TECHNIQUE FOR MEASURING THE STAGNATION TEMPERATURE OF SHORT-DURATION GAS FLOWS USING A RADIATION CALORIMETER

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The stagnation temperature is one of the governing parameters of a gas stream when one models the actual conditions of flow over models in wind tunnels and facilities. In a number of short-duration facilities the stagnation temperature is determined either by calculation from indirect measurements (e.g., the mass flow method), or from measurements in the receiver or the fore-chamber, which leads to considerable errors. The well-known methods and instruments for measuring gas stream temperature [1-4] have for the most part a large thermal inertia.

The present paper describes measurement of the stagnation temperature of a hot gas using a radiation-calorimetric sensor developed previously for measuring heat flux [5]. The method uses direct comparison of the gas stream stagnation temperature with the temperature of the hot sensitive element of the sensor.

Description of the Method of Temperature Measurement. According to the second law of thermodynamics, a body located in the stagnation region of a gas stream is cooled if its temperature exceeds the gas stagnation temperature, and is heated if its temperature is lower than the stream stagnation temperature. If there is no heat transfer one can conclude that the gas stagnation temperature T_0 and the body temperature in the stagnation region are the same.

Ordinarily, in the measuring technique one uses the method of successive approximations to choose the energy level supplied to the thermal sensor heater so that the sensor readings do not change when it is introduced into the gas stream. This method is time-consuming and does not afford high accuracy, since it is linked to a purely empirical choice of the sensor heater conditions, and requires strict constancy of the measured flow parameters. By using a dynamic method of determining the temperature from its rate of change [6], one can reduce the number of intercomparisons.

The measuring system used in this work is shown in Fig. 1. The sensitive element is the Nichrome foil 1, positioned perpendicular to the gas stream, and mounted on the insulating fixture 2. For thermal stability reasons the fixture is made of asbestos cement. The foil is heated by means of a dc electric current from the source 3 low-ohm rheostat 4. The windward-side foil temperature is monitored by recording the infrared (IR) radiation using the photomultiplier 5 and the oscillograph 6. The flexible fiber lightguide 7 relays the foil radiation out of the wind tunnel working section 8.

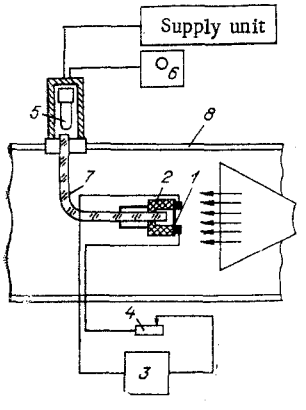

Fig. 1

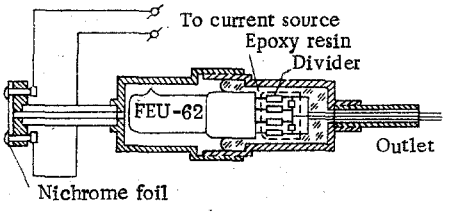

Fig. 2

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In the experiments we also used a more compact construction in which the foil, the lightguide and the photomultiplier were combined in one unit, located in the wind tunnel working chamber (Fig. 2). And here we carefully potted the high-voltage photomultiplier circuit using an epoxy compound to eliminate possible electrical microdischarges of the gas in the rarefied chamber.

We used two firings to determine the gas stream stagnation temperature at each tunnel operating condition. In each run we previously set up and recorded the foil heater temperature with no flow, and then recorded the change in the radiative emission of the foil in the flow. The preliminary foil channel temperature T_1 and T_2 were chosen to be close to the expected value of the gas stagnation temperature T_0, and $T_1 \neq T_2$.

The dynamic method of temperature determination used to reduce the oscillograms obtained was based on the use of the heat-balance equation and the empirical dependence of the sensor signal on the radiation temperature of the sensitive element. The heat-balance equation for the foil–gas system, in accordance with Newton's law of cooling can be written in the form of the simple differential equation

$$cm(dT/dt) = -\gamma(T - T_0),$$

where c is the heat capacity; m, foil mass; γ, heat-transfer coefficient; and T, foil temperature. It follows from this equation that the change in foil temperature with time is exponential

$$T - T_0 = (T_f - T_0)e^{-\beta t}, \quad (1)$$

where T_f is the initial foil heater temperature; and $\beta = \gamma/mc$. The exponential nature of the reduced dependence is confirmed by the actual form of the experimental oscillograms of recorded signal.

We used a type FÉU-62 photomultiplier with an oxide-silver photocathode, sensitive to radiative wavelengths in the range 0.4-1.2 mm to record the foil radiation.

From the spectral sensitivity, approximated by an appropriate function, we calculated the sensor signal V (the photomultiplier current) as a function of the foil temperature T (analogous to the calculation in [5]). In the temperature range 600-1000°K examined this relation can be expressed by the power law $V = \text{const } T^{\alpha}$ with exponent $\alpha \simeq 19.4$. The theoretifal relation agrees satisfactorily with the tabulated curve shown on a double logarithmic scale in Fig. 4.

For the power law and small foil temperature changes the relative sensor signal change is greater by a factor of α than the relative temperature change

$$dV/V = \alpha dT/T, \quad (2)$$

which ensures a high sensor sensitivity for a large exponent α.

Let T_1 be the sensor foil temperature in the first run and T_2 be the value in the second run. Then, according to Eq. (1), their time derivatives have the form

$$dT_1/dt = \beta(T_0 - T_1), \; dT_2/dt = \beta(T_0 - T_2). \quad (3)$$

In accordance with Eq. (2) we can express the time derivatives in terms of the sensor signal derivatives:

$$dT_1/dt = (T_1/\alpha V_1)dV_1/dt, \; dT_2/dt = (T_2/\alpha V_2)dV_2/dt. \quad (4)$$

Solving the simultaneous system of equations (3) and (4), we find a formula to determine the stagnation temperature

$$T_0 = \frac{T_1 T_2 (k_2/k_1 - 1)}{\frac{k_2}{k_1} T_2 - T_1}, \quad (5)$$

where $k_1 = [(dV_1/dt)]/V_1$, $k_2[(dV_2/dt)]/V_2$.

The quantities k_1 and k_2 are the relative or logarithmic derivatives of the sensor signal. We can measure them directly from the sensor signal oscillograms. It can be seen from Eq. (5) that greater accuracy can be attained if the derivatives k_1 and k_2 have opposite signs. This occurs if the temperature of the foil preliminary heater in the first run exceeds the gas temperature T_0, and is less than it in the second run, e.g., if $T_1 < T_0 < T_2$.

Sensor Calibration. The above sensor was calibrated in order to establish the experimental relation between the output signal and the foil heater temperature T. In this case the calibration is somewhat complicated. Since the foil is very thin (10-20 μm) one cannot weld a thermoelectric transducer to it. The contact of the foil with the thermocouple unavoidably leads to variation of the conditions of convective and radiative heat

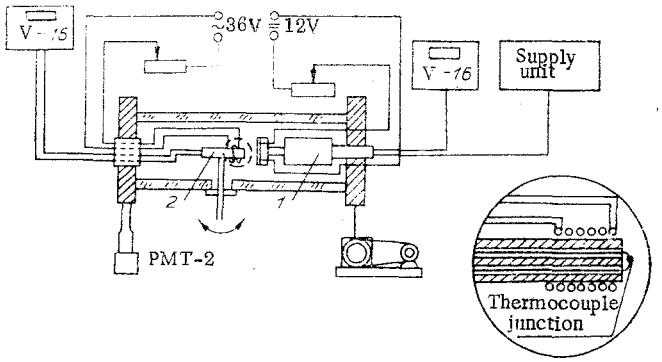

Fig. 3

transfer with the medium, and causes nonuniformity of the thermal field of the foil in the contact zone, and considerable concomitant drift of the photomultiplier signal. For foil temperatures above 800°C an optical pyrometer was used for the calibration in [5]. At lower temperatures one can use an IR temperature measurement method, but in these cases one determines the brightness temperature of the body surface. To find the true temperature one must know an accurate value of the spectral emissivity of the body at the given temperature, which is very often known only approximately.

In what seems a more reliable method one measures the spectral radiative curve of the foil, and from the maximum of this curve λ_{max}, using the Wien displacement law $\lambda_{max} T = 2884\ \mu m \cdot deg$ one determines the true body surface temperature T. To conduct this method one requires rather complex spectral analysis equipment in the IR region.

In our work we used a simple but rather laborious method involving short-duration contact of the thermoelectric transducer hot junction and the sensor foil, in order to compare their temperatures. The measuring scheme of the calibration is shown in Fig. 3. The sensor 1 is located in an evacuated volume – a section of glass tube pumped down to a pressure of $p \simeq 5$ Pa to reduce errors associated with convection of air around the sensing element. To measure the foil heater temperature we used a Chromel–Copel thermocouple 2 with indirect heating, a construction proposed by G. E. Pervushin. The thermocouple was located inside a ceramic tube, and its junction was flattened out and located near the end of the tube. An electrical spiral was wound around the tube, to raise the junction temperature to the desired value. The corresponding thermal emf was monitored with a V7-16 digital voltmeter. Then we effected a short-duration contact of the thermocouple junction and the heated foil sensor. If the thermal emf decreased we concluded that the foil was colder than the thermocouple junction, and vice versa. By choosing the spiral heating we could compare the thermocouple temperature with that of the foil to an accuracy of ±15°.

Another type of calibration was carried out with the aid of thermal indicators. The fusion temperatures of the thermal indicators were 570 and 640°C, respectively.

The foil temperatures thus obtained were set against the corresponding photomultiplier output current values. The results of the calibration are shown in Fig. 4 for two values of photomultiplier voltage. The calibration accuracy is estimated to be ±15°.

Measurement of Stagnation Temperature. The measurements using the above sensor were carried out in a low-density short-duration wind tunnel. The tunnel was equipped with an electrical ohmic heater. Two or more successive runs were used for each measurement, starting with the same initial conditions. The discrepancy in stagnation pressure was no more than 1%.

From the test oscillograms we determined the ratio of the sensor signal derivative at the initial time of gas stagnation to the original signal without flow (the quantities K_1 and K_2). Also , from the no flow signal level, using the calibration graph, we determined the foil heater temperatures T_1 and T_2. The data obtained were substituted into Eq. (5) and the stagnation temperature T_0 was calculated. Typical oscillograms are shown in Fig. 5.

Table 1 shows some measured results under various conditions in supersonic flow of nitrogen, argon, and carbon dioxide. The results are compared with the temperature T_0^p calculated from the mass flow, and with the temperature T_0^i as measured with a thermocouple of ordinary construction without a screen, located in the fore-chamber of the wind tunnel, and certainly giving low values.

TABLE 1

	Nitrogen		Argon		CO_2	
T_0, K	890	810	780	980	840	730
T_0^p	—	850	850	950	—	—
T_0^i	870	780	760	810	810	700

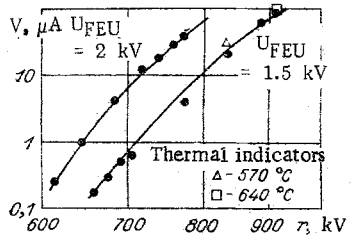

Fig. 4

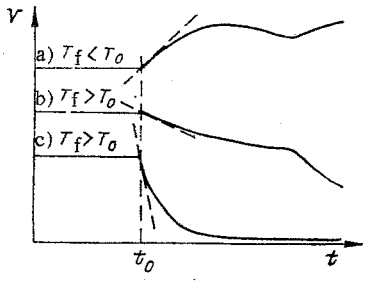

Fig. 5

It should be noted that, besides errors in calibration, one may meet an error, difficult to evaluate, associated with inadequate reproducibility of the runs in regard to stagnation temperature. One could avoid this difficulty and make the T_0 measurements in one run, evidently, by using two sensors with identical characteristics but with different temperatures of preheating of the sensitive element.

The above technique has good time resolution. The thermal inertia time constant of the sensitive element of Nichrome foil of thickness h = 10 μm is

$$\tau = \rho c h^2/4\varkappa \simeq 1.7 \text{ μsec.}$$

The dynamic error in temperature measurement using Eq. (2) can be expressed in the form

$$\Delta T_{dyn} = \tau dT/dt = (\tau/\alpha)(dV/dt)T/V$$

and does not exceed 0.1°K for the conditions of the experiment.

The radiation-calorimeter converter has the greatest sensitivity in regard to temperature, compared with other known transducers [1]. For example, the sensitivity of thermoelectric transducers in measuring high temperatures does not exceed 0.05 μV/K. The sensitivity of the resistance thermometer at a reference voltage of $U_0 = 1$ V and a temperature coefficient of resistance of $\alpha_t \simeq 0.004$ 1/K is 4 μV/K. The sensitivity of our sensor at T = 800°K is $dV/dt = \alpha V/t \simeq 25$ μV/K, can be increased by technical improvements.

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