in the transport movement affects the fluctuation of the instantaneous speed. At the same time, the instantaneous speed W at each point of the flow changes in time, fluctuating within some average value of the speed W_s. The speed of the air flow can be given as the sum of the average speed W_s and the root mean square pulsation speed W_p for the selected measurement time interval. The turbulence of the flow is estimated by the ratio W_p / W_s.

The choice of geometric parameters of the air collector is based on the fulfillment of the condition of free access of the air flow to the flow part of the air collector. This is achieved when the free cross-sectional area of the vortex diffuser is less than the free cross-sectional area of the sensitive element by at least 2.5 times. In this case, according to [16], the condition of minimum aerodynamic drag will be met, which affects the increase in dimensions of the measuring device, which cannot always be ensured when measurements are taken in the ventilation system.

The optimization of the design of the air collector is reduced to the minimization of its dimensions and aerodynamic drag, provided that the flow passing through the sensitive element of the thermoanemometer is rectilinear. The intermediate dimensions of the design elements of the air collector are determined by their coordination among themselves. The main element of design optimization is the grid, or rather the size of the honeycombs along and across the air flow, as well as the location of the sensitive element in the channel. As for the wire meshes, which are usually located behind the grid, their use affects the alignment of the speed field in the cross section of the flow part of the probe and increases the aerodynamic drag of the air collector. Since the probe of the thermoanemometer has integrating properties [12], the fulfillment of the requirement for equalization of the air flow loses its meaning, and therefore the need to install grids in the chamber disappears.

The method of determining the aerodynamic drag of the air collector for the flow rate measurement of the swirling air flow

The aerodynamic drag of the air collector affects the change in the load on the inflow fan and, as a result, the change in air flow in the ventilation system. In order to choose an air collector with minimum resistance, it was necessary to study several designs with different geometries. In addition to the results of physical quantities measurement, it was necessary to visualize the flow pattern of the air flow to determine the presence of swirl. These tasks were solved with the help of computer modeling of the process of air movement in the room. The computer modeling technique has significant advantages over physical measurements, which is primarily due to the low resolution of measuring devices and the complexity of manufacturing various options of air collector designs.

The computer model of the room with an air collector is shown in Fig. 2.

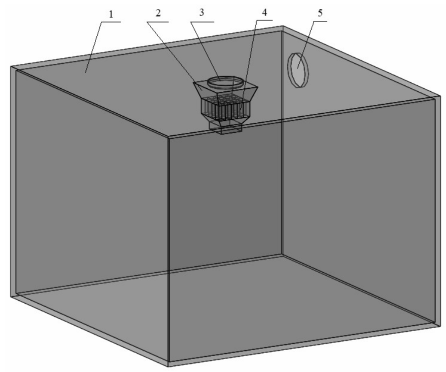


Fig. 2. Computer model of the research object:
1 – room, 2 – air collector, at the outlet of which a thermoanemometer probe is installed, 3 – inflow ventilation hole with a vortex diffuser, 4 – rectifying grid, 5 – exhaust ventilation hole

Source data for research:
– room dimensions are 4×4×3 m;
– the diameter of the inflow hole under the vortex diffuser is 450 mm;
– the diameter of the exhaust hole is 300 mm;
– length of section 1 – 200 mm;
– length of section 2 – 200 mm;
– length of section 3 – 100 mm;
– length of section 4 – 100 mm;
– honeycomb depths – 100 and 200 mm;
– side lengths of square honeycombs – 45, 60, 75, 90 mm;
– thickness of the honeycomb walls is 1 mm;
– inlet section of the air collector is 600×600 mm;
– section of the rectifying grid – 450×450 mm;
– cross section of the measuring section of the probe – 300×300 mm;
– air flow swirling angles – 0, 10, 20, 30, 40, 50 radians.

Without an air collector, the following flow pattern is observed: air enters the room through the inflow vortex diffuser and, before entering the exhaust hole, performs a swirling movement, loses speed and mixes with the surrounding air. Thanks to this, the temperature of the inflow air can be much lower than the temperature in the room.

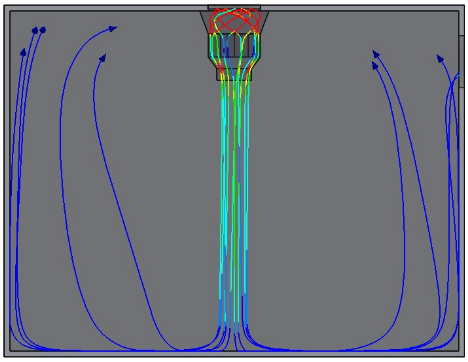
A completely different picture is observed when an air collector with a grid appears at the outlet of the diffuser. After it, a rectilinear jet of air is formed, which, after hitting the floor, spreads in all directions along its surface. Then the flow rises along the walls and, reaching the ceiling, goes to the center, where the air flows collide. After the collision, they turn downwards the room, creating a circulation between the walls and the center. The asymmetry in the described picture is introduced by the exhaust hole (see Fig. 2), through which the circulating air flows exit the room.

In order to determine the aerodynamic drag of the air collector in real operating conditions, it is necessary to establish the dependence of the resistance of the room with and without the air collector on the air flow rate and the angle of rotation of the flow, and then subtract the second value from the first value. Several designs of air collectors with different geometry were studied, for which similar dependencies were obtained.

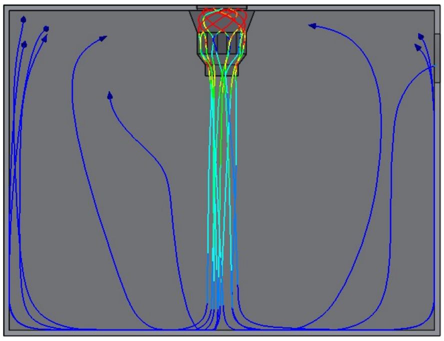
When carrying out calculations for various design parameters of the air collector when changing the air flow rate and the angles of its rotation, a series of dependences of the aerodynamic drag on these values was constructed.

Computer modeling made it possible to construct trajectories of air movement (Fig. 3), which can be used to draw conclusions about the nature of their behavior during the passage of the measuring section of the probe. Observing the structure of the flow in the flow part of the measuring probe for different values of the air flow rate and changing the length and width of the honeycombs of the rectifying grid, the optimal dimensions of the honeycombs for which the air flow acquired a rectilinear structure and at the same time had minimal aerodynamic drag were determined.

When measuring air flow on real objects, the aerodynamic drag of the air collector can be taken into account with the help of a correction. For this, it is necessary to have the aerodynamic characteristics of the fan and to know the operating point of the ventilation system. In practice, graphic dependences of the aerodynamic characteristics of the fan and load curves of the ventilation system are used.



a



b

Fig. 3. Trajectories of the air flow formed by the air collector at a swirl of 50 radians and an air flow rate of 1500 m^3/h for 200 mm deep grids with honeycomb sizes of:
a – 60 mm, b – 90 mm

When analyzing the dependencies of the aerodynamic drag of the air collector, the following trends are observed:

1. As the size of the honeycomb *S* decreases, the resistance slightly increases (Fig. 4).

2. With the increase in air flow rate *V* for the studied swirl angles, the aerodynamic drag increases significantly.

3. For air consumption less than 1000 m^3/h (corresponding to a 20-fold replacement of air in the room) the aerodynamic drag of all analyzed air collectors is less than 5 Pa, which practically does not affect the reduction of air flow for most industrial fans.

The dependence of the aerodynamic drag on the swirling angles of the air flow has a maximum, which shifts towards an increase in the swirling angle with an increase in the air flow rate. A further increase in the swirling angle leads to a decrease in resistance (Fig. 5).

Computer modeling showed that a fully rectified air flow is observed at the side dimensions of the honeycombs of 45 and 60 mm, while the depth of the rectifying grid can be reduced from 200 to 100 mm.

Given that an air collector with a honeycombs side of 60 mm will have less aerodynamic drag than a 45 mm one, this design is chosen as optimal. Below, all the results obtained after modeling and experiment will be given for it.

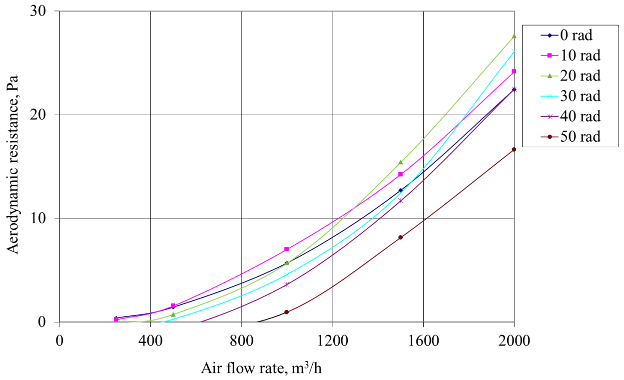


Fig. 4. Dependence of the aerodynamic drag of the air collector with the size of the honeycombs side of 60 mm and the depth of the rectifying grid of 200 mm on the air flow rate for different swirling angles

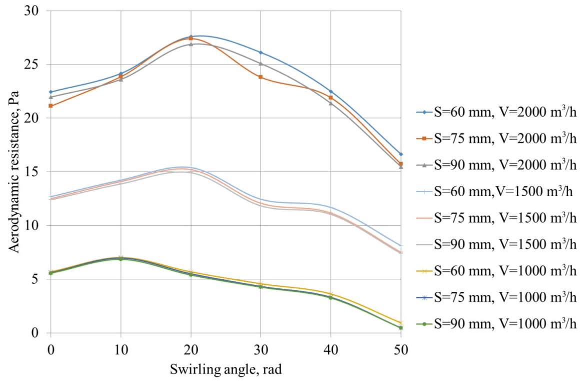


Fig. 5. Dependencies of the aerodynamic drag of air collectors on the swirling angles at air flow rates of 1000, 1500 and 2000 m³/h for a rectifying grid with a depth of 200 mm with side dimensions of the honeycombs of 60, 75 and 90 mm

Dependencies shown in Fig. 4 can be used as corrections when measuring air flow rates. To take it into account, it is necessary to use the aerodynamic characteristics of the fan. In our experiment, it is a Systemair 315L channel fan [17], the aerodynamic characteristics of which are shown in Fig. 6.

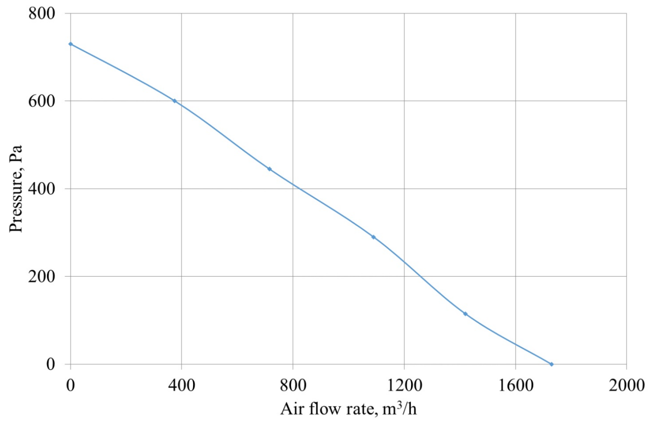


Fig. 6. Aerodynamic characteristics of the Systemair 315L channel fan

We will give an example of calculating the air flow rate using this method. Let's say the inflow diffuser has a swirling angle of 20 rad, and the measured air flow rate is 1500 m³/h. Using Fig. 4, we determine the aerodynamic drag of the air collector, which in this case will be ΔP=15.1 Pa. From the characteristics of the fan (see Fig. 6) for the air flow rate of 1500 m³/h, we determine the pressure, which is 80 Pa. Then the true pressure, by which the air flow rate is determined, will be 80–5.1=64.9 Pa. Let's look at Fig. 6 for this pressure and determine that the air flow rate is 1550 m³/h, that is, it will increase by 3.33%.

Experimental study of the feasibility of using an air collector

To confirm the feasibility of using the proposed air collector, an experimental plant (Fig. 7) was created, which was an open wind tunnel to which a life-size air collector with a rectifier and thermoanemometer probe placed inside was connected. To create a swirling flow, a VD 400 vortex diffuser was installed in front of the air collector.

The correctness of the design selection of the air collector was assessed by the coincidence of the calibration characteristics of the integral thermoanemometer probe in the presence of a vortex diffuser in front of the air collector and in its absence. The results of the research are shown in Fig. 8, which also shows the benchmark calibration curve of the thermoanemometer probe, obtained when a rectilinear, rectified air flow enters [12].

As we can see in Fig. 8, the difference between the two dependencies is about 12% on average. This correction should be taken into account when measuring on real objects. Obviously, to reduce the discrepancy between these curves, it is necessary to reduce the size of the honeycomb side or to increase the grid depth. It should also be noted that the heat transfer curve of the thermoanemometer probe in the absence of a vortex diffuser practically coincides with the benchmark calibration curve (especially in the range of 180≤Re≤800), which indicates that the selection of the air collector with the rectifying grid was made correctly. A small difference (no more than 6%) is observed only at 800≤Re≤1450.

The dependence in the presence of a vortex diffuser in front of the air collector has the following form:

$$Nu=0.59\cdot Re^{0.48}, \quad (1)$$

where Nu is the Nusselt number; Re is the Reynolds number. Scope of the formula application is: 170≤Re≤700.

The dependence in the absence of a vortex diffuser in front of the air collector has the following form:

$$Nu=0.34\cdot Re^{0.53}. \quad (2)$$

Scope of the formula application is: 270≤Re≤1460.

In order to more accurately calculate the correction when measuring the flow rate of a swirling air flow, it is necessary to subtract (2) from (1). Scope of correction application is: 270≤Re≤700.

The made measurements also allowed to determine the dependence of the aerodynamic drag of the air collector on the air flow rate. It looks like this:

$$P_{st}=7\cdot 10^{-6}\cdot G_w^{1.96},$$

where P_{st} is the aerodynamic drag, Pa, G_w – is the volumetric air flow rate, m^3/h.

Taking into account the small coefficient of the obtained dependence before the value of the air flow rate, we can talk about the small aerodynamic drag of the air collector, especially in comparison with the resistance of air distribution devices. So, for consumption of 2000 m^3/h, resistance will be only 21.3 Pa, which will practically not affect the reduction of air flow for the absolute majority of modern fans used in ventilation systems of buildings.

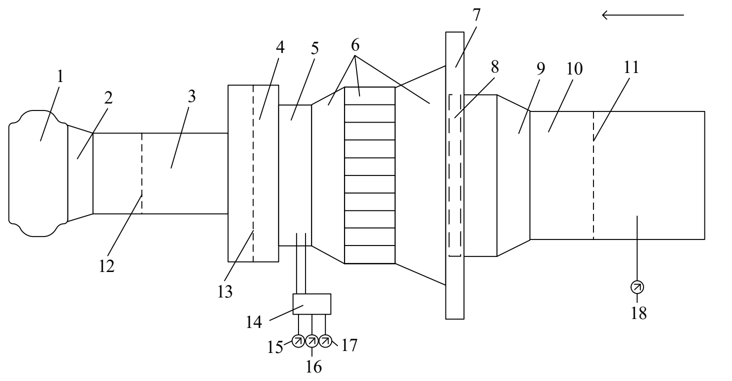


Fig. 7. Scheme of the experimental plant:
1 – channel fan with speed controller; 2 – adapter; 3 – duct;
4 – chamber of transition from round to square section;
5 – probe of the integral thermoanemometer; 6 – air collector consisting of a flow receiver, a rectifying grid and an acceleration section;
7 – assembly area; 8 – vortex diffuser; 9 – adapter; 10 – duct;
11–13 – measuring sections with built-in Pitot tubes;
14 – power supply unit; 15–17 – devices for measuring electrical quantities; 18 – pressure drop gauge

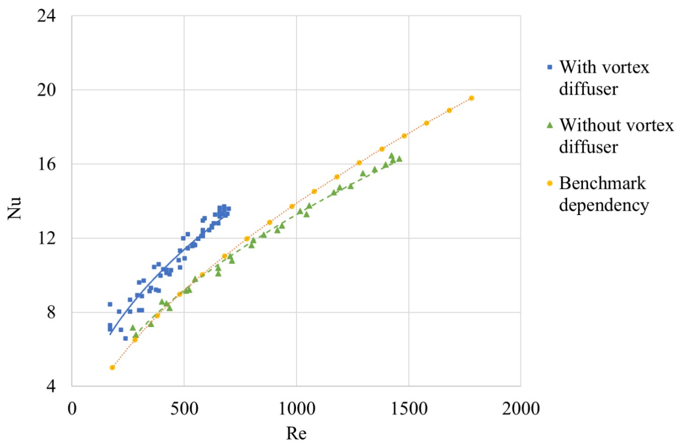


Fig. 8. Comparison of the heat transfer of the probe of the integral thermoanemometer during the inflow of direct and swirling air flows

Discussion of results

Unfortunately, experimentally, it was not possible to achieve coincidence of the calibrating curves when rectilinear and swirling air flows hit the probe of the integral thermoanemometer. Nevertheless, taking into account the introduction of the correction, it is possible to talk about sufficiently accurate measurements of the swirling air flow rate. It is possible to get rid of the correction when reducing the length of the honeycomb side and increasing the rectifying grid depth, but this will affect the increase in aerodynamic drag of the structure.

Conclusions

1. A universal air collector, which allows to measure air flow at the outlets of almost any air distribution devices of ventilation systems, has been developed.

2. The accuracy of the measurement does not depend on the structure of the air flow, since the latter is transformed into a single form inside the device. As a result, an air flow with a rectilinear profile flows onto the probe of the measuring device.

3. The developed air collector has minimal aerodynamic drag, due to which the air flow does not "sag".

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Розробка універсальної конструкції повітрозбірника для вимірювання витрати закрученого повітряного потоку за допомогою інтегрального термоанемометра

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Вимірювання витрат і середньої швидкості закрученого потоку повітря на повітророзподільних пристроях вентиляційних систем є досить складною задачею через натікання потоку повітря на вимірювальний пристрій під різними кутами. Як наслідок, при використанні точкових термоанемометрів або інших витратомірів можуть виникати значні похибки. Застосування інтегральних анемометрів полегшує вимірювальний процес. Однак похибки, пов'язані зі зміною кута натікання потоку повітря на чутливий елемент вимірювального пристрою, слід усунути. Для цього необхідно забезпечити прямолінійну структуру повітряного потоку за допомогою перехідного повітрозбірника й випрямляча. Метою роботи є розробка конструкції повітрозбірника, що дозволить вимірювати витрату закрученого повітряного потоку. Завдання – оптимізація геометричних параметрів повітрозбірника для забезпечення прямолінійної течії, мінімізація його габаритів й аеродинамічного опору. Правильність вибору конструкції повітрозбірника оцінювалася збігом градуювальної характеристики зонда інтегрального термоанемометра при наявності вихрового дифузора перед повітрозбірником та за його відсутності. Запропонований пристрій має прямокутну форму і складається з приймача, випрямляючої решітки, камери, розгінної і стабілізуючої ділянок, на виході яких встановлюється зонд термоанемометра. Приймач і розгінна ділянка звужуються по своїй довжині, а камера і стабілізуюча ділянка мають постійний переріз. Випрямляюча решітка встановлюється всередині камери і являє собою конструкцію зі стільників квадратної форми. За допомогою комп'ютерного моделювання досліджено декілька варіантів конструкції повітрозбірника з різними геометричними параметрами. Побудовано залежність аеродинамічного опору від витрати повітря. Як оптимальну обрано конструкцію повітрозбірника, для якої була створена фізична модель у натуральну величину. Експериментальним шляхом отримані градуювальні характеристики вимірювального зонда з повітрозбірником при натіканні закрученого повітряного потоку. Розроблений універсальний повітрозбірник дозволяє проводити вимірювання витрати повітря на виходах практично будь-яких повітророзподільних пристроїв вентиляційних систем будівель.

***Ключові слова**: повітрозбірник, термоанемометр, вимірювання витрати повітряного потоку, закручений повітряний потік.*

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