THERMOELECTRIC METHOD OF MEASURING VELOCITY FLUCTUATIONS IN A GAS STREAM

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A method is described of measuring velocity fluctuations by using a thermocouple connected to a rapid response temperature-measuring instrument. It is shown that the method permits investigation of velocity fluctuations in a high-temperature gas stream.

Theoretical and experimental investigations of combustion and heat-transfer processes in flucutating and turbulent streams indicate that velocity fluctuations in the stream have an appreciable influence on the intensity of these processes. Measurement of these fluctuations at high temperature, however, is known to present difficulty. Methods such as the electrical capacitor, diffusion, anemometer with glow discharge, etc. [1–3], are not sufficiently developed and are comparatively rarely used. The most widely employed method is that of the electrothermal anemometer, but it too does not permit investigations in high-temperature streams.

A thermoelectric method of measuring velocity flucuations, permitting investigation of high-temperature gas streams, has been developed jointly in the Institute of Technical Thermophysics of The Academy of Sciences of the USSR and the Kiev Polytechnic Institute.

The essence of the method lies in the measurement of the stream stagnation temperature by a thermocouple connected to a fast-response temperature-measuring instrument (with means for correcting dynamic errors of the thermocouple).

It is known that the stagnation temperature is determined by the relation

$$T' = T + rw^2/2c_p. \quad (1)$$

If the instantaneous value of the velocity at a given point in the flow is expressed in terms of the means velocity $\overline{w}$ and the flucutating component w', Eq. (1) may be put in the form

$$T' = \left(T + r\frac{\overline{w}^2}{2c_p}\right) + \frac{r}{2c_p}\,(w'^2 + 2\overline{w}w'), \quad (2)$$

where the term $(T + r\frac{\overline{w}^2}{2c_p})$ describes the general (mean) temperature level of the flow, while the expression $\frac{r}{2c_p}(w'^2 + 2\overline{w}w')$ represents the flucutating addition to the dynamic component of stagnation temperature.

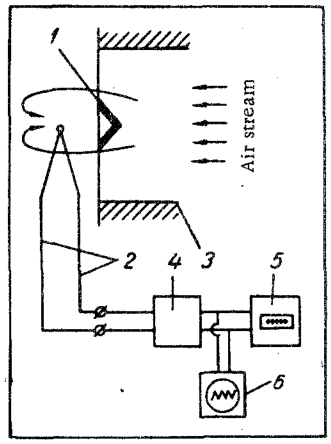

Fig. 1. Principal circuit of the measuring equipment: 1) Regulator; 2) thermocouple; 3) housing; 4) fast-response temperature-neasuring instrument; 5) loop oscillograph; 6) electronic oscillograph.

In the measuring circuit with a fast-response temperature-measuring instrument (Fig. 1), the signal characterizing the genral level is compensated by a reference voltage in the instrument control element [5, 6]. In this way a zero line is established on the oscillograph screen, and only the fluctuating component

$$\vartheta = \frac{r}{2c_p}\,(w'^2 + 2\overline{w}w')$$

is then measured relative to this line.

If the thermocouple junction is spherical in shape, it will receive all components of the fluctuating velocity vector, and then the general level of turbulence and fluctuations at the point will be measured. If the thermojunction is cylindrical (butt-welded electrodes),

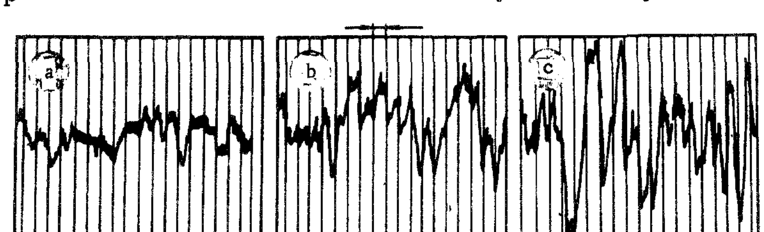

Fig. 2. Oscillograms of fluctuations at various differentiating circuit values: a) RC = 0.2; b) 0.6; c) 1.0.

it will respond to only certain components of the vector, depending on the orientation of the junction in the stream.

The flow of heat away from the junction along the thermocouple waves and leads, which affects the magnitude of the signal characterizing the general temperature level of the stream, will automatically be taken into account in the measuring circuit by the supply of a counter-emf by the reference-voltage control element of the instrument.

According to regular thermal regime theory [7], the variation of thermocouple temperature may in general be described by

$$\vartheta - t = (\vartheta_0 - t_0)\exp\left(-\frac{\tau-\tau_0}{\varepsilon}\right) - \\ -\exp\left(-\frac{\tau}{\varepsilon}\right)\int_{\tau_0}^{\tau}\exp\left(\frac{\tau}{\varepsilon}\right)F'(\tau)\,d\tau, \qquad (3)$$

where

$$\vartheta = \frac{r}{2c_p}\left(w'^2 + 2\,\bar{w}w'\right) = F(\tau).$$

The function $F(\tau)$ here is not known a priori. In addition, (3) contains the thermocouple time constant $\varepsilon = \gamma V c_p / S\alpha$, which also varies in a fluctuating stream, since the heat-transfer coefficient between the thermojunction and the stream washing it is proportional to velocity $w^{0.5}$. An exact analysis of (3) is difficult for this reason.

In a fluctuating stream the variation of the flucutating velocity component is discontinuous. The nature of these fluctuations may be represented graphically in the form of a rectangular harmonic, in which the instantaneous value of velocity during time $\tau - \tau_0 = f^{-1}$ remains constant.

Then for a single step, expression (3), with the condition $F'(\tau) = \text{const}$ and $\tau_0 = 0$, may be written in the form

$$\vartheta - t = (\vartheta_0 - t_0)\exp(-\tau/\varepsilon). \qquad (4)$$

Replacing the temperatures in (4) by corresponding values of the thermo-emf, and assuming the thermoelectric characteristic of the thermocouple to be linear within the limits of measurement, we may write, for a single step,

$$u = U[1 - \exp(-\tau/\varepsilon)]. \qquad (5)$$

Thus, without a correcting instrument, the thermocouple emf would reach a value corresponding to the temperature of the medium after some finite time interval, which would depend on the time constant of the thermocouple.

In a fluctuating stream with a rapid sequence of steps, the thermocouple emf, because of the inertia of the thermocouple, cannot follow the stream temperature, and sends out a signal corresponding to some mean temperature level.

When a measuring circuit with correction for the dynamic errors of the thermocouple is used (as shown in [6]), any variation in stream temperature will produce a practically instantaneous electrical signal, whose build-up with time will depend on the ratio of RC and ε in accordance with the expression

$$u = U + U\,\frac{RC-\varepsilon}{\varepsilon}\exp\left(-\frac{\tau}{\varepsilon}\right).$$

When the instrument operates under conditions of overcorrection ($RC > \varepsilon$), a large signal pulse, and therefore amplification of it, occur.

Experiments on velocity-fluctuation measurement using the method described were carried out with

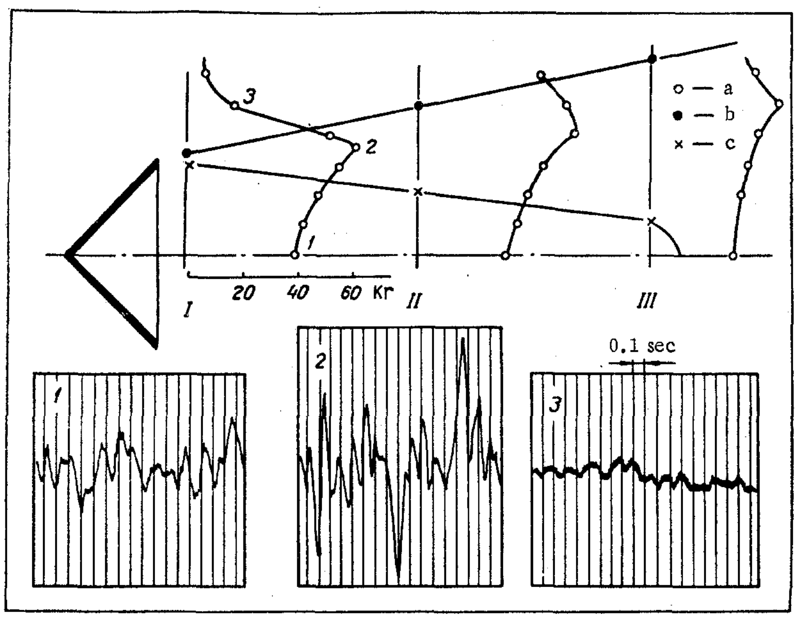

Fig. 3. Intensity of turbulence (%) at various sections (section I) 5 mm; II) 45; III) 85): a) Intensity of turbulence; b) boundary of constant velocity; c) line of zero velocity.

equipment whose principal circuit is illustrated in Fig. 1. A thermocouple with a cylindrical junction (the joint was butt welded) was mounted on a special traversing mechanism, in the turbulent wake behind a poorly streamlined body located in a high-speed gas stream. A fast-response temperature-measuring instrument was included in the thermocouple circuit; this consisted of a low-inertia amplifier with a battery of differentiating RC circuits (giving 22 settings from 0.2 to 3.5 sec).

The output signal from the instrument was fed into a loop oscillograph. An electronic oscillograph was used for adjustment of the system to particular operating conditions and for visual observation of the events. In the measurement, the thermocouple time constant (in our case $\varepsilon = 0.2$ sec) was first determined tentatively, and then a value was set up on the battery of circuits such that the RC value of the differentiating circuit gave the sharpest and most prominent fluctuating signals. It was found (Fig. 2) that the best record was obtained with $RC/\varepsilon = 3-5$.

The oscillograms were read by a method developed in the All-Union Electrotechnical Institute, and mean square values of the amplitude of the flucutating velocity component were determined for each point of the flow.

In order to verify the validity of the method decribed for measurement of intensity of velocity fluctuations, special investigations were carried out in a cold (isothermal) stream, and the results were compared with data obtained by other methods. The circulation region behind a U-shaped stabilizer was chosen as a test region, since this problem has received most attention in the literature [2, 3, etc.]. The angle of opening of the stabilizer was $\beta = 90°$, and its width varied from 20 to 60 mm. The investigations were carried out in the flow velocity range 25–50 m/sec. (velocity at the stabilizer section) at a flow temperature $t_b = 50°$ C.

Figure 3 shows the nature of the measured turbulence intensity $Kr = \sqrt{\overline{w'^2}}/w$ at various points on the section of the circulation zone behind the U-shaped stabilizer of width $B_{st} = 32$ mm and $\beta = 90°$. It may be seen that the intensity of turbulence in the flowing stream is of the order of 2–5% (so-called pipe turbulence). It increases sharply in the circulation zone, reaches a maximum in the boundary layer (point 2), and then decreases somewhat towards the center of the circulation zone (point 1).

Figure 4a shows how the intensity of turbulence varies as a function of stabilizer width. It may be seen that data obtained by various methods of measurement (thermal anemometer, diffusion, and thermoelectric methods) show good agreement in similar conditions.

Figures 4b and 4c show a comparison of the velocity-fluctuation oscillograms obtained by the electrothermal anemometer method (b) and the thermoelectric method (c). It may be seen that the nature of the velocity-fluctuation record is identical in the two cases.

The possibility of measuring velocity fluctuations by using the method described was also verified in a hot stream whose mean temperature reached 800° C. The investigations showed that the upper limit of temperature level of the flow investigated by the given method may be even higher, since it is determined only by the least resistance of the thermocouple used.

The oscillograms obtained represent graphs of the variation of the fluctuating-velocity component with time, and give a qualitative picture of the intensity of the velocity fluctuations in the stream. To obtain quantitative data, the measuring system was previously calibrated using a mesh with known level of turbulence (fluctuations).

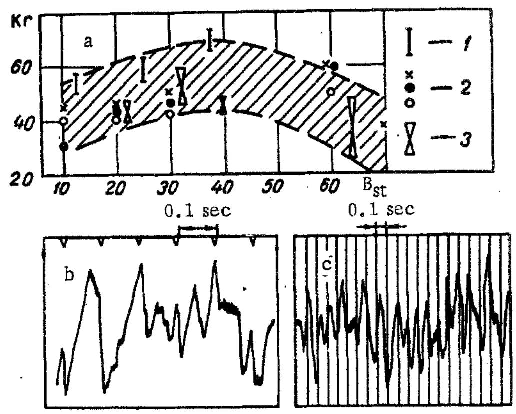

Fig. 4. Comparison of experimental results obtained by various methods: 1) diffusion method [3]; 2) thermal anemometer method [2]; 3) thermoelectric method.

The measuring system could include an electronic unit yielding an average value of the changing signals, and having as its output the level of turbulence intensity (fluctuations) at each point of the stream, to some definite scale.

NOTATION

T' and T) stagnation temperature and thermodynamic temperature of the stream; ω) instantaneous velocity at a given point; $\overline{\omega}$ and ω') mean and fluctuating velocity components; r) recovery factor; c_p) specific heat; γ, V, S) specific weight, volume, and surface area, respectively, of the thermocouple junction; α) heat transfer coefficient between the thermocouple junction and the stream washing it; f) frequency of fluctuations; τ_0 and τ) initial and variable time of the process; u) output signal of the measuring equipment; U) emf corresponding to the fluctuating term in expression (2); RC) parameter of the differentiating circuit; $Kr = \sqrt{\overline{w'^2}}/w$) intensity of velocity fluctuations (Karman number); B_{st}) width of the stabilizer; β) opening angle of the stabilizer.

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