$T_m = 1/2(T + T_W)$	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)

I. Z. Okun'

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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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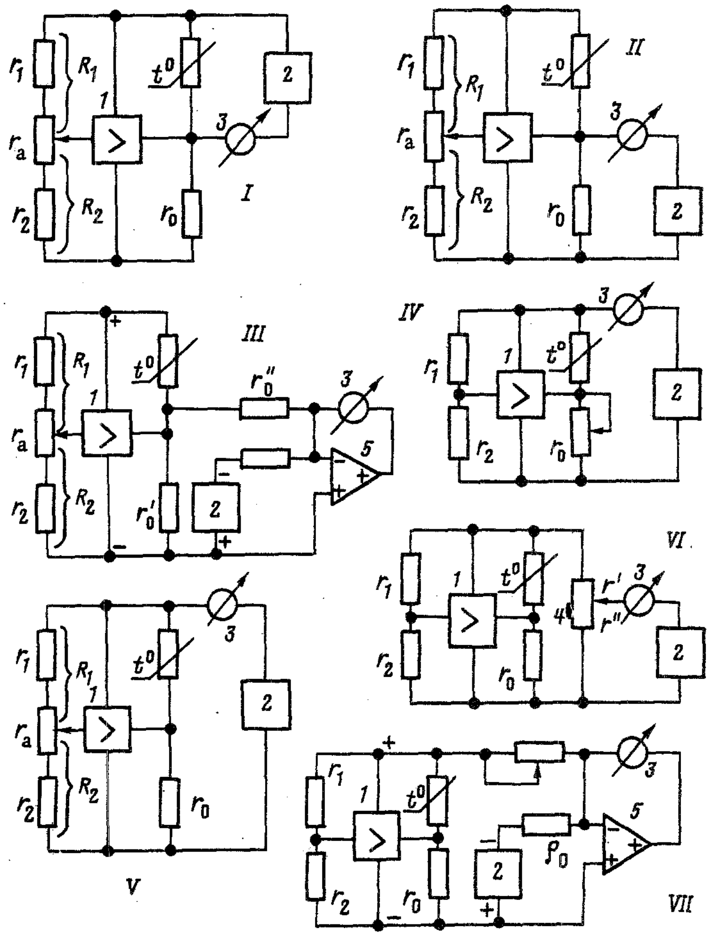

Fig. 1. Circuits of constant-temperature thermoanemometers with zero setting in an immovable medium: 1) feedback amplifier; 2) stabilized reference-voltage source; 3) measuring instrument; 4) potentiometer; 5) operational amplifier.

$$R(\theta) = r_0 \frac{R_1}{R_2},$$

$$\theta = \frac{B}{\frac{B}{293} + \ln \frac{R(\theta)}{R_{20^\circ}}} = \frac{B}{\frac{B}{293} + \ln\left(\frac{r_0 R_1}{R_{20^\circ} R_2}\right)} = F_\theta\left(r_0, \frac{R_1}{R_2}\right). \tag{1}$$

When the temperatures of the flow t and of the velocimeter θ change within the range of several tens of degrees, scattering coefficient H of the velocimeter in the first approximation may be considered dependent solely on the flow velocity v. From the equation of the heat balance of the velocimeter

$$i^2 R(\theta) = \frac{u^2}{R(\theta)} = H(v)(\theta - t) \tag{2}$$

the voltage u applied to it can be determined:

$$u = [H(v) R(\theta)(\theta - t)]^{1/2} = H^{1/2}(v)\left\{r_0 \frac{R_1}{R_2}\left[F_\theta\left(r_0, \frac{R_1}{R_2}\right) - t\right]\right\}^{1/2}.$$

Correspondingly, for the voltage of any arm of the bridge, and also for the voltage of the bridge supply diagonal, we can obtain an expression with an analogous structure:

$$u_i = H^{1/2}(v)\, \varphi_i\left(\frac{R_1}{R_2}, r_0, t\right). \tag{3}$$

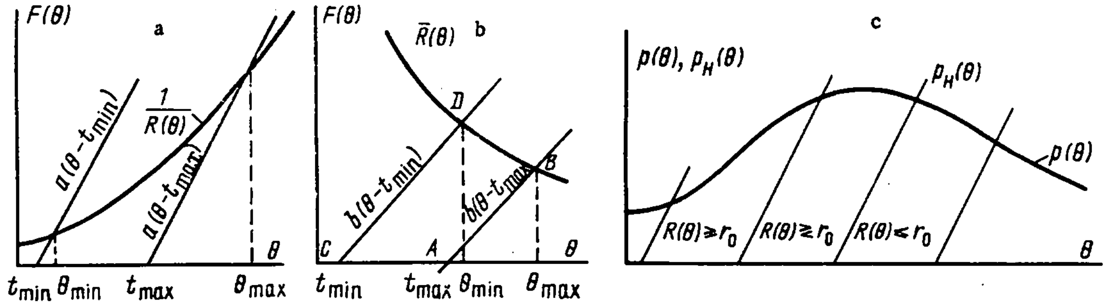

Fig. 2. Determination of the dependence $\theta = f(t)$: a) for circuits I and IV; b) for circuits II and III; c) for circuit V (for I–V, see Fig. 1).

Thus, the voltage u_i is determined by the production of two cofactors, one of which depends solely on the flow temperature t, and the other solely on its velocity v, and this is also the reason why manual compensation of the temperature error can be so simply effected. The relative error of speed measurement $\Delta v/v$, caused by a change Δt of the flow temperature during the time of measurement, with

$$H(v) = H_0 + bv^{\beta} \; (b, \; \beta \simeq \text{const [9]}), \tag{4}$$

is, as can be easily shown, equal to

$$\frac{\Delta v}{v} = -\frac{\Delta t}{\theta - t} \, \frac{H(v)}{\beta [H(v) - H_0]} \, . \tag{5}$$

The present article examines only thermoanemometers with zero setting in an immovable medium. When similar thermoanemometers are used in operations of thermal compensation, the velocimeter has to be protected by a removable jacket against direct flow past ($v = 0$, $H(v) = H_0$). After the jacket has attained the temperature of the flow, the voltage u_i, transmitted from the bridge to the measuring part of the circuit, is compared with some stabilized reference voltage U_0, and by changing the ratio of the resistances R_1/R_2 or the magnitude of r_0 in the bridge, and thereby by changing also u_i, it is made to remain constant, where $u_i - U_0 = 0$ (operation of "zero setting"). Then (3)

$$H_0^{1/2} \varphi_i \left(\frac{R_1}{R_2}, \; r_0, \; t \right) = U_0, \quad \varphi_i \left(\frac{R_1}{R_2}, \; r_0, \; t \right) = \frac{U_0}{H_0^{1/2}} \, .$$

As soon as zero has been set, the jacket is removed, and without changing the resistance of the bridge arms, the velocities are measured by measuring the difference $u_i(v) - U_0$:

$$u_i(v) - U_0 = U_0 \left\{ \left[\frac{H(v)}{H_0} \right]^{1/2} - 1 \right\} . \tag{6}$$

As mentioned before, the measuring voltage $u_i(v)$ may be the voltage behind any bridge arm or the voltage of the bridge- supply diagonal (in principle, currents flowing through the bridge arms that are proportional to these voltages may also be used for measurements).

Circuits with Voltage Measurement in the Bridge Arm. In circuit I (Fig. 1), a change in the ratio of the resistances of the bridge arms R_1/R_2 serves to maintain the velocimeter voltage u_0 constant when $H(v) = H_0$. In that case it follows from the equation of thermal balance (2) that

$$\frac{1}{\bar{R}(\theta)} = \frac{R_{20^\circ}}{R(\theta)} = a(\theta - t) \quad \left(a = \frac{H_0 R_{20^\circ}}{u_0^2} = \text{const} \right) . \tag{7}$$

A change in the temperature θ of the velocimeter and in its resistance $R(\theta)$ upon change in temperature of the flow t can be determined by the graphic solution of the transcendental equation (7) (Fig. 2a). It follows from the figure that the temperature θ increases more rapidly than t and that the superheating τ of the velocimeter relative to the flow changes within wide limits. This is a substantial shortcoming of the circuit in question because if the temperature of the meter is not to exceed the permissible value, either the range of changes in the flow temperature $t_{min} - t_{max}$ within which the measurements are carried out must be narrowed down or also, with a flow temperature $t \simeq t_{min}$, some small overheating of the meter must be tolerated, but that impairs the accuracy of the measurements.

In circuit II a change in the ratio R_1/R_2 helps, with $H(v) = H_0$, maintain the voltage u_i of the resistance r_0 constant (i.e., the current $i_0 = u_i/r_0$ through the velocimeter is maintained constant). It follows from Eq. (2) that

$$\bar{R}(\theta) = \frac{R(\theta)}{R_{20^\circ}} = b(\theta - t) \quad \left(b = \frac{H_0}{i_0^2 R_{20^\circ}} = \text{const}\right). \tag{8}$$

The graphic solution of Eq. (8) (Fig. 2b) shows that in this case the temperature θ of the meter increases more slowly than the flow temperature t; consequently, the range of changes in θ is narrower than the range of changes in t, which is an advantage of this circuit compared with the previous one.

The initial data for calculating the bridge circuit are the range of change in flow temperature $t_{min} \leq t \leq t_{max}$, the dependence of the thermistor resistance $R(\theta)$ on its temperature, and the dependence of the scattering coefficient H on the flow velocity v. If we specify the minimum value τ_0 of superheating the meter corresponding to the maximum flow temperature t_{max} (with increasing t, superheating τ decreases monotonically (Fig. 2b)), we can determine the maximum temperature of the meter $\theta_{max} = t_{max} + \tau_0$, the resistance of the meter $R(\theta_{max})$, and the current i_0 flowing through the meter when $H(v) = H_0$ (2):

$$i_0 = \left[\frac{H_0 \tau_0}{R(\theta_{max})}\right]^{1/2}. \tag{9}$$

The optimum value of τ_0 is on the order of magnitude of some tens of degrees [10, 11]. (An increase in τ_0 increases the power required by the bridge circuit, speeds up thermal aging of the meter, increases its intrinsic convective flow, and this makes measurements of low velocities of the medium difficult. Lowering of τ_0 impairs the "noise immunity" of the thermoanemometer [12], i.e., it impairs the accuracy of measurements.)

Then a straight line AB has to be drawn through the point $\theta = t_{max}$ of the axis of abscissas and the point $R(\theta_{max})$ of the curve $R(\theta)$ (Fig. 2b), and then the line CD through joint $\theta = t_{min}$ of the axis of abscissas parallel to AB (the slope of both straight lines is equal to b (8)). The point of intersection D of this straight line with curve $R(\theta)$ determines the minimum temperature θ_{min} of the velocimeter and its maximum resistance $\bar{R}(\theta_{min})$. If we stipulate the resistance r_0, we can determine the voltage u_M of the bridge supply diagonal corresponding to the velocities $v = 0$ and $v = v_{max}$. Since upon a change of temperature of the flow t, the current i_0 is maintained constant, it is obvious that u_M is largest when $t = t_{min}$ ($\theta = \theta_{min}$):

$$u_M(v = 0,\ t = t_{min}) = [H_0 \tau_0 / R(\theta_{max})]^{1/2}\,[r_0 + R(\theta_{min})], \tag{10}$$

$$u_M(v = v_{max},\ t = t_{min}) = [H(v_{max})\,\tau_0 / R(\theta_{max})]^{1/2} \cdot [r_0 + R(\theta_{min})]. \tag{11}$$

From the system of equations determining the ratio of the resistances of the bridge arms for two temperatures of the flow ($t = t_{min}$, $t = t_{max}$)

$$\frac{R(\theta_{min})}{r_0} = \frac{r_1 + r_a}{r_2}, \quad \frac{R(\theta_{max})}{r_0} = \frac{r_1}{r_2 + r_a}, \tag{12}$$

we can determine the ratios of the resistances r_1/r_2 and r_a/r_2:

$$\frac{r_1}{r_2} = \frac{1 + R(\theta_{min})/r_0}{1 + r_0/R(\theta_{max})}, \quad \frac{r_a}{r_2} = \frac{R(\theta_{min})/R(\theta_{max}) - 1}{r_0/R(\theta_{max}) + 1}, \tag{13}$$

and, by specifying r_2, we can determine r_1 and r_a.

In circuit II, with zero set, the arm r_0 is not loaded by the measuring circuit because in it the current is $i_m = (u_i - U_0)/r_m = 0$ (r_m is the sum of the resistances of the measuring instrument 3 and of the source 2 of the reference voltage U_0). When the velocity is measured, the current $i_m \neq 0$ flows through the measuring circuit and redistributes the currents and voltages in the arms of the bridge circuit. This causes a temperature error γ_t of the velocity measurement which, as can be easily proved, is equal to

$$\gamma_t = \frac{\Delta v}{v} = \frac{r_0}{r_m}\,\frac{1}{\beta\left\{1 + \left[\frac{H(v)}{H_0}\right]^{1/2}\right\}}\,\frac{t - t_0}{\alpha(\theta - t)(\theta - t_0)} \tag{14}$$

(here t_0 is the temperature of the flow upon graduation of the instrument; t, flow temperature at the given velocity measurement; $\alpha = B/t^2$, absolute resistance temperature coefficient of the thermistor at the temperature t). Circuit III is free of this shortcoming. In this case, the resistance r_0 of the arm is the same as in the regime of zero setting as well as in velocity measurement ($r_0 = r_0' \| r_0''$).

Circuits with Measurement of the Voltage of the Bridge Supply Diagonal. In circuit IV, constant voltage u_M in the bridge supply diagonal with $H(v) = H_0$ is attained by changing the resistance r_0. However, when u_M = const, the voltage u_0 of the velocimeter is also constant ($u_0 = u_M r_1/(r_1 + r_2)$), like with circuit I. Therefore, circuit IV has the same substantial shortcoming as circuit I (upon change of flow temperature t, superheating of the meter τ has to change within wide limits (Fig. 2a)), and it is therefore rather unsuitable for measuring flow velocities in a wide temperature range.

In circuit V, constant voltage u_M of the supply diagonal, with $H(v) = H_0$, is attained by changing the ratio of the resistances R_1/R_2. The dependences of superheating of the thermistor $\tau = \theta - t = f_1(t)$ and of the ratio of resistances $R_1/R_2 = f_2(t)$ with u_M = const can be determined by equating the power liberated in the thermistor

$$p = \frac{u_M^2 R(\theta)}{[R(\theta) + r_0]^2}, \tag{15}$$

with the power scattered by it

$$p_H = H_0(\theta - t) = H_0\left[\frac{B}{\ln\frac{R(\theta)}{R_{20^\circ}} + \frac{B}{293}} - t\right], \tag{16}$$

and taking (1) into account. The equations thus obtained are transcendental, and it is therefore better to determine the function $\tau(t)$ graphically, as shown in Fig. 2c. The point of intersection of the straight line $p_H = H_0(\theta - t)$ with the curve $p(\theta)$ determines the thermistor temperature θ, and consequently also its resistance $R(\theta)$, as well as the superheating τ.

Comparison of the three variants, a) $R(\theta) \geq r_0$; b) $R(\theta) \leq r_0$; c) $R(\theta) \gtrless r_0$, where we put for the sake of determinacy that

$$r_0 = [R(\theta_{min}) R(\theta_{max})]^{1/2}, \tag{17}$$

shows that when $R(\theta) \geq r_0$, superheating τ of the meter also increases with increasing t. When $R(\theta) \leq r_0$, superheating decreases with increasing t, and when $R(\theta) \gtrless r_0$ (the center section in Fig. 2c), τ changes slightly, i.e., the meter operates in a regime of almost constant superheating.

We require that when the flow temperature changes in the range $t_{min} \leq t \leq t_{max}$, the superheating of the velocimeter be not lower than the specified value τ_0, and with the aid of the relations (15) and (16) we determine the bridge supply voltage u_M = const (for $H(v) = H_0$ = const) and the maximum power required by it $P_{max}(H_0)$ (here we neglect the power scattered in the resistors r_1, r_2, and r_a, assuming that $r_1 + r_2 + r_a \gg R(B) + r_0$). For the variants a)-c) we obtain, respectively:

a) $u_M(H_0) = (1 + 1/k_1\xi_1)u_{min}$,

$$P_{max}(H_0) = \frac{1 + k_1\xi_1}{k_1(k_1 + \xi_1)} P_{min} \quad (k_1 \geqslant \xi_1);$$

b) $u_M(H_0) = (1/k_2 + 1/\xi_2)u_{min}$,

$$P_{max}(H_0) = \left(1 + \frac{\xi_2}{k_2}\right) P_{min} \quad \left(\frac{1}{k_2} \geqslant \xi_2\right);$$

c) $u_M(H_0) = (1 + 1/\xi_3)u_{min}$ (18)

$$P_{max}(H_0) = (1 + \xi_3) P_{min}, \tag{19}$$

where

$$\xi_i = \left[\frac{R(\theta_{min})}{R(\theta_{max})}\right]_i^{1/2} \quad (i = 1-3);$$
$$k_j = \frac{1}{r_0}[R(\theta_{min}) R(\theta_{max})]_j^{1/2} \quad (j = 1;\ 2); \tag{20}$$

$P_{min} = H_0\tau_0$ is the minimum power scattered by the velocimeter; $u_{min} = [H_0\tau_0 R(\theta_{min})]^{1/2}$ is the minimum voltage of the meter at which fulfillment of the condition $\tau \geq \tau_0$ in the entire range of changes of flow temperatures $t_{min} \leq t \leq t_{max}$ is ensured.

By stipulating t_{min}, t_{max}, τ_0, H_0, and a number of values of r_0, we can calculate u_M and determine (e.g., graphically, as shown in Fig. 2c) the range of temperature changes of the meter $\theta_{min} - \theta_{max}$, and then calculate ξ, k, P_{max} and compare the values of u_M and P_{max} for the variants a)-c). These calculations show that:

1) $\xi_1 > \xi_3 > \xi_2$;

2) the variant b) ($R(\theta) \leq r_0$) is uneconomical because it needs higher supply voltage and larger power of the supply source;

3) when the flow temperature changes within the range of several tens of degrees ($\xi_3 \simeq 2$-3), power P_{max} for the variant c) is somewhat lower and the voltage u_M somewhat higher than for variant a). The difference between the compared values P_{max} and u_M is small (on the order of magnitude of tens of percent).

Thus, in required power and voltage of the supply source, variants a) and c) are approximately equal. As mentioned above, an advantage of variant c) is that for it the superheating of the thermistor relative to the flow in the entire range of changes of its temperature t is almost constant and close to the value τ_0. Therefore, there is also only a small change in the intrinsic convective flow of the meter whose influence (which is substantial in measurements of low flow velocities on the order of several centimeters per second) can be taken into account in graduating a thermoanemometer.

The method of calculating the bridge circuit for variant c) is simple. When r_0 has a value satisfying relation (17), the power $p(\theta)$ liberated in the meter, and correspondingly the magnitudes of its superheating $\tau(\theta) = p/H_0$ for $\theta = \theta_{min}$ and $\theta = \theta_{max}$ are equal ($p(\theta_{max}) = p(\theta_{min}) = u_M^2\xi_3/r_0(1+\xi_3)^2 = p_0$), where $p(\theta) \geq p_0$, and, consequently, $\tau(\theta) \geq \tau_0 = p_0/H_0$. Thus, by specifying minimum superheating τ_0 near the boundaries of the range θ, we can determine the temperatures θ_{min} and θ_{max},

$$\theta_{min} = t_{min} + \tau_0, \quad \theta_{max} = t_{max} + \tau_0, \tag{21}$$

the values $R(\theta_{min})$, $R(\theta_{max})$, r_0 from (17), and ξ_3, u_M, P_{max} from (18)-(20). The maximum voltage of the bridge supply diagonal is equal ((3) and (18)) to

$$u_M(v_{max}) = (\xi_3^{1/2} + \xi_3^{-1/2})\,[H(v_{max})\tau_0 r_0]^{1/2}. \tag{22}$$

Then from system of equations (12) we can determine the ratios of the resistances r_1/r_2 and r_a/r_2:

$$\frac{r_1}{r_2} = 1, \quad \frac{r_a}{r_2} = \xi_3 - 1 \tag{23}$$

and, having specified r_2, we can calculate r_1 and r_a.

Circuits Containing an Element with a Manually Changed Transmission Factor. Two such circuits (VI and VII) are illustrated in Fig. 1. The voltage transmitted from the supply diagonal to the element with changed transmission factor $\varkappa$ is equal to

$$u_M = u\left(1 + \frac{r_2}{r_1}\right) = [R(\theta)H(v)(\theta - t)]^{1/2}\left(1 + \frac{r_2}{r_1}\right)\left(R(\theta) = r_0\frac{r_1}{r_2}\right). \tag{24}$$

The voltage at the output of the element $u_{out} = u_M\varkappa$ is compared with the reference voltage, with $H(v) = H_0$ (the velocimeter in the jacket) the value $\varkappa$ is set such that $u_M\varkappa = U_0$, and hence

$$\varkappa = \frac{U_0}{u_M} = U_0\frac{r_1}{r_1 + r_2}\,[H_0R(\theta)(\theta - t)]^{-1/2} = \varphi(t). \tag{25}$$

In velocity measurements, the voltage u(v) measured by instrument 3 is equal to

$$u(v) = \varkappa u_M(v) - U_0 = U_0\left\{\left[\frac{H(v)}{H_0}\right]^{1/2} - 1\right\} = f(v). \tag{26}$$

In circuit VI, the element with variable transmission factor is the potentiometer 4. During zero setting, it is not loaded ($\varkappa u_M - U_0 = 0$). However, when velocity is measured, current i_m flows in instrument 3, loads the potentiometer, and changes its transmission factor $\varkappa(t)$. Calculations show that the relative error of velocity measurement thus caused is equal to

$$\frac{\Delta v(t)}{v} = \frac{2}{\beta\left\{1 + \left[\frac{H_0}{H(v)}\right]^{1/2}\right\}}\,\frac{\rho_1 - \rho_2}{\rho_1 + r_m}, \tag{27}$$

where (see Fig. 1, VI) $\rho_1 = r'r''/(r' + r'')$ for a position of the potentiometer wiper corresponding to the graduation temperature t_0 of the instrument; $\rho_2 = r'r''/(r' + r'')$ for the position of the potentiometer wiper corresponding to the temperature t in the given velocity measurement, r_m is the sum of resistances of instrument 3 and source 2 of the reference voltage. This shortcoming is eliminated in circuit VII, for which the current flowing through the measuring instrument 3 is equal to

$$i(v) = \frac{U_0}{\rho_0}\left\{\left[\frac{H(v)}{H_0}\right]^{1/2} - 1\right\}. \tag{28}$$

In this case, i(v) does not depend on the temperature difference of the flow in measurements and graduation.

The above analysis shows that circuits of constant-temperature thermoanemometers with zero setting in an immovable medium are very simple and may be the basis for designing cheap portable instruments for widespread application. The method of calculating them is also simple. A great advantage of these instruments is that for their unification it suffices to unify the velocity characteristic of the scattering coefficient $H(v)/H_0$ of the thermistors; the spread of their values of resistance, resistance temperature coefficient, and H_0 is not of fundamental importance (this follows from formulas (6), (26), and (28)).

The error of velocity measurement with the above instruments is determined chiefly by the following factors: by changes in the temperature of the flow during measurement (see (5)) and of the characteristic $H(v)/H_0$ of the meter in operation (which may be caused by a dirty surface of the meter which impairs heat transfer from it); by instability ΔU_0 of the reference voltage; it follows from (4) and (6) that

$$\frac{\Delta v}{v} = \frac{2}{\beta\left\{1 + \left[\frac{H_0}{H(v)}\right]^{1/2}\right\}}\,\frac{\Delta U_0}{U_0}. \tag{29}$$

NOTATION

t	is the flow temperature;
θ	is the velocimeter temperature;
$R(\theta)$	is the velocimeter resistance;
r_0, r_a, r_1, R_1, R_2	are the resistances of the bridge circuit;
v	is the flow velocity;
H	is the scattering coefficient of the velocimeter;
H_0, u_0	are the scattering coefficient of the velocimeter and its voltage in an immovable medium, respectively;
U_0	is the voltage of the stabilized reference voltage source;
τ	is the superheating of the velocimeter relative to the flow;
τ_0	is the minimum value of τ;
u_M	is the voltage of the bridge supply diagonal;
p, P	are the electric powers in the sensor and in the bridge, respectively.

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