R is the electrical resistance of the foil;
S is the area;
β is the resistance temperature coefficient;
α is the heat-transfer coefficient from the surface to the fluidized bed;
q is the specific heat flux;
d is the particle diameter;
τ is the time.

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INFLUENCE OF THE INCOMPRESSIBLE STREAM TEMPERATURE ON COOLING OF A HOT WIRE

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Results are presented of an experimental investigation of the cooling of the hot wire of a thermoanemometer in an air stream for different wire and flow temperatures.

It is known that the results of measuring flow characteristics by a hot wire thermoanemometer contain systematic errors if the stream temperature changes during the experiment, albeit slowly, and differs considerably from the temperature at which the sensor was calibrated. To achieve a measurement accuracy under nonisothermal conditions which is close to the accuracy usually achievable in an isothermal flow, it is necessary to refine how the heat from the wire is eliminated as a function of the stream velocity and temperature and of the wire temperature.

A number of papers [1-12] has been devoted to this problem in recent years. Empirical formulas describing the cooling of the hot wire in a nonisothermal flow which have been proposed by different authors differ significantly among themselves. In discussing their reliability it is necessary to start from the fact that under isothermal conditions these formulas should go over into those verified well, e. g., into the most exact cooling law [5]:

$$\mathrm{Nu} = G(T,\ T_w)[A + B\,\mathrm{Re}^n], \tag{1}$$

$$G(T,\ T_w) = \left(\frac{T + T_w}{2T}\right)^{0.17}. \tag{2}$$

A detailed study [8] showed that the best calibration approximation is obtained for the wires of the thermoanemometer sensor types usually used when the coefficients A and B and the exponent n are determined

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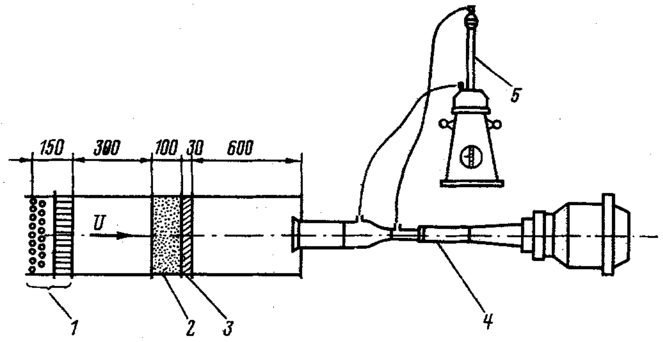

Fig. 1. Diagram of the experimental apparatus: 1) heater; 2) drying agent (SiO_2); 3) dust filter; 4) wind tunnel (DISA 55A60); 5) microanemometer (BETTs type).

separately for each probe. A prolonged test confirmed that the mean flow velocity can therefore be measured with a relative probable error of from 0.5 to 1% for small changes in the stream temperature (from 5 to 8°K). Hence, there results from an analysis of the empirical formulas in [1, 2, 5, 6, 10], describing the wire cooling law and in which the exponent of the Reynolds number is given in advance, that they are less accurate than those formulas in which the exponent of the Reynolds number is set up individually by calibration.

According to [10], the cooling law is described by (1) with an unknown additional temperature function $G(T, T_W)$. It can be obtained from the cooling law for the sensor being studied, represented in the form

$$Y = G(T,\ T_w)\left\{K_1 + K_2\left[\frac{H}{H_0}\left(\frac{T_m}{T}\right)^{-1.75} U\right]^n\right\}, \tag{3}$$

where the variable Y is defined as the ratio between the electrical current intensity Q_W needed to heat the wire to a constant temperature T_W and the difference between the wire T_W and fluid T temperatures multiplied by the temperature dependence of the fluid heat conduction coefficient λ:

$$Y = \frac{Q_w}{(T_w - T)(T_m/273)^{0.87}}. \tag{4}$$

The heat conductivity λ and the kinematic viscosity ν in the Nusselt and Reynolds numbers in [5] are taken at the effective wire temperature

$$T_m = \frac{1}{2}(T + T_w). \tag{5}$$

For a dry air flow it is assumed that

$$\lambda/\lambda_0 = (T_m/273)^{0.87},\quad \nu_0/\nu = \frac{H}{H_0}\left(\frac{T_m}{273}\right)^{-1.75}. \tag{6}$$

The wire parameters (length l and diameter d) are difficult to measure and the fundamental physical constants λ_0 and ν_0 of the fluid are included in formula (3), often used in the calibration:

$$K_1 = \pi l\lambda_0 A;\ K_2 = \pi l\lambda_0 B(d/\nu_0)^n;\ K_2' = K_2(H/H_0)^n. \tag{7}$$

Evidently, the function

$$Y = (K_1)_I + (K_2')_I U^n \tag{8}$$

describes cooling of a wire having the constant temperature $T_W = (T_W)_1$ by a flow with the velocity U and the constant temperature $T = (T)_1$. Statistical estimates can be found for the exponent n and the coefficients

$$(K_1)_I = K_1 C_I;\ (K_2')_I = K_2' G_I (T_m/273)_I^{-1.75n} \tag{9}$$

from the velocity calibration. The additional temperature function

$$Z \equiv \frac{G(T,\ T_w)}{G_I\,(\mathrm{const})} = \frac{Q_w}{(T_w - T)\left(\frac{T_m}{273}\right)^{0.87}\left[(K_1)_I + (K_2')_I\left(\frac{T_m}{T_{mI}}\right)^{-1.75n} U^n\right]}, \tag{10}$$

TABLE 1. Fundamental Sensor Parameters

Probe: material	Probe: number	l/d	R_0, Ω	$10^3 \alpha_e$, K^{-1}
W, $d=8$ mμ	101*	200	$1{,}842_2$	3,33
	102*	180	$1{,}450_5$	3,50
	151*	290	$1{,}255_2$	3,42
	152	290	$2{,}220_5$	3,49
	201*	390	$3{,}315_6$	3,45
	301*	600	$4{,}944_5$	3,43
	302	580	$4{,}932_1$	3,66
	151—W*	1170	9,760	$3{,}44_5$
	202—W*	1170	9,817	3,52
Pt/W, $d=4$ mμ	101—P	240	$2{,}460_4$	4,12
	102—P*	230	$2{,}723_3$	4,24
	152—P	350	3,902	4,13
	201—P	480	$5{,}366_5$	4,18

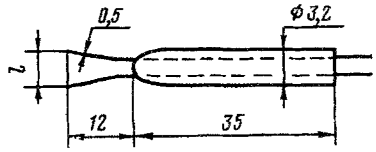

Fig. 2. Diagram of the shape of the probe housing and fundamental dimensions.

in which the values of the coefficients $(K_1)_I$ and $(K_2')_I$, the exponent n, and the effective temperature T_{mI} have the same magnitude that was described above, can be determined by means of measurements of the heat transfer from the hot wire in a stream for arbitrarily selected combinations of the velocity U and the temperatures T and T_W.

Experiments to determine the additional function were performed on the apparatus shown in Fig. 1. Atmospheric air was heated (to 3-kW intensity), passed through a layer of silica gel and a dust filter, and then sent to the small calibrating wind tunnel of the firm DISA (of the type 55A 60). The apparatus is completely heat insulated.

Probes with a hot wire placed perpendicularly to the flow direction were fastened in the measuring section. The fundamental probe data are presented in Table 1 and Fig. 2. All the sensors were fabricated at the Institute of Thermomechanics of the Czech SAN and differed only in their geometric dimensions (the asterisk in Table 1 denotes sensors with which the complete program of the experiments was performed).

The probe wires were connected in the circuit of a type 55M01 thermoanemometer of the firm DISA. The block diagram of the instruments is shown in Fig. 3. The air flow temperature was determined by the thermoanemometer sensor operating in the resistance thermometer mode. The resistance was measured by the thermoanemometer resistance bridge, or the more accurate Wheatstone bridge for different electrical currents and with extrapolation to zero current.

Cooling of the hot wire of each sensor was studied as a function of the parameters: the temperature of the wire T_W and the flow temperature T and velocity U. The accuracy of measuring these parameters and the electrical voltage E at the output of the thermoanemometer is presented in Table 2, in which the ranges or values of the parameters are also indicated. The sequences of five values of the stream temperature for each given flow velocity were distinguished as a function of the probe type and the flow velocity selected. However, the difference between the minimal and maximal temperatures T was always not less than 60°K for a given velocity.

Five typical graphs of the function Z determined by using (10) are shown in Fig. 4. The forms of the dependence of the function Z on the ratio between the effective temperature T_m and the stream temperature T show that it is convenient to approximate the function Z by the power law

$$Z = \frac{G(T, T_w)}{G_I} = C\left(\frac{T_m}{T}\right)^{-m}. \tag{11}$$

TABLE 2. Estimates of Measurement Accuracy and Range or Scales of the Fundamental Quantities

Quantity	Probable error of measurement	Scales (ranges) of parameters
E	± 3 mV	~
U	± 0.05 m/sec	10, 20, 30, 40, 50 m/sec
T	± 0.1 °K	275–360 °K
T_w	± 0.1 °K	$(300+k\cdot 50)$°K $k=0, 1, \ldots, 5$
T_m	± 0.2 °K	$(300+k\cdot 25)$°K $k=0, 1, \ldots, 4$

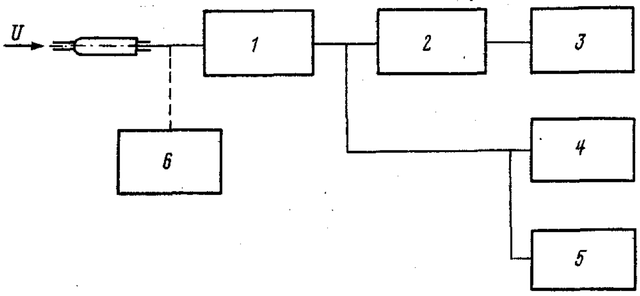

Fig. 3. Block diagram of the instruments: 1) thermoanemometer (DISA 55M01); 2) integrator; 3) dc digital voltmeter (MÉTRA MT 100); 4) rms voltmeter (DISA 55D35); 5) oscilloscope (TESLA BM 463); 6) Wheatstone bridge (Honeywell).

The systematic spread in the points measured for different stream temperatures is seen clearly (the scales of the stream temperatures are not identical for the different probes, but are always in the range 275-360°K). The spread will be the greater, the smaller the elongation of the hot wire. The probable reason for the appearance of this effect can be explained by the fact that the stream temperature T plays a more significant part in determining the effective wire temperature T_m than does the temperature of the wire T_w. This fact will be the more definite, the smaller the wire elongation. Bradbury and Castro [3] arrived at the same conclusion when they analyzed their measurements of the attenuation of the temperature of a pulse-heated wire. Analysis of the measurement results from this viewpoint must be continued. Let us note that the systematic errors in calculating the values of the function Z by means of (10) are neglected in estimating the results of the measurements for all measurements in which the ratio between the effective temperature and the stream temperature is greater than 1.05. The calculations were processed by the least squares method.

Statistical estimates of the exponents m and n in the generalized cooling law for a hot wire thermoanemometer are represented in Fig. 5:

$$\mathrm{Nu}\,(T_m/T)^m = A + B\,\mathrm{Re}^n. \qquad (12)$$

At the same time, as the exponent n on the number Re approaches the value 0.45 relatively rapidly with the increase in the wire length according to Collis and Williams [5], the exponent m of the additional temperature function is lowered more slowly with the increase in length and even has a sign opposite to the sign of the exponent on the function according to Collis and Williams.

The relative rms error σ is determined on the basis of the relative deviations

$$\delta U_i = \frac{U_i - U_i'}{U_i},$$

where U_i ($i = 1, 2, \ldots$) is the measured flow velocity at the temperatures T_i and T_{wi}, and U_i' is the value of the velocity calculated on the basis of the formula derived from (3), (4), and (11):

$$U = \left(K_2 \frac{\nu_0}{\nu}\right)^{-1} \left[\left(\frac{T_m}{T}\right)^m Y - K_1\right]^{1/n}.$$

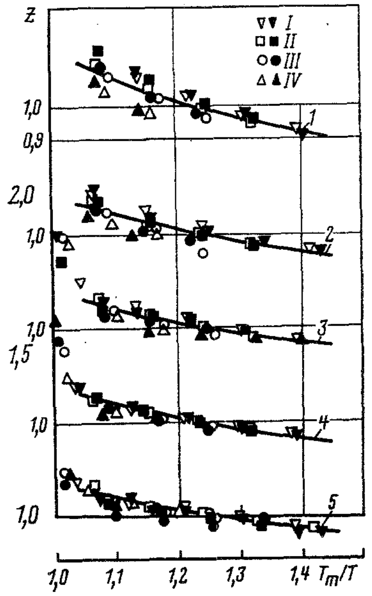

Fig. 4

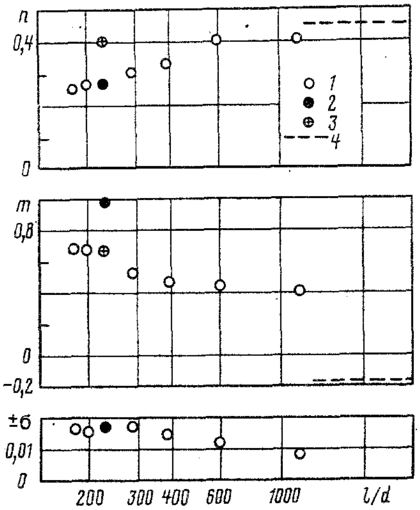

Fig. 5

Fig. 4. Examples of the dependence of the additional temperature function Z on the ratio between the effective temperature T_m and the stream temperature T: 1) probe No. 101; 2) No. 151; 3) No. 201; 4) No. 301; 5) No. 151-W; stream temperature scale $T_1 < T_2 < \ldots < T_5$ to which the points $I(T_1 \cdot T_2)$, $II(T_3)$, $III(T_4)$, $IV(T_5)$ correspond (the open points correspond to a 20 m/sec velocity, and the dashes to 50 m/sec).

Fig. 5. Statistical estimates of the exponents m and n of the cooling law (12) (σ is the rms relative error of interpolation of the flow speeds measured by using (12)): 1) wire; 2) wire with Pt film; 3) Koch and Gartshore measurement [10]; 4) Collis and Williams data [5].

Here K_1, K_2, m, and n are empirical coefficients and exponents. The error σ does not exceed 0.02, which confirms the satisfactory approximation of the additional temperature function.

There follows from the investigation of the cooling of the thermoanemometer wire heated to a temperature from 300 to 550°K in a dry air flow whose temperature varies in the 275-350°K range that:

1) The influence of changes in these temperatures on cooling of the wire can be taken into account with a mean relative accuracy of about 2% by using the generalized Collis–Williams cooling law (12). The coefficients A, B and the exponents m, n depend on the separate properties of each probe (material, elongation of the wire, etc.), and hence their values must be determined by calibration;

2) If a moderate reduction in accuracy (0.5-1%) is allowable, then the exponent m can be determined by calibration in an isothermal stream just by changing the hot wire temperature.

NOTATION

A, B	are the coefficients of the wire cooling laws (1), (11);
G	is the additional temperature function;
H	is the stagnation stream pressure;
K_1, K_2	are the coefficients of the wire cooling law expressed in the form (3);
Nu	is the Nusselt number;
R_0	is the electrical resistance of the wire at the thawing point of ice, $T_0 = 273°K$;
$R_W = R_0(1 + \alpha_e(T_W - 273))$	is the electrical resistance of the wire heated to the temperature T_W;
Re	is the Reynolds number;
T	is the stream stagnation temperature;

$T_m = 1/2(T + T_w)$	is the effective temperature;
m	is the exponent in the additional temperature function (10), (11);
n	is the exponent in the Reynolds number (1), (3), (12);
α_e	is the temperature coefficient of the specific electrical resistance;
$\lambda(T_m)$	is the fluid heat conduction coefficient;
$\nu(T_m)$	is the kinematic viscosity coefficient.

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MANUAL BALANCING OF THE TEMPERATURE ERROR IN CONSTANT-TEMPERATURE THERMOANEMOMETERS (WITH ZERO SETTING IN AN IMMOVABLE MEDIUM)

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The article presents a comparative analysis and a method of calculating bridge circuits for constant-temperature thermoanemometers with manual balancing of the temperature error.

Thermoanemometers are widely used in investigations of mass-transfer processes [1-3], and instruments that operate on the same principle are also used in gas chromatography [4]. Semiconductor thermistor sensors are mechanically stabler than wires, they have a much higher resistance and resistance temperature coefficient (which simplifies the measuring circuits), and they make it possible to measure the linear velocity (when the thermistor is bead-shaped). However, automatic balancing of the temperature error in thermoanemometers with direct-heating semiconductor sensors is a complicated problem. Yet in many cases the temperature of the flow t remains practically constant during the time of measurement, and then much simpler thermoanemometers may be used; they have manual balancing of the temperature error effected directly before the speed is measured [5-8]. A comparative analysis of the operation of these instruments shows that the most efficient manual balancing of the temperature error can be achieved by constant-temperature thermoanemometers.

Such thermoanemometers are based on a bridge circuit whose one arm contains a thermistor velocimeter and a feedback amplifier. The input terminals of the amplifier are connected to the measuring diagonal of the bridge, and the output terminals to the bridge supply diagonal (Fig. 1). By changing the bridge-supply voltage, the amplifier maintains the temperature θ of the meter and, consequently, also its resistance $R_{20^\circ} \exp\left(\frac{B}{\theta} - \frac{B}{293}\right)$ practically constant, and with specified $R_{20}°$ and B, the resistance $R(\theta)$ and temperature θ are determined by the resistance values of the bridge arms r_0, R_1, and R_2:

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