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INFLUENCE OF THE ASPECT RATIO AND DIAMETER OF THE PROBE FILAMENT OF A THERMOANEMOMETER ON ITS READING

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UDC 532.526.4:551.508.5

The results are presented of an experimental investigation of the influence of the aspect ratio of the probe filament of a thermoanemometer and of the absolute value of its diameter on the magnitude of the heat losses from the probe filament to the holders when measuring the average velocity of a gas stream.

The use of a thermoanemometer to measure the average velocity of a gas stream is possible only in the case when the dependence of the heat emission of the probe filament of the thermoanemometer on the physical parameters of the stream and its geometrical dimensions is known. An exact determination of the heat-exchange law of a filament by theoretical means under the actual conditions of flow over it does not seem possible, which leads to the necessity of using calibration equations in practical measurements.

The heat exchange between a filament and a gas stream for infinitely long filaments was studied experimentally by Collis and Williams [1], who suggested the equation

$$\mathrm{Nu}\left(\frac{T_m}{T_\infty}\right)^{-0.17} = 0.24 + 0.56\,\mathrm{Re}_w^{0.45}, \tag{1}$$

where

$$\mathrm{Nu} = \frac{V^2}{\pi\lambda_t l \Delta T R_w};\quad \mathrm{Re}_w = \frac{Ud}{\nu_m};\quad T_m = \frac{T_w + T_\infty}{2}.$$

Filaments of finite length are used in practical measurements, which leads to the necessity of introducing corrections to the heat-exchange law (1) allowing for the heat loss from the proble filament to the probe holders. In recent years the efforts of experimenters have been directed toward the establishment of that minimum admissible relative filament length $(l/d)_{\mathrm{adm}}$ for which the measurement error due to the finite filament length is unimportant or can be neglected in practical measurements. The available test data [1-4], however, are in poor agreement with each other, which hinders their practical use. For example, in [1] it is recommended to use filaments with $(l/d)_{\mathrm{adm}} \geq 2000$, in [2] $(l/d)_{\mathrm{adm}} \geq 700$, while in [3] $(l/d)_{\mathrm{adm}} \geq 400$. In [4],

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 5, pp. 820-826, November, 1978. Original article submitted October 5, 1977.

TABLE 1. Dimensions of Proble Filaments of Thermoanemometer

Woolaston filament (platinum fiber in a copper jacket)								Platinum filament			
d, μm	l/d	d, μm	l/d	d, μm	l/d	d, μm	l/d	d, μm	l/d	d, μm	l/d
4,1	178	5,4	169	8,3	180	14,5	174	22,6	194	31,9	202
	335		325		352		334		376		359
	507		489		523		498		582		561
	668		651		688		769		789		613
	830		807		1223		1230		952		758
	990		1115		1735		1662		1164		811
	1640		1441		3801		2496		2412		981
			1609				4221		3460		1133
											1310
											2446

where thick filaments with d = 100 μm were investigated, noticeable heat loss from the filament to the probe holders was observed up to values of $(l/\mathrm{d})_{\mathrm{adm}} = 16{,}000$.

There is reason to think that the minimum admissible value $(l/\mathrm{d})_{\mathrm{adm}}$ depends on the absolute value of the filament diameter, so that in the present state we studied filaments not only with different values of l/d but also with different diameters. The dimensions of the filaments are given in Table 1. The Reynolds number, calculated from the filament diameter, was varied from 0.005 to 33.

In the article we present new test data contributing to the refinement of the available information on the question under consideration and making it possible in some measure to establish the reasons for the above-indicated disagreements in the experimental results of [1-4].

The size of the correction to the heat-exchange law (1) due to the use of filaments of finite length was determined on the basis of a calibration of the thermoanemometer probe by velocity in the potential stream of a wind tunnel with a low turbulence intensity ($\sqrt{\overline{U'^2}}/U_\infty = 0.1-0.2\%$). As the control instrument we used a Pitot tube, the readings of which were recorded with a highly sensitive alcohol manometer. The tracking of the alcohol level, the reading, and the recording of the manometer readings were accomplished automatically with an electronic device employing photodiodes and optical lenses. The rms error of the manometer was $\sigma = 0.004$ mm of water column.

In the present tests we used only angular thermoanemometer probes (Fig. 1), over the holders of which the gas stream flows longitudinally, since it was shown in [2, 5] that the interaction of the stream with the holders of straight probes when they are transverse to the flow is reflected noticeably in the flow over the probe filament.

In order to weaken the possible influence of vibration and bending of the filament on its readings, it was soldered to the probe holders with small preliminary tension. The temperature coefficient of resistance of the filament material was determined experimentally and equaled 0.0035 1/deg for all the filaments. All the measurements were performed at a constant superheat $\Delta T = 223°$ of the probe filament relative to the surrounding medium.

Preliminary investigations showed that the length of the unetched sections of a Wollaston filament does not have a noticeable effect on its heat exchange with the gas stream (Fig. 1a), and hence the characteristic dimensions of a Wollaston filament are the length and diameter of its etched section.

To record the probe readings we used the measuring bridge of an ÉTAM-3A thermoanemometer with output to a VK-7/10A digital voltmeter, for which the measurement error was ±0.001 V.

The test results are presented in Fig. 1 in the form of the dependence

$$\mathrm{Nu}\left(\frac{T_m}{T_\infty}\right)^{-0.17} = f\left(\mathrm{Re}_w^{0.45}\right). \tag{2}$$

For a constant filament diameter the dependence (2) is determined to a large extent by the value of l/d, with the influence of l/d being strengthened somewhat with an increase in Re_{w}. As l/d increases this dependence approaches Eq. (1) and all the test points fit well to a straight line. From this it follows that as $l/\mathrm{d} \to \infty$ the influence of the Reynolds number on the Nusselt number obtained in the present tests agrees with the tests of Collis and Williams [1].

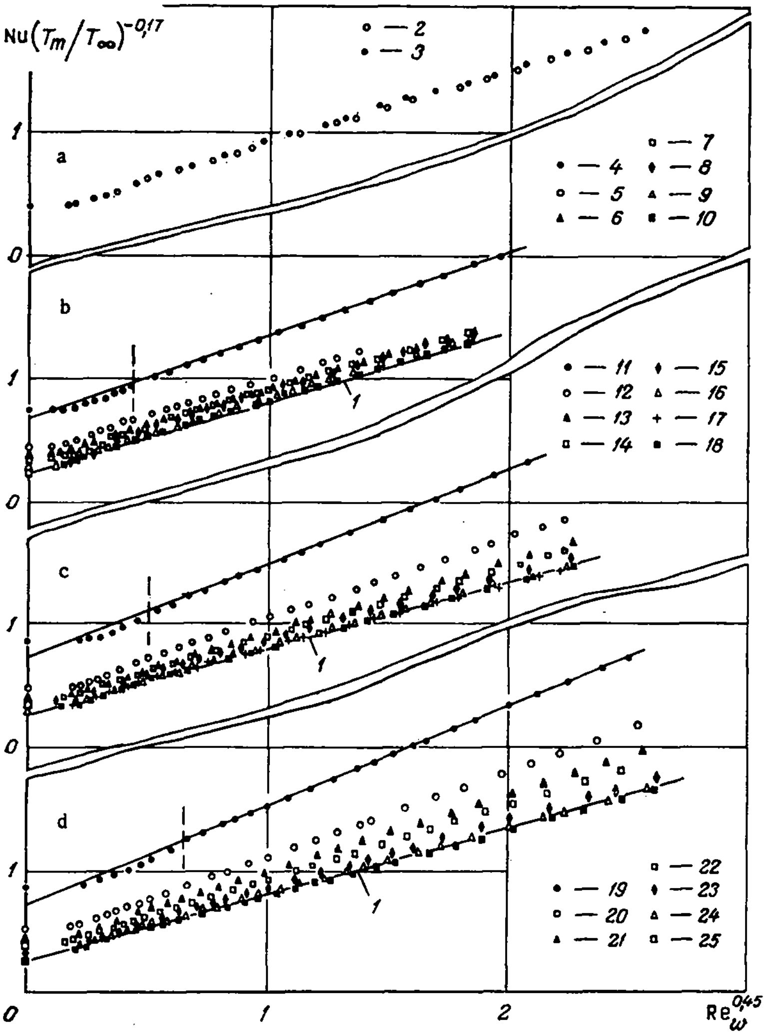

Fig. 1. Influence of aspect ratio l/d on heat emission of filament as a function of $Re_w^{0.45}$ for different filament diameters: 1) Eq. (1); a) d=8.3 μm; l/d=688; 2) l =5.7 mm; L=32 mm; 3) l =5.7 mm; L= 5.9 mm; b) d=4.1 μm; 4) l/d=178; 5) 335; 6) 507; 7) 668; 8) 830; 9) 990; 10) 1640; c) d=5.4 μm; 11) l/d= 169; 12) 325; 13) 489; 14) 651; 15) 807; 16) 1115; 17) 1441; 18) 1609; d) d=8.3 μm; 19) l/d=180; 20) 352; 21) 523; 22) 688; 23) 1223; 24) 1735; 25) 3801;

The departure of the test points from a straight line at small values of $Re_w^{0.45}$ is due to the influence of natural convection on the heat exchange of the filament, and the Reynolds number at which this departure is observed (dashed line in Fig. 1) is determined by the filament diameter.

An important result of the present investigation was the establishment of the experimental fact that at $l/d < (l/d)_{adm}$ the heat flow from the filament to the probe holders depends not only on the aspect ratio l/d of the filament but also on the absolute value of its diameter d.

From Fig. 2a it follows that at Re_w = const the value of Nu grows with an increase in the filament diameter. The influence of the diameter of the filament on its heat losses is strengthened with an increase in the Reynolds number (see Fig. 1).

This important fact was not noticed in earlier investigations and may be one of the reasons for the disagreement of the experimental data of [1-4] on the influence of l/d on the probe readings.

From the present tests it follows that the minimum admissible value $(l/d)_{adm}$ grows with an increase in the filament diameter. For example, whereas $(l/d)_{adm}$ = 1100 at d = 4.1 μm, $(l/d)_{adm}$ is already 3000 at d = 14.5 μm.

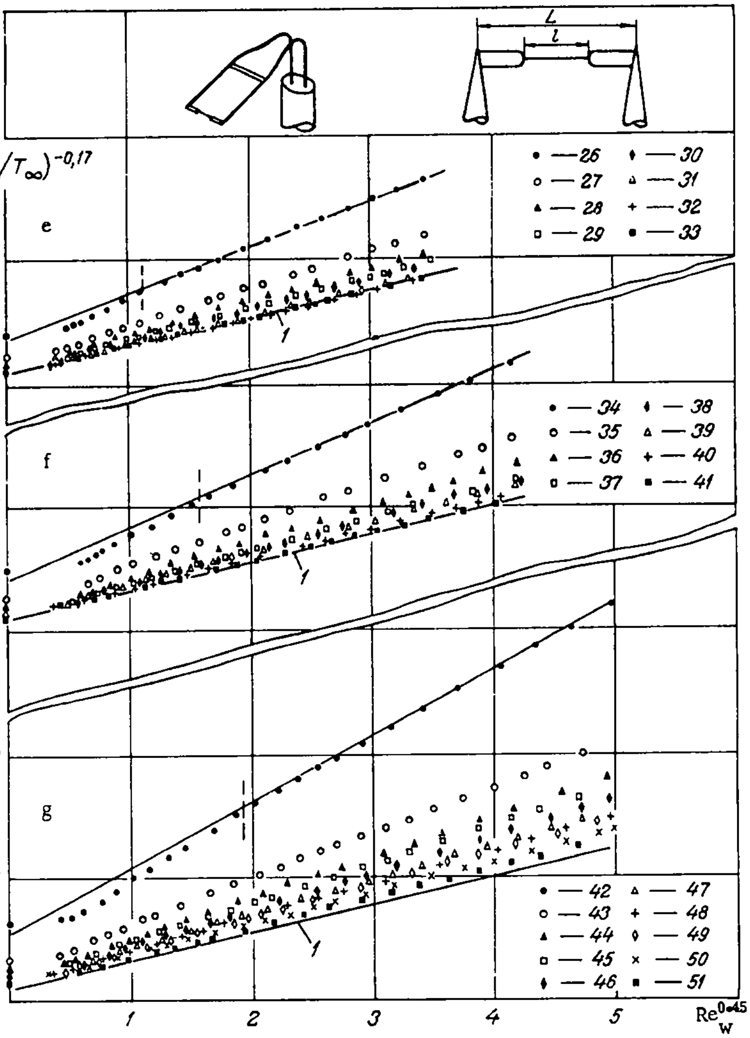

Fig. 1. (Continued). e) d=14.5 μm; 26) l/d=174; 27) 334; 28) 498; 29) 769; 30) 1230; 31) 1662; 32) 2496; 33) 4221; f) d=22.6 μm; 34) l/d=194; 35) 376; 36) 582; 37) 789; 38) 952; 39) 1164; 40) 2412; 41) 3460; g) d=31.9 μm; 42) l/d= 202; 43) 359; 44) 561; 45) 613; 46) 758; 47) 811; 48) 981; 49) 1133; 50) 1310; 51) 2446.

As $d/l \to 0$, however, all the test curves obtained with different filament diameters arrive at one and the same value of $Nu(T_m/T_\infty)^{-0.17}$ corresponding to flow over an infinitely long filament (dashed line in Fig. 2b).

If the heat-exchange law for filaments of finite length is represented in the form of the equation

$$Nu\left(\frac{T_m}{T_\infty}\right)^{-0.17} = A + B\,Re_\infty^{0.45}, \tag{3}$$

which allows not only for the convective heat exchange between the filament and the gas stream but also for losses due to heat flow to the probe holders, then in this case the coefficients A and B will no longer be constants [as occurs in Eq. (1) for infinitely long filaments] but will consist of functional dependences

$$A = f_1(l/d,\ d);\ B = f_2(l/d,\ d),$$

which can be approximated (Fig. 3) by empirical equations:

$$A = 0.13 - \left(22.97\,\frac{d}{d_0} - 79\right) \times (l/d)^{-1}, \qquad B = 0.5 - \left(25.68\,\frac{d}{d_0} - 16\right) \times (l/d)^{-1} \tag{4}$$

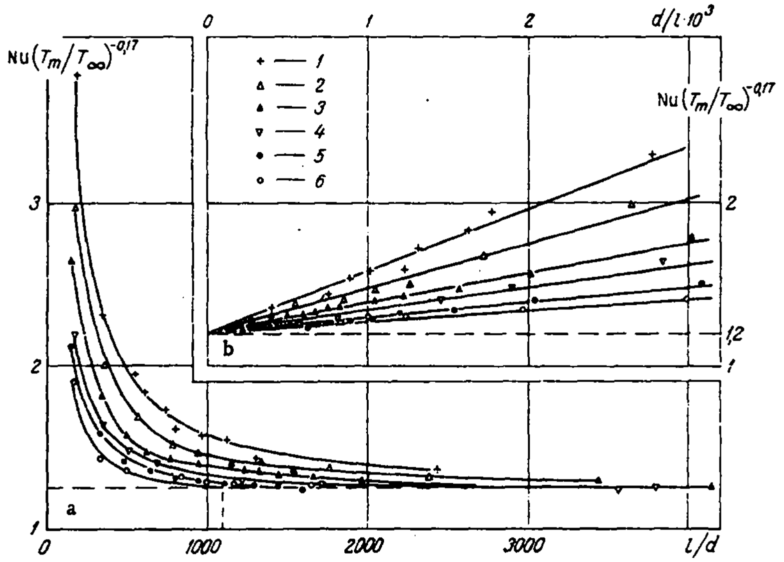

Fig. 2. Influence of filament diameter on heat transfer of filament as a function of the aspect ratio l/d at $Re_w^{0.45} = 1.8$; 1) d = 31.9 μm; 2) 22.6; 3) 14.5; 4) 8.3; 5) 5.4; 6) 4.1.

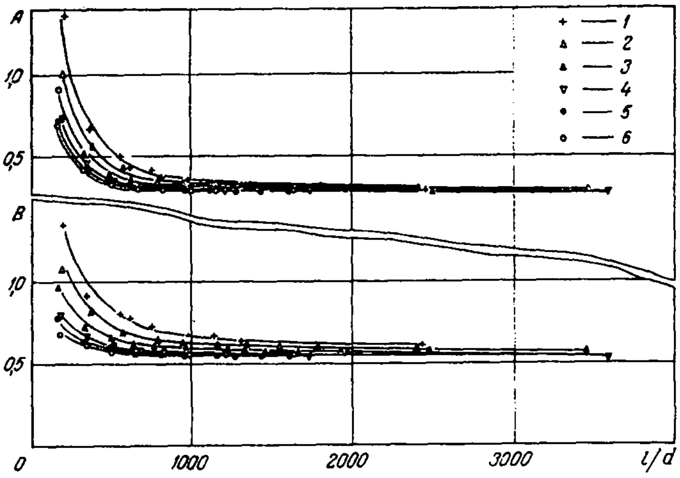

Fig. 3. Dependence of coefficients A and B in Eq. (3) on l/d for different filament diameters: 1) d = 31.9 μm; 2) 22.6; 3) 14.5; 4) 8.3; 5) 5.4; 6) 4.1.

for $l/d \leq 500$ and

$$A = 0.25 + \left(21\frac{d}{d_0} + 22\right) \times (l/d)^{-1},$$
$$B = 0.53 + \left(24.16\frac{d}{d_0} + 8\right) \times (l/d)^{-1} \tag{5}$$

for $l/d > 500$.

Here a filament diameter of 5.4 μm was chosen as d_0. As $l/d \to \infty$ the values of A and B will be 0.25 and 0.53, respectively, for all filament diameters. These values of A and B differ slightly from the constants of Eq. (1).

Equations (3)-(5) can be used to estimate the total heat losses from a filament of finite length in a wide range of variation of its aspect ratio l/d and absolute diameter d.

NOTATION

Nu	is the Nusselt number;
T_m	is the characteristic temperature;
T_w	is the filament temperature;
T_∞	is the stream temperature;
V	is the voltage drop on the probe filament;
R_w	is the resistance of the hot filament;
l	is the length of the etched section of the probe filament;
L	is the distance between filament holders;
d	is the diameter;
λ_1	is the coefficient of thermal conductivity of air at the characteristic temperature T_m;
ΔT	is the superheat of the filament relative to the stream temperature;
U	is the velocity of the oncoming stream;
ν_m	is the coefficient of kinematic viscosity of air at the characteristic temperature T_m;
Re_w	is the Reynolds number;
$\sqrt{U'^2}$	is the rms value of pulsations of the longitudinal velocity component.

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EMPIRICAL HEAT-EXCHANGE EQUATION FOR A HYDRORESISTOR THERMOANEMOMETER

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UDC 53.082.6

An empirical equation is obtained which well describes the heat-exchange process at the sensor of a hydroresistor thermoanemometer in the range of Reynolds numbers from $3 \cdot 10^3$ to 10^5 and with a Prandtl number of 7.5.

The hydroresistor thermoanemometer is one of the principal instruments in the investigation of the microscale variability of the velocity field of oceanic currents [1, 2]. In its technical data it is little inferior to the best models of film thermoanemometers, while the high reliability under natural conditions has established its predominant role. Despite the fact that the properties of this measuring device are similar in many ways to the properties of an ordinary thermoanemometer, there are important differences in the construction of the sensor and the character of its heat exchange with the surrounding medium.

The proposed empirical equation describing the steady process of heat exchange in existing models of hydroresistor thermoanemometers is analogous to King's equation for a wire thermoanemometer [3]. It can be used to calculate the sensitivity to velocity pulsations in various modes of heating of the sensor.

The sensor of a hydroresistor thermoanemometer is represented schematically in Fig. 1. Cooling of a heated layer of electrically conducting liquid (seawater) at the surface of the head of the insulator 2 near the round microelectrode 1 occurs during longitudinal flow over it. The heating is accomplished by an alternating voltage applied between the microelectrode and the metallic holder 3. The frequency of the voltage is chosen so that the reactive component of the impedance of the sensor is much less than the active component:

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 5, pp. 827-833, November, 1978. Original article submitted December 13, 1977.

0022-0841/78/3505-1305$07.50