EFFECT OF AVERAGED FLOW TEMPERATURE ON READINGS OF A HOT-WIRE ANEMOMETER

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Experimentally verified expressions that take into account the effect of the averaged flow temperature on the readings of a hot-wire anemometer are proposed.

One of the main problems that arise in the conduction of hot-wire anemometer measurements of velocity is due to the effect of changes in the averaged temperature of the medium under investigation on the heat transfer from the hot sensitive element of the gauge. From the practical viewpoint this effect will be manifested in a change in the values of coefficients A and B in the calibration relation

$$U^2 = A + Bu^n. \tag{1}$$

The error introduced into the results of measurements of the averaged velocity by a change in the averaged flow temperature has been estimated differently by different authors. Thus, according to Jorgensen's data [1], for a wire operating in air at ~570°K a 1°K change in temperature leads to an error of ~ 1%, while, according to Bradshaw's data [2], it is about 2%. An obvious way of eliminating this error is to calibrate the gauge at different flow temperatures in the range appropriate to the experiment. This procedure, however, takes a great deal of time, and such calibration curves, obtained at several flow temperatures, and also graphic interpolation methods, are only satisfactory when graphic interpretation of the calibration data is used.

Computer processing of experimental data, corresponding to the present-day level of scientific experimentation, requires an analytical representation of the effect of flow temperature on the results of velocity measurement.

The few investigations [3-6] of this problem, which are analyzed in [7], have been carried out for wire gauges. The results of these investigations can be correlated in the form of a correcting relation

$$U_c^2 = U_e^2 f(T_w;\ T_c;\ T_e) = U_e^2 f(R_w;\ R_c;\ R_e), \tag{2}$$

where U_c is the corrected hot-wire anemometer output voltage, from which the velocity is determined in accordance with a calibration obtained at temperature T_c. Such a correcting relation assumes a priori that either coefficients A and B in (1) are independent of the fluid temperature when

$$f(T_w;\ T_c;\ T_e) = f(R_w;\ R_c;\ R_e) = \frac{T_w - T_c}{T_w - T_e} = \frac{R_w - R_c}{R_w - R_e},$$

as was postulated in [6], or they respond in equal degree to its variation (for any other expression).

An experimental test of the known correcting relations of type (2) showed that even in the narrow temperature range from 294 to 301°K the error introduced by a change in averaged temperature into the results of measurements of the averaged velocity of air flow by a gauge with a wire of diameter 0.005 mm was not completely eliminated and in the best case was 0.1-0.2% per °K when the relative overheating of the wire $\alpha = (R_w/R_c) - 1 = 0.8$. This can be attributed to the different dependence of coefficients A and B in the calibration relation (1) on the flow temperature. Hence, we carried out special investigations to determine the effect of the averaged air-flow temperature on these coefficients.

The program of investigations included careful calibrations at different flow temperatures and relative overheatings α = 0.6, 0.8, and 1.0.

The investigations were carried out with a hot-wire anemometer, operating in constant-resistance (temperature) conditions, which was designed and built in Kazakh State University, and a 1218-T1.5 standard gauge

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(TSI, U.S.A.) with a platinum wire of diameter 0.005 mm (wire length 1.3 mm). The use of a platinum wire was dictated by the need to exclude the possible drift of the calibration characteristic of the gauge, which can be caused by oxidation of the wire, as happens with a tungsten wire or, in the case where it is coated with platinum, by diffusion of tungsten through the platinum coating [8].

The calibrations were conducted in the rectangular (40× 80 mm) working section of an open-circuit wind tunnel, in which the flow velocity could be smoothly regulated in the range ~3–30 m/sec with a turbulence intensity $\sqrt{\overline{u'^2}}/u$ = 0.3%. The air was driven through the tunnel from the room by a DV-1KM fan. The cleanness of the air in the working section after its passage through a FP-100U absorbent filter mounted behind the fan, and also the devised method of preparing the gauges for the measurements, ensured the stability of the calibration characteristic in not less than 200 h of continuous operation in the experimental conditions.

The temperature of the air flow in the working section was regulated by the operation of an electrical heater mounted in the immediate vicinity of the fan intake and a BK-1500 air conditioner mounted in the workroom (the volume of the room was ~100 m^3). The calibrations were conducted at 1°K steps in the range 294–303°K. The temperature of the air flow during each calibration was kept constant to within ± 0.1°, and was monitored by a TL-18 mercury thermometer (scale division 0.1°).

The flow velocity was determined from the readings of a Pitot tube (outside diameter 0.7 mm, wall thickness 0.12 mm) with the intake orifice reamed out at an angle of ~80° and the static pressure measured on the side wall of the working section. The use of the static pressure on the wall instead of the local static pressure presumes that its change within the boundary layer (under the action of the quantity $\rho\overline{v'^2}$) is negligible. The design of the intake orifice for sampling of the static pressure was similar [8], which minimized the errors of measurement due to flow separation, turbulence, flow distortion at the orifices, and ruled out the need for any correction to the readings obtained with these orifices.

The readings of the Pitot tube were pretested in the 55D41/42 calibration device, which is part of the hot-wire anemometric equipment of the DISA Elektronik firm (Denmark). The difference between the velocity values, obtained from the readings of the prepared Pitot tube and by the DISA Elektronik technique, which guarantees an error of velocity measurement ≤50 mm/sec, i.e., less than 0.25% (this value does not include the error of the measuring device, e.g., a micromanometer), was less than 0.05%.

To increase the accuracy of velocity measurement we determined the dynamic head with an inductive pressure transducer [9, 10] connected in the bridge circuit of an IVP-2 inductive hf converter. An increase in accuracy (especially in measurement of low pressures) was achieved by the linearity of the calibration characteristic of the transducer in the pressure range 0–300 Pa [10], which allows its calibration from only two points: 0 and the maximum required pressure (but less than 300 Pa), which can be measured very accurately (with an MKV-250-0.02 micromanometer, for instance). When the readings were recorded by a V7-16 digital voltmeter the error of pressure measurement did not exceed 0.5% of the value being measured.

Before conducting the experimental investigations we made a preliminary estimate of the effect of the averaged flow temperature on the coefficients A and B of the calibration relation (1) in the case where R_W = const and, hence, T_W = const.

As is known [2, 11, 12], the calibration characteristic for a hot wire can be put in the form

$$I^2R_w^2 = U^2 = R_w(R_w - R_e)(A_1 + B_1u^n). \quad (3)$$

The coefficients A_1 and B_1 have the form

$$A_1 = 0.42\frac{\lambda\pi l}{\beta}\mathrm{Pr}^{0.2},\ B_1 = 0.57\frac{\lambda\pi l}{\beta}\mathrm{Pr}^{0.33}\left(\frac{d}{\nu}\right)^n. \quad (4)$$

Thus, the effect of the temperature of the investigated medium on coefficients A and B of relation (1) will be brought about by its effect on the parameters λ, ν, Pr, and R_e:

$$A = R_w(R_w - R_e)A_1,\ B = R_w(R_w - R_e)B_1. \quad (5)$$

For air at atmospheric pressure the temperature dependence of the coefficients λ, ν, and the Prandtl number Pr in the range 283–313°K can be put, sufficiently accurately for the present analysis, in the form

$$\lambda \approx T^{0.88}\,\mathrm{const},\ \nu \approx T^{2.0}\,\mathrm{const},\ \mathrm{Pr} \approx T^{-0.105}\,\mathrm{const}, \quad (6)$$

then $A_1 \sim T^{0.88}$ and $B_1 \sim T^{2(0.44-n)}$. The index n in the range of Re usually encountered in hot-wire anemometry has values 0.26–0.55 [2, 13], although the value of n for clean wires is very probably close to 0.4 or n > 0.4,

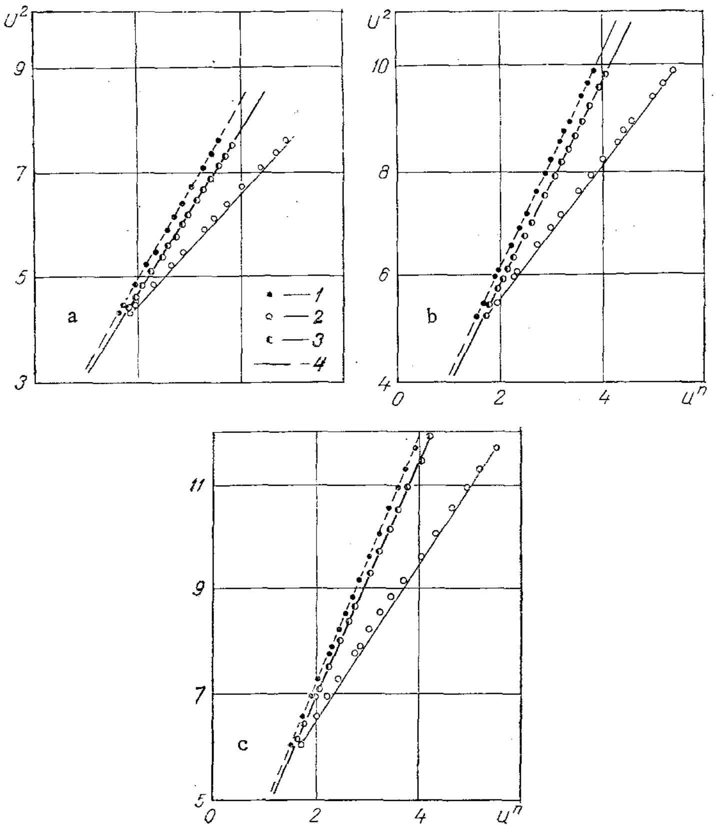

Fig. 1. Characteristic results of calibration of 1218-T1.5 gauge with platinum wire of diameter 0.005 mm (a, b, c — α = 0.6, 0.8, and 1.0, respectively): 1) coordinates $U^2 = f(u^{0.4})$ at T_c = 294°K; 2) $U^2 = f(u^{0.5})$ at T_c = 294°K; 3) $U^2 = f(u^{0.4})$ at T_c = 303°K; 4) calculation from (8), U^2, V^2; u^n, m/sec^n.

i.e., the index in the calibration characteristic (1) depends on the contamination of the wire [13]. Hence, the effect of air-flow temperature on coefficients A and B when R_w = const will act mainly through coefficient B, since it is apparent from (4) and (5) that when the temperature changes, the coefficient A_1 and cofactor $R_w \cdot (R_w - R_e)$ change in opposite directions. We can conclude from this that the effect of flow temperature on the calibration relation coefficients can be taken into account in the form of a function of the parameter $(R_w - R_e)/(R_w - R_c)$. The form of this relation cannot be found theoretically, since even expressions (4) are purely qualitative and are hardly ever used for calculations of the calibration characteristic coefficients [12]. Since the effect of temperature on the values of the coefficients A_1 and B_1, however, can be represented in the form of a power relation in T, a correction for the effect of averaged flow temperature on the calibration coefficients can be sought in the form of a power relation in the parameter $(R_w - R_e)/(R_w - R_c)$, since a change in electrical resistance of the wire is directly proportional in a first approximation to a change in temperature.

Figure 1 shows typical results of calibrations obtained at temperatures 294 and 303°K. It is an interesting fact that calibration relation (1) corresponds most closely to a power law with n = 0.4 for all the investigated conditions. The difference in values of the measured and calculated velocities does not exceed 1.5% for velocities ~3-30 m/sec, temperatures 294-303°K, and relative overheatings of the wire α = 0.6, 0.8, and 1.0 (each calibration included 15-20 velocity values). This result indicates that the value of n is independent of the overheating and the averaged flow temperature, and is determined by the design of the gauge, the state of the wire surface, and the quality of its welding to the gauge prongs.

An analysis of the obtained experimental data shows that if the correcting coefficients

$$K_A = \left(\frac{R_w - R_e}{R_w - R_c}\right)^{0.25} = \left(\frac{T_w - T_e}{T_w - T_c}\right)^{0.25},$$
$$K_B = \left(\frac{R_w - R_e}{R_w - R_c}\right)^{1.5} = \left(\frac{T_w - T_e}{T_w - T_c}\right)^{1.5}, \qquad (7)$$

TABLE 1

U, m/sec	α		
	0,6	0,8	1,0
3	4,4	3,6	2,8
30	4,1	3,4	2,4

are introduced into the calibration relation (1), the difference in the measured velocities and the velocities calculated from the relation

$$U^2 = K_A A_c + K_B B_c u^{0.4} \tag{8}$$

also do not exceed 1.5% for all the investigated ranges of velocity, averaged flow temperature, and relative overheating of the wire.

Below we give quantitative estimates of the velocity measurement errors (as a percentage of the measured value), that arise if a correction is not made to the calibration characteristic in the case where the calibration temperature T_c = 294°K, and the temperature of the investigated air flow T_e = 296°K, i.e., the difference in temperatures is 2°, and the initial adjustment of the hot-wire anemometer converter is unaltered (Table 1). From this we derive conclusions that are of importance for practical use of a hot-wire anemometer:

1) an increase in wire overheating to α = 1.0 does not significantly reduce the effect of a change in averaged flow temperature on hot-wire anemometer readings;

2) the effect of flow temperature when R_w = const in the velocity range ~ 3-30 m/sec is not greatly affected by the velocity.

NOTATION

U, hot-wire anemometer output voltage; u, flow velocity; A, A_1, B, B_1, coefficients of calibration characteristic of gauge; n, index in gauge calibration characteristic; R, electrical resistance of gauge wire; T, temperature; α, relative overheating of wire; ρ, density of investigated medium; λ, ν, Pr, thermal conductivity, kinematic viscosity, and Prandtl number of investigated medium; l, d, β, length, diameter, and dimensional (Ω per °K) proportionality factor in linear temperature dependence of electrical resistance of gauge wire; K, correcting temperature coefficient; u', v', longitudinal and transverse components of fluctuation velocity. Subscripts: w, wire; c, initial calibration; e, varying value; A, for coefficient A; B, for coefficient B.

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CALCULATION OF PLANE POROUS RADIATORS WITH SURFACE COMBUSTION

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Results of theoretical and experimental studies of porous radiators for heating various materials are compared.

In the present article, which is a continuation of [1], we discuss a procedure for calculating porous radiators, and also compare analytic and experimental results.

Figure 1 is a schematic diagram of a commercial installation used for the heat treatment of metal products. The filterable injectant is a mixture of methane and air with volume concentrations $Y_f \approx 0.10$, $Y_A \approx 0.90$, which corresponds to the stoichiometric composition. Air and methane are fed through valves 1 and 4 and rotameters 2 and 6, which determine the flow rates of these gases, to the mixer 3. The prepared fuel mixture is then forced to the porous plate 8 by the rotary gas blower 14. The flow rate of the mixture is measured by the type RS-100 gas meter 13. A constant ratio between the components of the injectant is maintained by the null regulator 5 in the supply line. This regulator is a proportioning device consisting of a valve and cavities for methane and air separated by two diaphragms whose deformation depends on the pressure of the supplied gas. The null regulator 5 was described in detail in [2]. The pressure of the gas–air mixture supplied to the gas distributing cavity of the burner was monitored by U-tube water manometers 7.

The operating conditions of the radiator (burner) under consideration depend on the heat load on the surface of the permeable plate, its porosity, the thermophysical properties of the interacting media, the form of the injectant and its rate of injection, and also on the fuel–air ratio. The temperature T_2 of the radiator surface depends strongly on the excess air ratio $\bar{\alpha}$, as follows from Fig. 2a. Our experiments were performed for $\bar{\alpha} = 1$, values of ξ_Σ from 15.98 to 80.10, temperatures of the radiator surface T_2 from 1040 to 1400°K, and a filtration rate of the fuel–oxidant mixture v_Σ from 0.04 to 0.10 m/sec. According to [3], the optimum limits of the variation of the injection velocity for porous radiators with surface combustion are 0.10–0.17 m/sec, for which the values of the temperature of the radiator surface T_2 are maximum, and obtaining higher velocities v_Σ in standard commercial installations is economically inexpedient. As follows from Fig. 2b, this conclusion agrees with our experimental results. For heat loads $q_2 \leq 4.5 \cdot 10^5$ W/m^2, where $q_2 = j_F Q_F$, the radiator temperature T_{2F} averaged over a time interval $\tau = 600$ sec is increased as a result of increased heat release at the surface of the porous plate proportional to the transverse flux density of the fuel gas j_F. For larger values of q_2 the flame is observed to separate from the surface of the porous wall, and the values of T_{2F} are decreased.

The empirical relation for determining the filtration velocity of the fuel–air mixture $v_{\Sigma 0}$ for which there is a separation of the flame from the surface of the porous plate for $\bar{\alpha} \sim 1$ has the form [3] $v_{\Sigma 0} = 5.42 \times 10^{-3}\, dT_2^2$, where d is the pore diameter in meters. Thus, for the plate we studied for $T_2 = 1300$°K and $d = 10^{-4}$, we obtain $v_{\Sigma 0} = 0.91$ m/sec. The experiments reported in the present article were performed with injection velocities appreciably lower than $v_{\Sigma 0}$ (cf. Fig. 2b).

The coefficient η, defined by Eq. (10) of [1] and characterizing the completeness of combustion of the injectant, can be written as

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