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INTEGRAL THERMO-ANEMOMETERS FOR AVERAGE TEMPERATURE AND AIRFLOW MEASUREMENT IN DUCTS, AT ANEMOSTAT OUTLETS AND IN VENTILATION GRILLES

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When creating ventilation systems, it is important to correctly calculate the volumes of air inflow and outflow. If an error is made in the calculation or a redistribution of air flows is required, measurements are indispensable. The existing methods for determining the air flow rate by using point measurements in the cross-section are laborious and time-consuming, and taking readings at different time points introduces a significant error into the result. A. M. Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine has developed a new hot-wire anemometer whose use greatly simplifies the measuring process. This device allows one to measure the average values of temperature and air velocity (flow rate) in the cross-section of air ducts or at the inlets and outlets of grilles and anemostats, and can be used in real time to monitor and control air flow rate and temperature in ventilation systems. The probe of the hot-wire anemometer is a metal shell with guides on which a sensitive element is laid. Its principle of operation is to change the heat transfer coefficient at different air leakage velocities. The anemometer is preliminarily calibrated in laboratory conditions at various velocities. There has been obtained a calibration dependence that can be used to measure the air flow rate at the inlets and outlets of air distribution devices and directly in the air ducts. To improve the measurement accuracy, it is necessary to provide the 90° angle of airflow leakage on the hot-wire anemometer probe. For this, special air collectors and air flow rectifiers are used.

Keywords: *hot-wire anemometer, measurements, sensitive element.*

Main Part

When studying ventilation systems, it is necessary to measure the flow rates and average temperatures of air flows in ducts, at outlet grilles, and in ventilation installations. GOST 12.3.018–79 "Ventilation systems. Aerodynamic test methods" establishes the requirements for testing ventilation systems, including the requirements for measuring equipment, the location of the measurement section, the number and coordinates of measurement points. The test method is rather complicated, it is not suitable for real-time observation and, moreover, can introduce significant errors in the measurement process.

To measure the air flow velocity or rate in ventilation systems, anemometers are used [1]. There are several types of these devices, different both in the principle of operation and measurement of various physical quantities: pressure difference (the device is a differential manometer [2], and the probe is a Pitot tube), electrical resistance or current strength (the device is a hot-wire anemometer [3], and the probe is usually a heated string, but there may be others, for example, a thermo-film [4]), as well as rotation frequency (the device is a mechanical rotation frequency meter, and the probe is a vane or cups [5]). Each of the anemometers has its own field of application, depending on external conditions, the state of air environment, the structure of flow, and the measurement range of air flow velocity.

For ventilation systems installed in residential, administrative, office, and other premises not related to production, there is a constraint on the maximum velocity of airflow in air ducts, which should not exceed 6 m/s. In the range of air velocity variation from 0.5 to 10 m/s, the most accurate instruments are hot-wire anemometers. Their disadvantages include the sensitivity to turbulence [6] and the angle of airflow leakage on the string surface, which introduces an error in measurements. Probes of modern hot-wire anemometers are compact (the minimum diameter is 10–15 mm), which makes it possible to carry out point measurements [7] in measurement sections according to the coordinates established by the GOST. Such a measurement process is quite laborious, since the dimensions of measuring probes are often several times smaller than the cross-

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sections of ventilation ducts (the minimum diameter of industrial air ducts is 80 mm). Besides, the airflow velocity distribution is irregular over the cross-section of an air duct, and there may be turbulent pulsations in it. In [8], an assessment of the measurement accuracy in ventilation systems is given. It is shown that it is impossible to take into account all the factors affecting the error, which is why when commissioning and certifying ventilation systems, it is necessary to include an error of at least 20%.

In this regard, the probe must have a design with the help of which it is possible to carry out simultaneous measurements of airflow velocity at several points of the measurement section, followed by summation and obtainment of the total flow rate therein. This idea is embodied in the Testo420 instrument from Testo, the renowned manufacturer of measuring instruments. In this anemometer, the probes are collector-united differential and static pressure sensors with multiple holes lengthwise. Both collectors are connected to the inputs of an electronic differential pressure gauge. The device is designed to operate at an average air velocity of 5 m/s and higher.

The vane anemometer is designed to determine the velocity in the range from 0.5 to 30 m/s. Its advantages include good resistance to measuring the velocity of turbulized air flows. Small-diameter vanes are used for measurements in air ducts, and vanes with diameters from 60 to 100 mm are used at inlets and outlets of air distributors. In the case of exceeding the dimensions of measurement sections relative to the size of the probe, the technology of scanning the section with point measurements is applied, followed by the calculation of the total flow rate. It should be taken into account that the vane size is large enough, which directly affects the flow structure, introducing distortions into the measurement process [9].

Swirling air flows for all three types of probes can be measured when air collectors and flow rectifiers are used. At the same time, the air collector and flow rectifier must correspond to the shape and flow cross-section of the probe flow path.

Modern anemometers allow simultaneous measurement of temperature and flow rate with an additional temperature sensor. They are also equipped with a number of auxiliary functions that facilitate the process of mathematically processing measurement results, for example, that of averaging over time interval [10]. However, the averaging of velocity measurements over the cross-section of an duct has been implemented only in the Testo420 instrument.

In order to reduce the time and increase the accuracy of measurement, a probe has been developed – an integral hot-wire anemometer (Fig. 1), which is designed to measure the average temperature over the duct cross-section and the velocity (or flow rate) of the airflow in ducts of various shapes, as well as to determine the thermal energy transported by air. The working range of velocity measurement for it is from 0.5 to 10 m/s. For cylindrical and rectangular ducts, the hot-wire anemometer probe is made of a shell (body) 1, holders 2 in the spacing grooves of which a flexible sensing element 3 is fixed, and a terminal block 4. The sensing element (SE) (Fig. 2) consists of a central core 1 having a high specific electrical resistance, which is weakly dependent on temperature. The core is covered with an electrically insulating sheath 2, over which a thin enameled wire 3 is wound, its resistance having a known temperature dependence. The ends of the core and wire are connected to a terminal block 4 placed on the outer surface of the duct. The SE is located in the plane of the cross-section of the probe flow path with a placement step from 0.03 to 0.075 of the hydraulic section diameter. The SE placement step is so chosen that the relative area of the probe flow section is not less than 0.85, which is a compromise solution, since, on the one hand, it is necessary to have low aerodynamic resistance, and on the other hand, obtain a velocity distribution close to the real one in the measurement section, which is directly related to the SE length and its placement step.

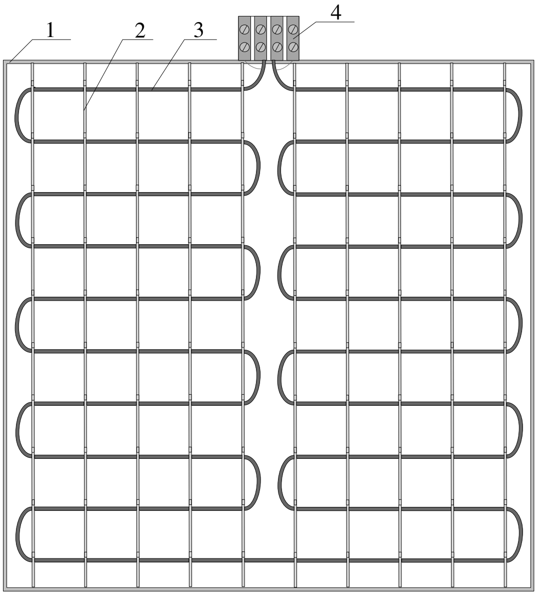

Fig. 1. A sketch of the measuring probe of a hot-wire anemometer

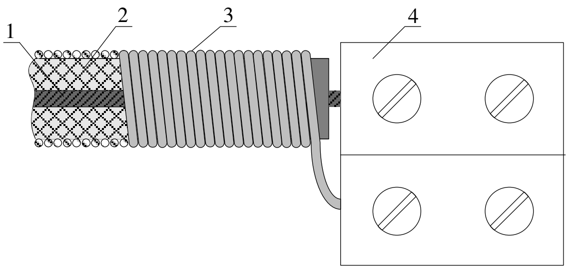

Fig. 2. A scheme of connecting the central core and the SE wire to the terminal block

The measuring probe has two modes of operation: passive and active. The passive mode is used to measure the integral airflow temperature when the probe is a flexible resistance thermometer. The measuring current passing through wire 3 (see Fig. 2) is small, and the released heat energy has practically no effect on the temperature measurement accuracy. The active mode is designed to measure the flow rate or the average velocity of the airflow passing through the duct. In this mode, the heating of the SE is carried out by the current flowing through the central core. On the SE surface, its value must provide a heat flux density of at least 6,000 W/m^2 for measuring the velocity in the range from 0.5 to 10 m/s. With increasing airflow velocity, the thermometer resistance sensitivity and accuracy decrease. Therefore, to increase it, it is necessary to increase the electric current. The resistance of the wire, when heated, increases according to the dependence from which it is easy to determine the SE surface temperature, which depends on airflow velocity and the radiant component of the total heat flow. The resistance of the hot-wire anemometer can be determined by the formula

$$R = R_0 + \gamma \cdot T_{\text{surf}} ,$$

where R is the resistance of the hot-wire anemometer; R_0 is the resistance of the hot-wire anemometer at a temperature of 0 °C; γ is the coefficient of resistance dependence on temperature; T_{surf} is the SE surface temperature.

The correspondence between the SE velocity and temperature is determined in the steady-state temperature mode. Three mechanisms are involved in the process of heat exchange: convective, radiant, and conductive. The participation of conductive heat transfer in the heat exchange at the points of contact of SE surfaces with holder grooves (see Fig. 1) can be neglected, since the contact between the surfaces is pointwise, and is affected only by the dynamic airflow pressure, which at a maximum permissible velocity of 6 m/s will not exceed 20 Pa. During measurements, the airflow temperature is equal to the temperature of probe walls and the air collector or the flow path of the air duct, differing little from the average temperature of the surfaces of the enveloping structures of the premises where the measurements are taken. Therefore, one can assume that the conditions during probe calibration and use during measurements will be practically the same. The SE surface temperature under these conditions, when the airflow velocity changes from 0.5 to 10 m/s, will change from about 100 °C to 40 °C, and the radiant heat flux will vary from 12% to 1.4% of the total heat flux dissipated by the probe SE for the constant-current method. The constant- temperature method, in contrast to the previous one, narrows the range of variation of the radiant component of the heat flux. During calibration or measurements with the use of this probe design, one should take into account the correction associated with the radiant flux. The calculation of the radiant heat flux itself is carried out by the well-known formula

$$Q = C_s \cdot \varepsilon \cdot F \cdot \left(\left(\frac{T_{\text{surf}}}{100} \right)^4 - \left(\frac{T_{\text{air}}}{100} \right)^4 \right),$$

where C_s is the Stefan-Boltzmann constant; ε is the emissivity factor, in our case it is taken equal to 1; F is the SE surface area; T_{air} is the air temperature.

To study the influence of the longitudinal and transverse components of the thermal conductivity vector, as well as the wavy surface of the SE (Fig. 2) on the heat transfer coefficient, two SE versions were made from smooth wire of different thermal conductivity: stainless steel (12.6 W/(m·K)) and nickel (58 W/(m·K)). In these designs, the SEs served both as a heater and a resistance thermometer. Comparison of the three characteristics of the SEs showed good agreement of results (deviations from the dependence for the SE wavy surface did not exceed 3%) [11]. This allowed us to conclude that the waviness reduced the SE surface by a factor of 0.95 relative to the surface with the diameter measured between the wave tops (the wave height of 0.06 mm is commensurate with the boundary layer thickness). In this case, the waviness did not affect the calibration characteristic of the probe SE. As for the thermal conductivity, it does not affect the dimensionless heat-transfer functions for small diameters of the SE relative to its length. The studies carried out made it possible to simplify the model of the thermal state of the probe SE and describe it by the equation

$$Q = I^2 \cdot R = I \cdot U = \alpha \cdot \pi \cdot d \cdot l \cdot \left(T_{\text{surf}} - T_{\text{air}}\right) + Q_p ,$$

where Q is power; I is electric current; U is electric voltage; R is electrical resistance; d is the SE diameter; l is the SE length; α is the heat transfer coefficient (convective + radiant); Q_p is the heat power losses through the holders and terminal block.

The airflow velocity measurement, using an integral hot-wire anemometer, as well as wire sensors, can be performed both by the constant-resistance method (T_e=const) and by the constant-current method. In practice, for hot-wire anemometers, the constant-temperature method is often used.

In our case, the measurements are carried out by the constant-current method. The central core of the hot-wire anemometer is made of either manganin or constantan, which makes its resistance insensitive to temperature. The presence of stabilized voltage sources removes the technical difficulties in maintaining the required current for correct measurements of electrical power. With changing airflow velocity, the SE resistance changes, the velocity being calculated according to its measured value.

The measurement duration includes the settling time (about 60 s) and the averaging time of the measurement result for at least 60 s. As a result, in the measurement section of the probe, we obtain the average volumetric velocity for this period of time. The SE inertia and the high thermal conductivity of the copper wire do not allow measurements of the velocity pulsation component.

The probes are calibrated in an open wind tunnel by two methods: according to the readings of the "reference" integral hot-wire anemometer, designed according to the principle described above, and by the method of balancing electrical and thermal power. In this case, to eliminate the influence of radiation fluxes between the hot-wire anemometer and the string integral resistance thermometers located in front of the hot-wire anemometer and after it, corrugated holed screens are installed, returning radiation energy fluxes to the flow path of the probe and ultimately increasing the airflow temperature difference between the wind tunnel inlet and outlet. In this case, the airflow rate measurements are carried out by the constant-temperature method, and the airflow temperature measurements are carried out by string resistance thermometers designed to calculate airflow rate by the method of balancing electrical and thermal power

$$Q = c_p \cdot G_m \cdot \left(T_{\text{air2}} - T_{\text{air1}}\right),$$

where c_p is the specific heat capacity of air at a temperature of $0.5 \cdot (T_{\text{air2}} + T_{\text{air1}})$; G_m is the mass airflow; T_{air2} and T_{air1} are the air temperatures at the outlet and inlet of the wind tunnel.

To increase the accuracy of measuring the temperatures T_{air2} and T_{air1}, the reference hot-wire anemometer's heat release power should be as high as possible. Therefore, the power is regulated by a voltage value of up to 220 V, while it can reach a maximum value of 2 kW. For graduated hot-wire anemometer probes, the power dissipated by the SE is from 35 to 100 W. The calibration of the reference probe of the hot-wire anemometer is carried out at the Vitashinsky nozzle by means of a Pitot-Prandtl tube and a differential pressure gauge. The calibration of portable and stationary probes is carried out in the zone of steady rectilinear air flow in the wind tunnel flow path.

The hot-wire anemometer readings do not allow the airflow direction to be determined. If there are local circulations, reverse flow or swirl airflow in the flow path of the measurement section, they introduce an error in the measurement results. In order to eliminate the influence of these factors, the measurements should be carried out in the duct sections where the airflow is straight. For example, when determining the performance of axial fans, the probe must not be installed in the discharge duct, since at an airflow swirl angle of 30°, the heat transfer coefficient will increase by 1.3 times compared to the direct (non-swirl) airflow mode [12]. Therefore, the airflow rate must be measured at the suction duct inlet where there is no swirl.

The computational studies carried out to clarify the influence of the asymmetric distribution of the airflow velocity in the duct section on the integration error showed that with the irregularity coefficient equal to 3, this error in the velocity measurement range from 0.5 to 5 m/s will not exceed 1%. Moreover, with an increase in the measurement range, the irregularity coefficient decreases, and the integration error remains constant. This is mainly due to the irregularity of temperature distribution on the SE surface. Since the SE surface is an enameled copper wire with a diameter of about 0.1 mm, the high thermal conductivity of the material makes the surface sensitive to the thermal influences that cause a change in temperature and its further leveling. The equalization of the SE surface temperature is a response to pulsating airflow effects.

In the studies, the SE diameter varied from 1.8 to 3.5 mm, and its length was chosen based on the aerodynamic resistance of the probe, which, in turn, depends on the blockage of the duct. For all the probes, the ratio of the areas of flow and total cross-sections was not less than 0.85. The SE placement can be either radial or circumferential. From the technological point of view, it is easier to place the SE circumferentially. For cylindrical probes, the SE pattern can be either in the form of an Archimedean spiral or circular zigzags, and for rectangular ones (see Fig. 1), straight zigzags.

To understand how the process of integrating the flow rate of the air passing through the measurement section of a circular probe works, we represent its area equal to the area of the tape with the same width *h* along the whole length. The tape itself is a shape close to the Archimedean spiral. The minimum number of turns of the spiral is 4. The more turns, the longer the tape and SE, which means that the flow rate is determined more accurately. The SE is placed along the whole length of the center line of the non-existent tape, determining the average airflow velocity along its width. Here, the distributed velocity field is considered as the total volumetric velocity consisting of the sum of discrete volumetric velocities w_i passing through elementary areas (of equal area) into which the tape is conventionally divided along its whole length. The averaging of the airflow velocity is carried out relative to the curvilinear center line of the *i*-th elementary area of width *h* and the SE unit section of length l_i, equal to the diameter of wire 3 (see Fig. 2). Under the influence of the velocity of airflow through the *i*-th elementary area, the electrical resistance in the *i*-th section of the SE changes. Since all the SE sections have electrical series connections with each other and are a single copper wire, then all the changes in resistances in the SE sections are automatically summed up, and the total resistance of the total wire length is obtained.

To determine the airflow rate, it is necessary to measure the electric voltage at the ends of the SE core, the airflow temperature, and the SE surface temperature. Probes with diameters of 160, 200, 250, 300 and 350 mm were studied experimentally. The heat flux density, reduced to the SE surface, varied from 2,000 to 1,2000 W/m^2, which made it possible to increase sensitivity in the range of velocity field measurements from 0.5 to 10 m/s.

In the measurement of heat transfer coefficients from the SE to the air, the experimental data array contained 87 measurements (three models, with the SE placement in the form of an Archimedean spiral; shell diameters of 160, 200, 250 mm, and a 15–30 mm pitch between adjacent turns. The studies have shown that the heat transfer coefficient depends only on the diameter of the flexible heating element, and the airflow velocity in the flow cross-section of the hot-wire anemometer duct. With a decrease in pitch between the turns, the blockage of the flow path of the hot-wire anemometer probe and its aerodynamic resistance grow, which increases the air velocity in the flow cross-section and, accordingly, heat transfer. When air moves through the probe flow path, its spatial orientation (horizontally, vertically) does not affect the heat transfer coefficient, since, due to the small diameter of the SE, free convection around it cannot noticeably distort the nature of flows at low velocities due to the fact that they are carried outside the measurement section.

There were investigated several designs of probes connected with a parabolic air collector in which the inlet section had a diameter of 0.3 m, and the outlet one, 0.2 m. The probe flow-section diameter was 0.2 m, and the SE diameter was 0.0025 m. The SE was placed in the probe section in the form of an Archimedean spiral with 6 turns. This design was developed to measure the airflow rate at the outlet of the anemostat. With a rotating poppet valve in the design, it was possible to change the aerodynamic resistance of the system. Fig. 3 shows the measurement results for 4 operating modes: without anemostat and with three different poppet valve mounting positions.

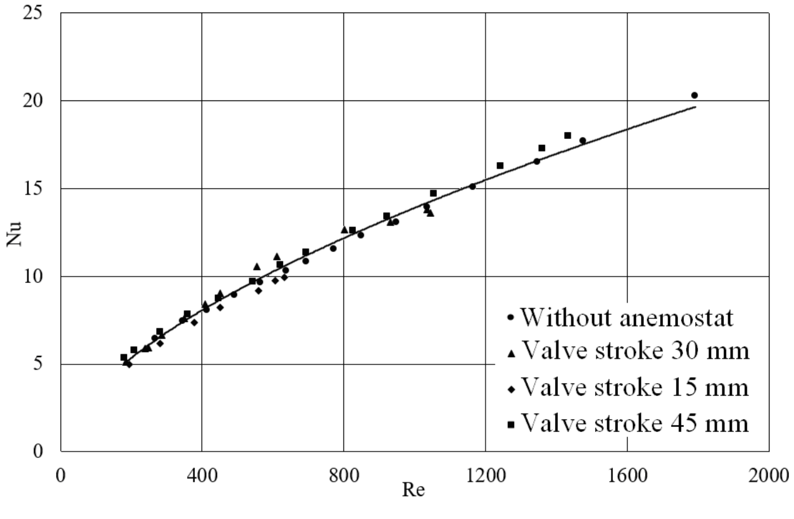

Fig. 3. Results of the study of heat transfer from the probe of the integral hot-wire anemometer

It can be concluded that the results of studying heat transfer in different modes practically do not differ from each other, and they can be approximated by a single generalizing dependence in dimensionless form

$$\mathrm{Nu}=0.2282\cdot\mathrm{Re}^{0.5947},\ \mathrm{Nu}=\frac{\alpha\cdot d}{\lambda},\ \mathrm{Re}=\frac{w\cdot d}{\gamma},$$

where λ is the thermal conductivity coefficient; w is the airflow velocity in the flow section of the hot-wire anemometer probe; γ is kinematic viscosity.

The measurement results deviation from the approximated curve does not exceed 4%.

The Use of Integral Hot-Wire Anemometers

It is necessary to distinguish between two design versions of probes of integral hot-wire anemometers.

Option 1. Stationary probes are designed to monitor and control the airflow in order to create the required indoor climate at minimum energy costs. A stationary probe is installed in a straight section of the ventilation duct in places where a straight airflow is observed. It is usually characterized by straight duct sections, flanged on either side of the probe. The length of each section is equal to six hydraulic duct diameters. The probe itself is a section of the duct, with an SE located in its middle cross-section.

Option 2. Portable probes are designed to examine and adjust the combined extract and input ventilation system. Airflow measurements are carried out at the outlets and inlets of anemostats, air distributors, ventilation grilles, and in the ventilation units themselves. In these cases, one observes an irregular turbulized airflow structure which can have both swirl and reverse flows resulting in large measurement errors. Thus, in [12], the influence of the angle of airflow leakage on heat transfer is analyzed, and it is shown that the heat transfer coefficients for direct and swirl airflows can differ by more than 1.5 times. Other causes of turbulence can cause even greater deviation from true results. To get rid of these errors, it is necessary to transform the airflow by means of a funnel (bell) and a rectifier which have the shape of the probe section. When choosing the size of the funnel, one must take into account the fact that the funnel together with the probe should not influence the airflow measurement, i.e. it must have negligible aerodynamic resistance relative to the resistance between the outlets of the air distributor and the ventilation unit. To fulfill this condition, the flow area of the probe cross-section must be at least 2.5 times the flow area of the air-distributor cross-section.

The selection and study of the designs of air collectors for measuring the parameters of the airflow at the outlet of air distribution devices will be considered in subsequent works.

Conclusion

The developed integral hot-wire anemometer can be used to measure the airflow rate and air temperature in ventilation systems. The main thing is to ensure the conformity of the airflow structure during calibration and research on a real object, for which additional matching and rectifying devices are used. The designs of such air collectors together with integral probes for various flow structures require further research in order to minimize the errors introduced by air collectors into the measurement process.

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Інтегральний термоанемометр для вимірювання середньої температури і витрати повітря в каналах, на виходах анемостатів і в вентиляційних решітках

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Під час створення систем вентиляції важливо правильно розрахувати обсяги припливу і відпливу повітря. Якщо під час розрахунку допущена помилка або потрібен перерозподіл потоків повітря, без вимірювань не обійтися. Існуючі способи визначення витрати повітря за допомогою точкових вимірювань в перерізі трудомісткі і вимагають значних витрат часу, а зняття показань в різні моменти часу привносить в результат значну похибку. В Інституті проблем машинобудування ім. А. М. Підгорного НАН України розроблений термоанемометр нової конструкції, використання якого значно спрощує вимірювальний процес. Він дозволяє проводити вимірювання середніх значень температури і швидкості (витрати) повітря в перерізі повітропроводів або на входах і виходах решіток і анемостатів. Прилад може використовуватися в режимі реального часу для контролю і керування витратою і температурою повітря в системах вентиляції. Зонд термоанемометра включає порожнистий каркас з направляючими, на які укладено чутливий елемент. Принцип роботи приладу полягає в зміні коефіцієнта тепловіддачі за різної швидкості натікання повітря. Попередньо в лабораторних умовах проводиться градуювання термоанемометра за різних швидкостей. Отримано градуйовану залежність, яка може використовуватися під час вимірювань витрати повітря на входах і виходах повітророзподільних пристроїв і безпосередньо в повітроводах. Для підвищення точності вимірювань необхідно забезпечити кут натікання повітряного потоку на зонд термоанемометра, що дорівнює 90°. Для цього використовуються спеціальні повітрозбірники і випрямлячі повітряного потоку.

Ключові слова: *термоанемометр, вимірювання, чутливий елемент.*

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