INVESTIGATION OF LOCAL AND AVERAGE HEAT TRANSFER BETWEEN A SPHERE AND AN AIRSTREAM

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Results are described of investigations of local and average heat transfer between a single sphere and an airstream at normal and reduced pressures in the Reynolds number range 50 to $97 \cdot 10^3$.

The present investigation to determine local and average coefficients of heat transfer between an isolated sphere and a stream of air was undertaken in connection with a study of the same quantities for spheres in close-packed and loose cubic arrangements, the aim being to facilitate comparison of the data.

The local heat transfer of an isolated sphere has been the subject of a limited number of investigations whose main results will be examined below. Average heat transfer between a sphere and a stream of air has been dealt with by a number of authors, both in the USSR [1–3] and abroad [4–9]. For comparison with our data we shall make use of only the most recent papers or of those which contain a generalization of earlier work.

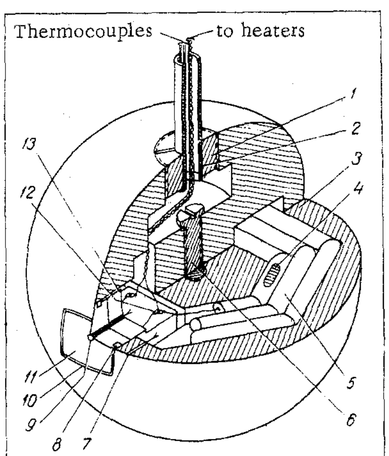

Fig. 1. Schematic cutaway view of the experimental sphere: 1) copper bushing; 2) glass tube; 3) copper hemisphere; 4) sphere heater; 5) porcelain tubes; 6) retaining screw; 7) location of sphere thermocouple; 8) groove for plug heater; 9) plug thermocouple; 10) glass cloth; 11) copper plug; 12) connector; 13) teflon insert.

Our method of measuring the local heat transfer of a sphere does not differ in principle from that first proposed, as far as we know, by Smidt and Wehner in 1936 [10]. In this method a small section or plug is isolated on the surface of a heated sphere, insulated from the remainder, and equipped with an independent heater and thermocouple. In the absence of heat exchange between the plug and the sphere, the heat transfer on the plug surface may be computed from the power generated by the plug heater.

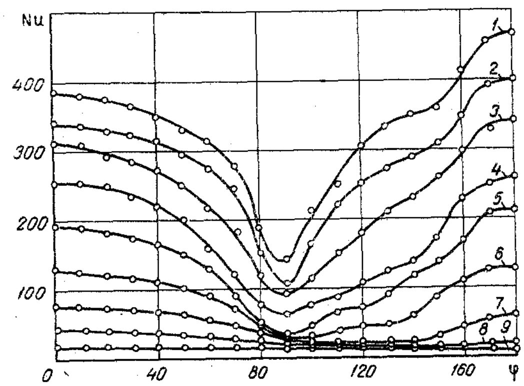

Fig. 2. Dependence of local heat transfer over the sphere perimeter on its angle of rotation φ (degrees) at Re values: 1) 97 100; 2) 81 900; 3) 63 200; 4) 37 300; 5) 28 000; 6) 11 500; 7) 6100; 8) 1500; 9) 50.

The construction and instrumentation of the copper sphere, diameter 50 mm, used in our investigations are shown in Fig. 1. The solid copper sphere was made in two halves, fastened by the screw 6. In each half of the sphere there was a hexahedral milled slot 2.2 mm deep, in which the electric heater 4 was located. The heater was a spiral of nichrome wire 0.2 mm in diameter and about 1.3 m long, enclosed in thin-walled (0.5 mm thick) porcelain tubes 5 of outside diameter 3.8 mm. A copper plug 11 of square section (dimensions 6.6 × 6.6 or 8.6 × 8.6 mm) was located between the two hemispheres, and had a spherical outside surface. The thickness of both plugs was 5 mm. Along the perimeter of the plug there was a groove 0.5 mm wide, in which was enclosed the plug heater 8, made of enameled constantan wire 0.15 mm in diameter. The teflon insert 13 served as a mounting block inside the sphere. In the center of the plug a 0.5-mm diameter drilled hole was provided to allow passage of a copper-constantan thermocouple formed from 0.12 mm wire. The thermocouple junction 9 was soldered flush with the outer surface of the plug.

A similar thermocouple 7 for measuring the sphere temperature was clamped between the two hemispheres at a distance of about 1 mm from the edge of one side of the plug. The sphere support 2 was a glass tube of outside diameter 6.2 mm, through which passed all the leads from the heaters and thermocouples. The support was connected with a graduated circle, on which the angle of rotation of the sphere could be read to an accuracy of 0.2°. The insulation between the plug and the sphere was glass cloth 0.2 mm thick.

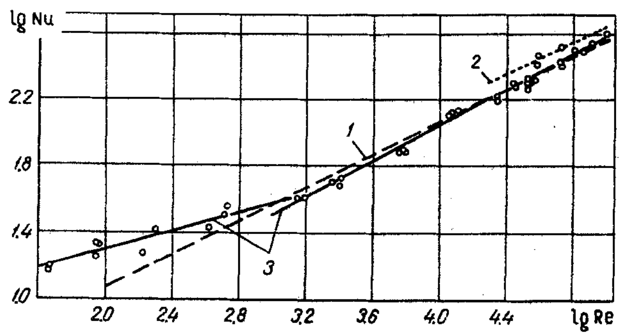

Fig. 3. Heat transfer at the forward stagnation point of a sphere: 1) according to the data of [8]; 2) [5]; 3) the authors.

The investigations of local and average heat transfer for the sphere were carried out on three facilities:

1) a wind tunnel (working section diameter 1.25 m, Re range $1.3 \cdot 10^4$ to $9.7 \cdot 10^4$);

2) a test rig with a high-pressure blower (in channels of section 20×20 and 25×25 cm, Re range from $1.4 \cdot 10^3$ to $5.1 \cdot 10^4$);

3) a test rig with a vacuum pump (in a channel of section 20×20 cm, Re range 50 to 550).

In rig 3 the pressure did not drop below 13.5 N/cm^2, permitting low values of Re, but still outside the molecular flow regime. The considerable decrease in Grashof number Gr when operating at reduced pressure reduced the effect of natural convection in the total heat transfer at small values of Re.

The blockage of the tunnel section by the sphere did not exceed 0.16% for the wind tunnel and 3.4% for the channels, i. e., it was much less than in the tests of Wadsworth [5] and Cary [6] (16 and 11%, respectively).

For rigs 1 and 2 the mean flow velocities and corrections were determined by preliminary calibration of the channel section with the aid of a three-channel cylindrical probe. In rig 3 the air velocity was measured with the aid of a lemniscate.

The thermocouple cold junctions were located directly in the channel, permitting immediate measurement of the temperature drop Δt between the sphere surface and the air stream.

The electrical arrangement for measurement and control of temperature and current consisted of two independent units: 1) a supply unit for the sphere and plug heaters (measurement to an accuracy of 0.01 A), also containing current controls, and 2) a temperature measurement unit (potentiometer and mirror galvanometer). The accuracy of temperature measurement was 0.05° C.

The test began when the air stream was brought up, with the aid of a gate valve (or a rheostat in the wind tunnel), to the required velocity value. Then the sphere heater was switched on, and continued to operate for 10–30 min, after which time the sphere surface temperature remained constant for the duration of the test. After the sphere was heated, the plug heater was brought on, and the power supplied to the heater was controlled with a rheostat in such a way as to make the temperature of the plug identical with that of the sphere. Then the sphere was rotated by 10°, and the plug heater power was readjusted.

During the tests, measurements were made of the current supplied to the sphere and plug heaters, the air stream temperature, and the temperature drop Δt. The heat flux from the plug (local heat transfer) was determined from the power supplied to the plug heater. The measured heat transfer from the plug surface may be regarded as local with respect to the sphere, since the plug surface area was less than 1% of the total sphere surface area.

In computing Re and Nu, all the data were referred to the sphere diameter, to the total section area of the channel, and to the arithmetic mean temperature $t_m = (t_s + t_a)/2$. The heat loss to the support was less than 1% and was not taken into account. No correction was made for radiative heat transfer.

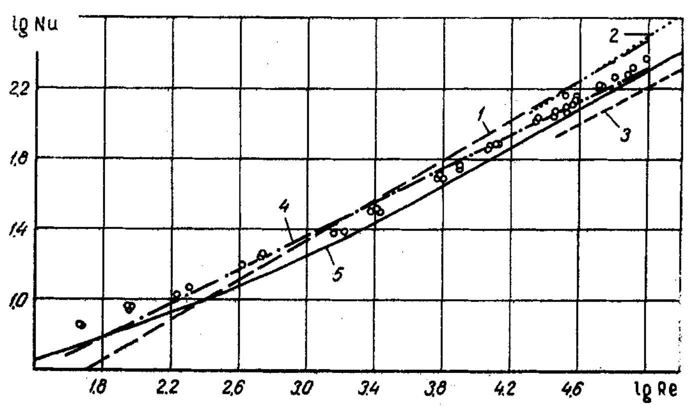

Fig. 4. Average sphere heat transfer; 1) according to the data of [4]; 2) [5]; 3) [6]; 4) the authors; 5) [7].

The main results are shown in Figs. 2–4.

It follows from an examination of Fig. 2 that, with increase in the angle of rotation of the sphere, at all Re values, the values of Nu fall smoothly, and then, beginning at about 60°, the smooth fall is maintained only for small Re (<6000), while for the remaining Re values the fall-off proceeds more steeply, the larger the Re number. At $\varphi = 85°$ and the highest Re values there is a clearly expressed minimum. As Re decreases, the minimum shifts to $\varphi = 100°$ and is drawn out over the greater part of the sphere. After passing through the minimum, the Nu value increases smoothly, for all Re values (except for Re = 50), reaching its greatest value at $\varphi = 180°$. In general, the picture of local heat transfer variation corresponds to the hydrodynamic picture of flow over a sphere. The analogous curves of Cary and Wadsworth [5, 6] show the same nature of variation of Nu.

We also attempted a quantitative treatment of our test data on local heat transfer, and Fig. 3 shows all our local heat transfer data at the forward stagnation point of the sphere, expressed in the coordinates lg Re–lg Nu. A least-squares fit yields a relation of the form

$$\mathrm{Nu} = 2 + 4.12\,\mathrm{Re}^{0.31} \tag{1}$$

for the Re region 50 to 2000, and

$$\mathrm{Nu} = 0.945\,\mathrm{Re}^{0.54} \tag{2}$$

for the Re region 1600 to 90 000. The maximum deviation of the experimental data from the correlation curve is ±15% for (1) and ±8% for (2).

Figure 3 also shows for comparison curves corresponding to the experimental data of Wadsworth ($\mathrm{Nu} = 1.57\,\mathrm{Re}^{0.49}$), and to the relation $\mathrm{Nu} = 1.144\,\mathrm{Re}^{0.50}$, obtained theoretically by Sibulkin [8]. It may be seen that the Sibulkin curve describes our data quite well for the region Re > 1600, but is not suitable for small Re values.

Moreover, an approximate relation has been obtained for calculating the local heat transfer coefficient at any point on the forward part of the sphere with $\varphi \leq 80°$; it has the following form:

$$\mathrm{Nu} = 0.00883\sqrt{7150 - \varphi^2}\,\mathrm{Re}^{0.54}. \tag{3}$$

The maximum relative error in using this relation does not exceed ±8%.

Figure 4 shows the average heat transfer data for the sphere. Throughout the Reynolds number range investigated the experimental points are correlated well by a relation of the form

$$\mathrm{Nu} = 0.84\,\mathrm{Re}^{0.48}. \tag{4}$$

The mean deviation of the experimental points from the correlation curve does not exceed ±5%, while the maximum deviation is found in the small Re region and is +12%.

For comparison, Fig. 4 also shows straight lines plotted from the experimental data of other investigators, as follows: McAdams [4] ($\mathrm{Nu} = 0.37\,\mathrm{Re}^{0.60}$, Re range 17 to 70 000); Wadsworth [5] ($\mathrm{Nu} = 0.25\,\mathrm{Re}^{0.62}$, Re 20 000 to 240 000); Cary [6] ($\mathrm{Nu} = 0.37\,\mathrm{Re}^{0.53}$, Re 44 000 to 151 000); Yuge [7] ($\mathrm{Nu} = 2 + 0.493\,\mathrm{Re}^{0.50}$, Re 10 to 1800, and $\mathrm{Nu} = 2 + 0.3\,\mathrm{Re}^{0.54}$, Re 1800 to 150 000).

It may be seen from the figure that our experimental data are located in the middle of the data of the above-mentioned investigators. The data of Yuge come closest to our correlation, and for medium Re values—the data of McAdams. The increased Nu values of Wadsworth in the high Re region are evidently due to the greater intensity of turbulence (blockage of the channel section) than in our tests. A critique of the Cary method is given in [9].

The data of Shchitnikov [3], obtained recently for a narrow Re range, are in good agreement with our data.

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