DETERMINATION OF THERMAL INERTIA OF MICROTHERMOCOUPLES IN AN AXISYMMETRIC AIR JET

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Results are presented of an experimental investigation of the inertia of microthermocouples in an air jet by the regular thermal regime method. It is shown that for Re numbers from $2 \cdot 10^2$ to 10^4 in the temperature range 50 to 230°C, the test data can be fitted to a correlation.

At the present time considerable attention is being given, in parallel with investigations of turbulent velocity fluctuation fields, to study of temperature fluctuations in gas flows. In experimental measurements of rapidy changing temperatures low-inertial thermal sensors of small dimensions with sufficient mechanical strength and rigidity must be used.

It is known [1, 2], that the capability of a thermal sensor to react to a change in thermal state depends on its construction and size and the physical properties of its material, as well as on the conditions of heat transfer and the method of attachment. In spite of this, calculation of thermal inertia analytically is mathematically very difficult. Only a limited volume of test data has been published on thermal inertia of different classes of thermal sensors under specific conditions of operation.

In this paper the inertia of the thermocouples was studied experimentally using the regular thermal regime method. The time constant was defined to be the time required for the temperature difference between the gas and the sensor, following a step change of temperature, to decrease to 63% of its initial value. Chromel–Copel and Chromel–Alumel thermocouples with an exposed junction, constructed as shown in Fig. 1, were tested. The hot junction was formed by the well-known method of welding, using a carbon electrode. Different sizes of weld were obtained by varying the welding conditions.

The dimensions of the hot junction shown in Table 1 were determined in three mutually perpendicular planes using a "Zeiss" microscope with a resolution of 0.001 mm, and thermocouples with junctions close to spherical shape, without pits and other defects, were chosen.

Tests were carried out on the equipment shown schematically in Fig. 2. The equipment consisted of an electrical heater 1 and a tube 2 of diameter 40 mm, at the end of which were attached circular nozzles 3 and 4 of diameters 3.2 and 20 mm, respectively. The nozzle axes were located in one plane and intersected at an angle of 90°. The junctions of the thermocouples being tested were mounted at the intersection points.

The electric air heater 1 is supplied from a 220 V ac source through a laboratory autotransformer 5 of Latr-I type, included in the primary winding of the step-down transformer 6. To reduce heat loss to the surrounding medium the heater is insulated using asbestos cloth 7.

In the experiments air from the engineering mains is first discharged continuously from nozzles 3 and 4. The ratio of energies of the two intersecting jets is chosen so that when they are operating simultaneously there is no effect of the heated jet on the emf of the test thermocouple, and the temperature of the thermocouple junction becomes equal to that of the air at the center of the cold jet. In order to produce a stepwise change in the temperature of the medium surrounding the thermocouple junction, nozzle 4 is shut off by the damper 8, the flow of cold air is stopped and the regular thermal heating conditions begin. The provisional closing time of the nozzle damper is no more than 0.005 sec.

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TABLE 1. Basic Geometrical Dimensions of Thermocouples

Thermocouple No.	Chromel – Alumel					Thermocouple No.	Chromel – Copel				
	d, mm	D_1, mm	D_2, mm	D_3, mm	D_e, mm		d, mm	D_1, mm	D_2, mm	D_3, mm	D_e, mm
T_1	0,2	0,398	0,356	0,357	0,373	T_7	0,2	0,446	0,406	0,358	0,410
T_2	0,2	0,520	0,483	0,532	0,515	T_8	0,2	0,538	0,452	0,517	0,523
T_3	0,2	0,806	0,804	0,742	0,790	T_9	0,2	0,618	0,504	0,605	0,586
T_4	0,3	0,889	0,780	0,886	0,860	T_{10}	0,3	0,549	0,575	0,783	0,675
T_5	0,3	0,920	0,928	0,901	0,918	T_{11}	0,5	1,239	1,142	1,224	1,205
T_6	0,5	1,310	1,336	1,322	1,325	T_{12}	0,5	1,246	1,350	1,355	1,322

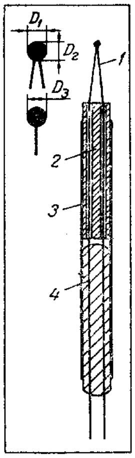

Fig. 1

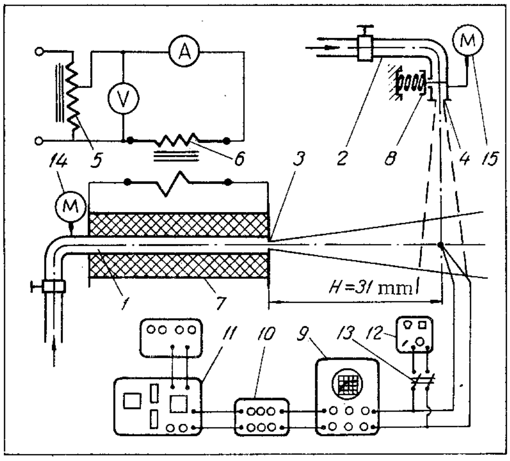

Fig. 2

Fig. 1. Construction of the thermocouple; 1) exposed thermoelectrode; 2) ceramic insert; 3) tube, Ø 4 × 0.5, steel 1Kh18N-9T; 4) thermoelectrodes insulated with glass cloth.

Fig. 2. Schematic diagram of experimental equipment.

The thermocouple emf is amplified using the constant current amplifier 9 of type Disa 51 VOO (with a cathode ray tube). The gain is adjustable from 10 to 10^4; the input resistance is 1 mohm. The amplified signal is passed through the resistance box 10 to the N-102 type loop oscillograph 11. A type VIII loop, with a frequency characteristic of 0-200 Hz and resistance 10 ohm is used to record the thermocouple heating. Matching of the loop to the amplifier output is accomplished via the resistance box 10. Visual observation of the process on the amplifier cathode ray tube screen is used to choose the film speed and the timing mark frequency. Time markers are generated from an external source.

To measure the thermocouple emf at the beginning and end of regular conditions the type PP potentiometer 12 is included in parallel at the amplifier input. The potentiometer PP is isolated by the switch 13 during operation of the N-102 oscillograph.

Measurement of the heating rate of the air stream at the thermocouple junction location is carried out using a calibrated total pressure tube of diameter 0.5 /0.2 and a differential U-tube water manometer. The air flow rate through the nozzle is controlled by means of needle valves, mounted on the air supply mains. Control of constant flow rate when the temperatures are established is accomplished using type MO reference manometers 14 and 15, whose limits of measurement are 6 and 2.5 kg/cm^2, respectively, with scale reading of 300 divisions.

The tests were carried out with different velocities w_m of the heated air stream incident on the junction, values in the range 25 to 180 m/sec being used. The temperature jump Δt was varied in the range 20 to 205°C.

Figures 3 and 4 show the dependence of the thermal inertia constant of thermocouples T_2, T_3, T_7, T_{12}, respectively, on the velocity w_m of the stream incident on the junction and on the temperature jump Δt, with w_m = const, as constructed from the test results.

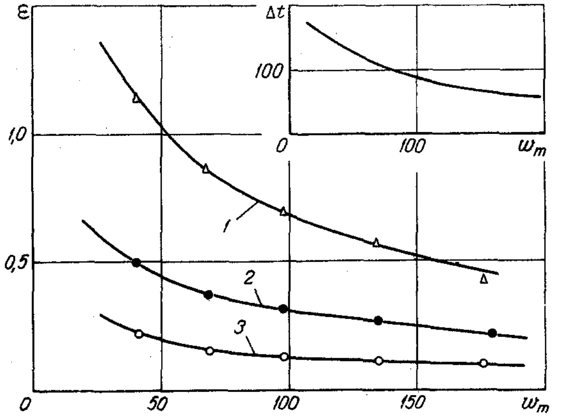

Fig. 3

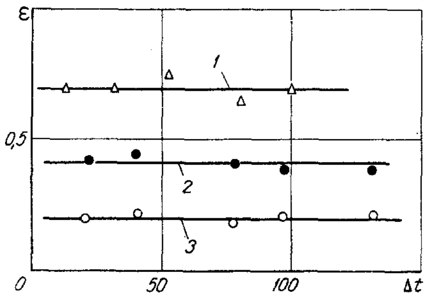

Fig. 4

Fig. 3. Variation of the thermocouple thermal inertia constant (sec) and of the temperature jump, as a function of the velocity of the stream incident on the junction (m /sec); 1, 2, and 3) thermocouples T_{12}, T_3, T_7; Δt, °C.

Fig. 4. Effect of temperature jump on thermocouple time constant with w_m = const: 1, 2, and 3) thermocouples T_{12}, T_3, T_2; ε, sec; Δt, °C.

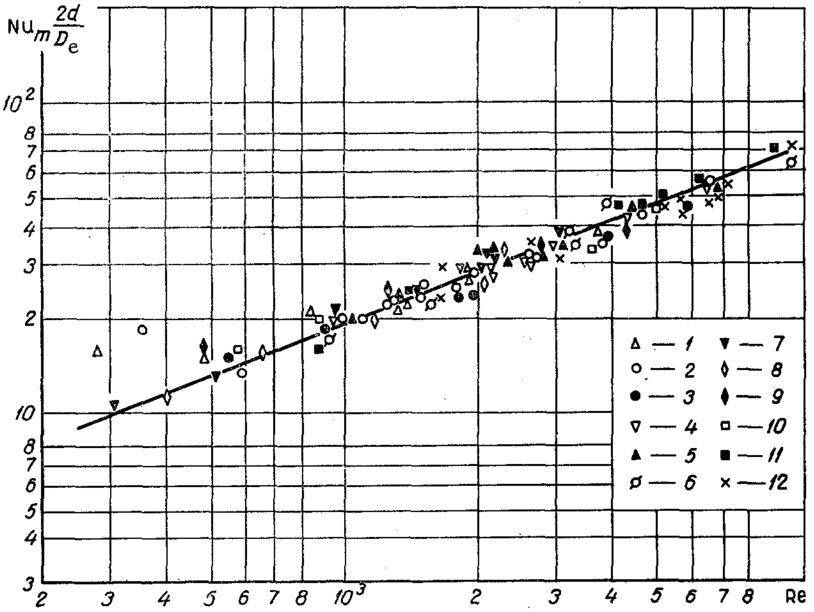

Fig. 5. Experimental data on thermocouple thermal inertia in generalized coordinates. 1-12) Thermocouples T_1-T_{12}.

Figure 3 shows that there is similarity in the curves for thermocouples of different geometrical characteristics, and that as $w_m \rightarrow \infty$ the time constant ε tends to a finite value characteristic of each thermocouple.

Figure 4 shows no dependence of the thermal inertia constant ε on the temperature jump. This can be explained by the fact that the physical properties of the thermocouple materials over the temperature range used apparently do not vary significantly. Unfortunately the authors did not have data on the physical properties of Chromel, Alumel, and Copel alloys. By examining the components of these alloys [3], it can be seen that for their basic constituents, copper and nickel, the specific heat increases by 6-7% for a temperature change from 20 to 200°C, the specific weight decreases by 1%, while the experimental error lies in the range of ±10%.

Tentative calculations indicate that the parameter Bi has a value less than 0.025 in the text. For small values of Bi the nonuniformity of the temperature field of the thermocouple junction can be neglected because of its smallness [4], and to correlate the experimental results the conventional dependence is used to determine the thermal inertia constant of the sensor

$$\varepsilon = \frac{c\rho V}{\alpha S}. \tag{1}$$

Following simple transformations, Eq. (1) reduces to the form

$$\mathrm{Nu} = \frac{\alpha D_e}{\lambda_b} = \frac{c\rho D_e^2}{6\varepsilon\lambda_b} = f(\mathrm{Re}). \tag{2}$$

Here the equivalent diameter of a spherical thermocouple junction is determined to be

$$D_e = \frac{D_1^3 + D_2^3 + D_3^3}{D_1^2 + D_2^2 + D_3^2}. \tag{3}$$

Since the variation of physical properties of the thermocouple material lies within experimental error, we shall arbitrarily take the specific heat of the material to be $c = 4.1868 \cdot 10^3$ J/kg ·deg, and the density to be $\rho = 10^3$ kg/m^3.

Then Eq. (2) can be written in the form

$$\mathrm{Nu}_m = \frac{10^3 D_e^2}{6\varepsilon\lambda_b 1.163} = f(\mathrm{Re}). \tag{4}$$

The functional relation (4) was assumed on the basis of a generalization of the test data obtained.

Figure 5 shows experimental results with Chromel–Copel and Chromel–Alumel thermocouples, in generalized coordinates. It can be seen that the test data show satisfactory interagreement, within the limits of experimental accuracy, and, in the range $\mathrm{Re} = 2 \cdot 10^2 - 10^4$, are described by the correlation

$$\mathrm{Nu}_m = (0.345 \pm 0.035)\,\mathrm{Re}^{0.58}\left(\frac{D_e}{2d}\right) \quad \text{for } \mathrm{Pr} = 0.72. \tag{5}$$

The factor $D_e/2d$ in Eq. (5) accounts for the effect of the heat given out from the junction to the thermoelectric leads on the thermal inertia of the sensor in the jet.

NOTATION

D_1, D_2, D_3	are the diameters of thermocouple junction in three mutually perpendicular planes, mm;
D_e, R_e	are the equivalent diameter and radius of thermocouple junction, mm;
d	is the diameter of thermoelectrode, mm;
V, S	are the volume and surface area of thermocouple junction, respectively, calculated from the equivalent diameter, mm^3, mm^2;
w_m	is the maximum velocity in the jet at distance H from the nozzle, m/sec;
c, ρ, λ_c	are the specific heat, density, and thermal conductivity of the thermocouple alloy, respectively, J/kg ·deg, kg/m^3, W/m ·deg;
t_1, t_2	are the stagnation temperatures at the beginning and end of regular thermal regime, °C;
$\Delta t = t_2 - t_1$	is the temperature jump, °C;
α	is the heat-transfer coefficient, W/m^2 ·deg;
$\mathrm{Bi} = \alpha R_e/\lambda_c$	is the Biot number;
$\mathrm{Nu} = \alpha D_e/\lambda_b$	is the Nusselt number;
$\mathrm{Nu}_m = c\rho D_e^2/6\varepsilon\lambda_b$	is the modified Nusselt number;
$\mathrm{Re} = w_m D_e/\nu$	is the Reynolds number;
Pr	is the Prandtl number.

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