MEASUREMENT OF TEMPERATURE IN A NON-STEADY-STATE GAS FLOW

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A method is described for measuring the temperature of a non-steady-state gas flow with a thermocouple which is an inertial component of the first order.

Wire-type thermosensors can be used to perform measurements of local temperature in a gas flow, and thus to measure the temperature field, a quantity most important in determining nonuniformity. Despite well-known shortcomings and complications, researchers use this method widely and are seeking methods for its improvement.

The most accurate determinations of gas-flow temperature from thermocouples are produced by methods based on knowledge of the form of the transfer function characterizing the thermocouple dynamic properties. Among such methods, we have, in particular, the electrothermal analogy method, when the transfer function coefficient corresponds to the index of thermosensor thermal inertia.

For a thermosensor which is an inertial component of first order (for example, a thermocouple with butt-welded thermoelectrodes, with no braking chamber), the equation relating thermosensor and flow temperatures can be written in the form

$$T_f^*(\tau) = T_t(\tau) + \varepsilon(\tau)\frac{dT_t(\tau)}{d\tau}. \qquad (1)$$

According to Eq. (1), the major factor in determining flow temperature from the thermosensor indications is reliable determination of the thermosensor thermal inertia factor, the value of which depends on the construction and thermophysical properties of the sensitive element and the conditions under which it exchanges heat with the surroundings. Under non-steady-state gas-flow conditions, this heat exchange is also of a non-steady-state character, which complicates determination of the thermal inertia factor. As is well known, the dependence of the thermal inertia factor of a thermosensor on these parameters is described by the expression:

$$\varepsilon(\tau) = \frac{C}{S\alpha(\tau)\psi(\tau)}.$$

The heat-liberation coefficient in turn is a function of the hydromechanical and thermophysical similarity criteria:

$$\alpha = \alpha(\mathrm{Re}, \mathrm{Nu}, \mathrm{Pr}).$$

The temperature distribution nonuniformity criteria are functions of the non-steady-state heat-exchange criteria

$$\psi = \psi(\mathrm{Bi}, \mathrm{Pd}).$$

At the same time, it is known that the main parameters characterizing the state of the gas flow are the total pressure p^*, the static pressure P, and the total temperature T^*. If we know the values of these parameters at every moment of the process, we can then establish the numerical dependence of the thermal inertia factor of the thermosensor on the heat-exchange conditions with the medium. This method assumes simultaneous measurement of the parameters P^*, P, and T_t at one and the point in the flow with subsequent calculation of the thermal inertia factor $\varepsilon(\tau)$ with the known sensor diameter d_t, and solution of Eq. (1).

To measure the flow parameters one might use a combination wedge with thermosensor, total and static pressure sensors located close together, as in Fig. 1.

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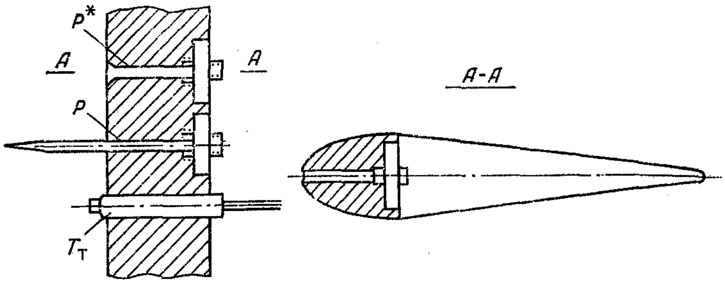

Fig. 1. Combination measurement wedge.

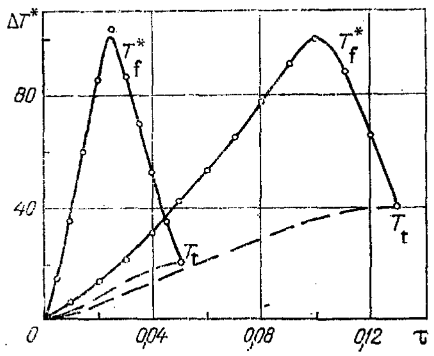

Fig. 2. Result of thermosensor indication corrections for various rates of flow temperature change. ΔT*, °K; τ, sec.

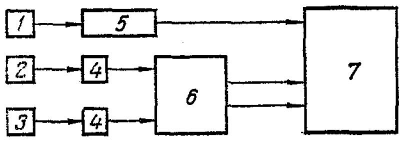

Fig. 3. Block diagram of non-steady-state gas flow temperature measurement system.

The process is carried out as follows: from the measured values of $P^*(\tau)$, $P(\tau)$, and $T_t\cdot(\tau)$ the values of the major gasdynamic functions are calculated: local values of velocity $w(\tau)$, density $\rho(\tau)$, viscosity $\mu(\tau)$, thermal conductivity of the flow $\lambda_f(\tau)$, and the hydrodynamic similarity criterion:

$$w(\tau) = \sqrt{kR}\, M(\tau) \sqrt{T(\tau)}; \tag{2}$$

$$\rho(\tau) = \frac{P(\tau)}{RT(\tau)}; \tag{3}$$

$$\mu(\tau) = \mu_0 \left(\frac{T(\tau)}{T_0}\right)^m; \tag{4}$$

$$\lambda_f(\tau) = \lambda_0 \left(\frac{T(\tau)}{T_0}\right)^n; \tag{5}$$

$$\mathrm{Re}(\tau) = \frac{w(\tau)\rho(\tau) d_t}{\mu(\tau)}. \tag{6}$$

In the first approximation it is assumed that the thermosensor temperature T_t corresponds to the true temperature of the braked flow T^*_f.

The criterial heat-exchange equation

$$\mathrm{Nu} = A\,\mathrm{Re}^p \mathrm{Pr}^r \tag{7}$$

is then solved, being written for an open junction (cylinder) with transverse passage of the flow in the form [1]:

for Re $\leqslant$ 1179.1

$$\mathrm{Nu}(\tau) = 0.52\,\mathrm{Re}(\tau)^{0.47}\,\mathrm{Pr}(\tau)^{0.38},$$

for Re > 1179.1

$$\mathrm{Nu}(\tau) = 0.18\,\mathrm{Re}(\tau)^{0.62}\mathrm{Pr}(\tau)^{0.38}.$$

From the values of Nu(τ) thus obtained and the known d_t we find the values of the heat liberation coefficient for convective heat exchange

$$\alpha_c(\tau) = \frac{\mathrm{Nu}(\tau)\,\lambda_f(\tau)}{d_t} \tag{8}$$

and radiant heat exchange (if such is found)

$$\alpha_r(\tau) = \varepsilon_b\sigma\frac{T_t(\tau)^4 - T_e^4}{T_t(\tau) - T_e}. \tag{9}$$

Each form of heat exchange exerts its own effect on the sensor thermal inertia factor and these effects can be represented by corresponding inertia factors [2]:

$$\varepsilon_c(\tau) = \frac{C}{S\alpha_c(\tau)\,\psi(\tau)}; \tag{10}$$

$$\varepsilon_r(\tau) = \frac{C}{S\alpha_r(\tau)}; \tag{11}$$

$$\varepsilon_{tc} = \frac{L^2}{2a}, \tag{12}$$

where

$$\psi(\tau) = \frac{1}{1 + \mathrm{Bi}(\tau)};$$

$$\mathrm{Bi}(\tau) = \frac{\alpha_c(\tau)\,d_t}{\lambda_t}.$$

For nonstationary gas processes in which the flow temperature changes over a time $\tau \leqslant 1$ sec the temperature of the surrounding walls and mounting details can be considered constant (T_e = const, ε_{tc} = const).

The net thermal inertia factor is given by

$$\varepsilon(\tau) = \frac{1}{\dfrac{1}{\varepsilon_c(\tau)} + \dfrac{1}{\varepsilon_{tc}} + \dfrac{1}{\varepsilon_r(\tau)}}. \tag{13}$$

After determination of $T^*_f(\tau)$, Eq. (1), repeated calculations are performed with Eqs. (2)-(13).

The values of the derivative $dT_t(\tau)/d\tau$ in Eq. (1) can be determined by various methods. Since the goal is to completely automate the gas flow temperature measurement process, an analytical method for finding the derivative by approximation of the temperature dependence using discrete values of the parameters T_t and τ with a cubic spline is used, producing an error of not more than 1% [3].

The accuracy of gas-flow temperature measurements using the corrected thermosensor temperature values with local measurement of the flow parameters P*, P, and T_t, computation of the thermal inertia factor, and solution of Eq. (1) was tested experimentally by comparing calculated T^*_f values with true flow temperature values under conditions where the latter were known exactly at flow velocities of w = 10-200 m/sec. It was found that the highest accuracy was obtained when the thermal inertia factor $\varepsilon(\tau)$ was calculated with consideration of change (when it occurs) in all three flow parameters. The error in flow temperature determination did not exceed 5%. Figure 2 shows changes in thermosensor and true flow temperatures with corrected value points.

It was also established that the accuracy with which the thermosensor thermal inertia factor, and thus true flow temperature, can be determined is affected not only by the reliability with which flow parameters are determined, but also by the accuracy with which the sensitive element diameter is determined. An error of 0.05 mm in determination of the thermocouple junction diameter will lead to an error in flow temperature determination of 20% (for a true junction diameter of $d_t = 0.2$ mm). Moreover, the quality of the junction may vary from one couple to another. Therefore, it is necessary to know the true, so-called "equivalent" junction diameter.

The method of non-steady-state gas flow measurement described was realized with a system whose block diagram is shown in Fig. 3, containing the following components: sensors for determination of temperature T_t (Chromel–Alumel thermocouple with junction diameter 0.2 mm) 1, static pressure P 2, and total pressure P* 3, located immediately next to each other in the flow, DMI low-inertia pressure meters 4, IS-1241 dc amplifier 5, IPV-2 converters 6, driving an M-6000 computer 7. The computer reads 14 parameters (eight thermosensors, six pressure sensors) 200 times in 0.22 sec, converts the readings to the physical parameter values, and stores them in memory. The data are then smoothed, the thermosensor indications being approximated and corrected by the algorithm described above. The cycle of reading all 14 sensors requires 100 μsec, making it possible to record parameters varying at rates up to 100 Hz.

NOTATION

T^*_f, non-steady-state gas flow temperature; T_t, thermosensor temperature; ε, thermal inertia factor of thermosensor; τ, time; C, total heat capacity of thermosensor sensitive element; S, total heat-exchange surface between sensitive element and flow; α, heat-liberation coefficient; ψ, temperature distribution nonuniformity coefficient in sensitive element; Re, Nu, Pr, Bi, Pd, hydromechanical and thermophysical similarity numbers; P*, total flow pressure; P, static flow pressure; T^*, total flow temperature; d_t, sensitive element diameter; w, gas flow velocity; ρ, flow density; μ, flow viscosity; λ_f, flow thermal conductivity; k, gas adiabatic constant; R, universal gas constant; M, Mach number; T, thermodynamic flow temperature; μ_0, λ_0, μ and λ values at T = 288°K; A, m, n, p, r, coefficients; α_c, heat-liberation coefficient due to convection; α_r, heat-liberation coefficient due to radiation; ε_b, emissivity of sensitive element material; σ, Stefan–Boltzmann constant; T_e, temperature of walls of environment; ε_c, ε_r, ε_{tc}, thermosensor thermal inertia factors due to convective, radiant, and conductive heat exchange; L, length of sensitive element within flow; a, thermal diffusivity of sensitive element material; λ_t, thermal conductivity of sensitive element material.

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