HEAT TRANSFER OF A SPHERE IN A JET FLOW

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The results of an experimental investigation of the heat transfer between a sphere and an axisymmetric air jet are presented.

A number of practical problems involve heat transfer between a body and a jet flow. In this case the heat transfer process can be sharply intensified by creating a high level of turbulence in the jet.

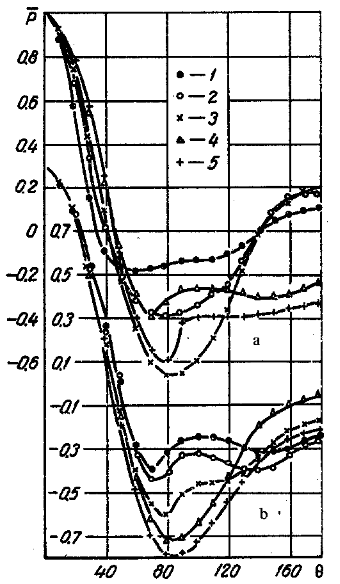

Fig. 1. Pressure distribution over the surface of the sphere as a function of the parameters D, d, l: a) l/D = 1: 1) D/d = 0.49; 2) 0.74; 3) 1.1; 4) 2.0; 5) 2.5; b) D/d = 2.0: 1) l/D = 1; 2) 3; 3) 5; 4) 8; 5) 15.

This paper is concerned with a study of the effect of the basic parameters of jet flow on heat transfer with a sphere. The heat transfer coefficient of the sphere was determined by the regular regime method. In the experiments we employed solid brass and bronze spheres 20.0, 36.0, 45.3, 54.0, 63.0, 72.0, 81.0 mm in diameter. The construction of all the spheres was the same. To measure the temperature of the sphere the junction of a copper-constantan thermocouple was imbedded at its center. The sphere was supported by hollow metal tubes through which the thermocouple leads were led. In no case did the ratio of the diameters of the support and the sphere exceed 5–6%. In practice, the support had no effect on the flow pattern around the sphere, since it was located behind the sphere in the direction of flow. In order to reduce the heat losses through the support, the latter was separated from the wall of the sphere by a textolite pad 1.5–2.0 mm thick.

A traverse mechanism enabled us to displace the spheres vertically along the jet axis to the required distance from the nozzle. All the nozzles employed had a Vitoshinskii profile. The contraction ratios of the nozzles, corresponding to exit section diameters of 10, 15, 20, 30, 40, 62, 90 mm, varied from 5 to 400. The air entered the nozzles through a settling chamber with a series of smoothing screens. All this made it possible to obtain a rather uniform velocity and pressure field at the nozzle exit.

In order to determine the cooling rate, each sphere was first heated to 60–70° C, and then placed in the flow; values of the difference between the temperature of the sphere and the flow temperature were recorded at equal time intervals correct to ±0.05° C using a mirror galvanometer. The heat capacities of the spheres were measured by the calorimeteric method correct to ±2%. The radiative heat transfer coefficient of the sphere was less than 1% of the mean value of the convective coefficient; accordingly it was disregarded.

Apart from the thermal measurements, we also investigated the pressure distribution at the surface of the sphere. For this purpose we used plastic spheres of the same size as the metal spheres with 0.3-mm pressure-tapping holes.

The intensity of the turbulent fluctuations of the flow was measured with an ETAM-3A hot-wire an anemometer.

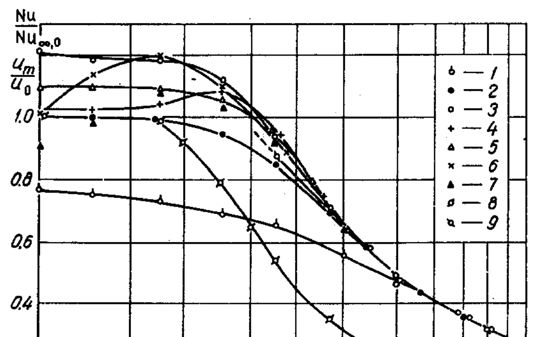

Fig. 2. Variation of heat transfer and maximum flow velocity along jet axis (results of experiments for $Re_0 = 7 \cdot 10^4$–$16 \cdot 10^4$): 1) D/d = 0.12; 2) 0.16; 3) 0.49; 4) 0.74; 5) 1.1; 6) 1.7; 7) 2.0; 8) variation of u_m/u_0; 9) Eq. (3).

Results of the experiments. To confirm the reliability of the measurements and for purposes of comparison with known results [1, 2, 3, etc.], the heat transfer was studied in a closed-circuit wind tunnel with an open working section 500 mm in diameter. The level of flow turbulence in the tunnel was 0.5%. The experimental data can be represented in the form

$$\mathrm{Nu} = 0.147\,\mathrm{Re}^{0.64}, \tag{1}$$

where the physical parameters of the air were determined from the free-stream temperature. The mean deviation of the experimental data from Eq. (1) does not exceed 4% on the interval $10^4 \leq \mathrm{Re} \leq 1.6 \cdot 10^5$. Comparison with the data of other investigators showed that the best agreement is with the results of Yuge [2], which in the region $10^4 \leq \mathrm{Re} \leq 6.5 \cdot 10^4$ almost coincide with our own results.

On the initial section of the jet, where $l/D \leq 5$, the flow pattern depends importantly on the ratio of the diameters of the nozzle exit section and the sphere. Special measurements showed that if $D/d > 10$, then varying the flow width has almost no effect on the flow pattern and the flow may be assumed to be free. According to the results of [4] at $D/d \leq 0.1$ jet flow over a sphere may be regarded as the propagation of an axisymmetric semibound turbulent jet along a curved surface.

In Fig. 1a we present certain data showing the transition from one flow regime to the other when the flow width varies with respect to nozzle diameter on the initial section of the jet. At $D/d \leqslant 1.5$ the flow over the sphere is separationless irrespective of Reynolds number for $\mathrm{Re}_0 > 2 \cdot 10^4$. As the nozzle diameter increases relative to the diameter of the sphere, separation of the laminar or turbulent boundary layer takes place at $D/d \geqslant 1.5$. There is a transition region $D/d = 1.2$–1.8, where at constant Reynolds number and turbulence level a change in D/d may lead to qualitative changes in the flow pattern. Subsequent increases in D/d do not have a significant influence on the flow pattern, leading only to a more extreme development of flow velocity over the surface of the sphere. In the region $D/d \geq 1.2$ an increase in Reynolds number and initial level of turbulence and a decrease in the relative flow width cause the onset of the supercritical flow regime. The principal role is played by the initial level of flow turbulence. For example, when $D/d = 2$ and $l/D = 3$ at $D = 90$ mm and $\varepsilon_0 = 0.8\%$ the supercritical regime was observed on the interval $4 \cdot 10^4 \leq \mathrm{Re}_0 \leq 16 \cdot 10^4$, but at $D = 40$ mm and $\varepsilon_0 = 0.4\%$ and subcritical regime only was observed in the region $2 \cdot 10^4 \leq \mathrm{Re}_0 \leq 8 \cdot 10^4$.

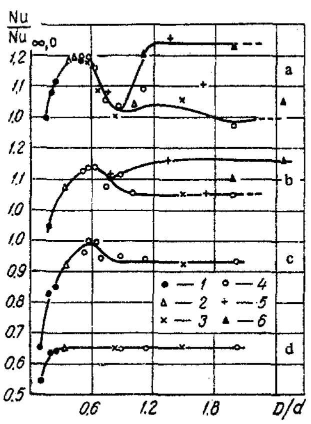

Fig. 3. Heat transfer of sphere as a function of diameter ratio: a) $l/D = 3$; b) 8; c) 12; d) 20; 1) D = 10; 2) 20; 3) 30; 4) 40; 5) 62; 6) 90 mm.

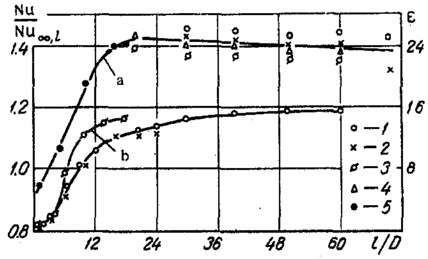

Fig. 4. Effect of variation of the level of flow turbulence along the jet axis on the heat transfer of a sphere: a) variation of $\mathrm{Nu}/\mathrm{Nu}_{\infty,l}$; 1) $D/d = 0.16$; 2) 0.22; 3) 0.33; 4) 0.42; 5) 2.0; b) variation of ε (%) at $u_0 = 20$–70 m/sec; 1) D = 15; 2) 40; 3) 62 mm.

The change in flow pattern with distance from the nozzle along the axis of the jet is shown in Fig. 1b for the case $D/d = 2$. Even at a distance $l/D = 5$ the flow regime is transitional owing to the increase in the level of free-stream turbulence.

On the principal section of the jet, where $\varepsilon \approx 15$–20%, only supercritical flow is observed irrespective of the value of D/d at $\mathrm{Re}_0 \geq 2 \cdot 10^4$.

The variation of the heat transfer and maximum flow velocity along the axis is shown in Fig. 2 for various ratios D/d. The law of variation of the maximum velocity is shown only for the case D = 40 mm, since for the other nozzles the deviation from this curve did not exceed 2.5% on the initial section of the jet. For the principal section of the jet all the data merge into a single curve, which is well-described by the known equation [5]

$$\frac{u_m}{u_0} = \frac{0.96}{0.29 + 2al/D}, \tag{2}$$

where a value 0.07 was taken for a.

All the heat transfer data were referred to their corresponding values for the same Reynolds numbers in a homogeneous flow. In Fig. 2, the ordinates are values of $\mathrm{Nu}/\mathrm{Nu}_{\infty,0}$, where $\mathrm{Nu}_{\infty,0}$ is the Nusselt number calculated from Eq. (1) and corresponding to a homogeneous flow, whose velocity is equal to the velocity of the jet in the nozzle exit section.

In most cases the heat transfer varies little on the initial section of the jet, and starting from a distance $l/D = 5$, gradually decreases. On the interval of values $D/d = 0.7$–1.0 and also 1.5–2.0 the nature of the variation of the heat transfer along the jet axis differs somewhat from the other cases. At $D/d = 2$ (D = 40 mm) we get separation of the laminar boundary layer on the surface of the sphere, as with a homogeneous flow. However, the heat transfer coefficient near the nozzle is somewhat lower than the value corresponding to a free-air flow, which is attributable to the insufficient development of the flow velocity on the surface of the sphere due to the limited dimensions of the jet. When D/d = 1.7, the nozzle diameter is equal to 62 mm, and the pressure field on the surface of the sphere near the nozzle has a fluctuating character, i.e., the flow regime is transitional between subcritical and supercritical. Consequently, the heat transfer coefficient is somewhat higher than in the previous case. In both cases at $l/D = 5$ the heat transfer coefficient has a maximum, which corresponds to an increase in the level of flow turbulence and hence to the onset of the supercritical flow regime.

The appearance of a maximum of the heat transfer coefficient at a distance $l/D = 8$ in the region D/d = = 0.7–1.0 was caused by a reduction in its value near the nozzle as compared with the other cases, as explained below.

Details of the dependence of heat transfer on the variation of D/d at different distances from the nozzle are presented in Fig. 3. We will consider case a($l/D = 3$), which relates to a sphere located on the initial section of the jet. When the jet is very thin (D/d < 0.2), part of the surface of the sphere falls within the region of strong damping of the flow velocity in the jet and the heat transfer is less than in a homogeneous flow. In the region D/d = 0.2–0.7 the heat transfer coefficient is 10–20% higher than the value in a homogeneous flow. This is attributable to the absence of separation, the large velocity gradient near the forward stagnation point on the sphere, and the strong influence of the high level of turbulence on the entire boundary layer.

As D/d increases, although the flow regime remains separationless, on the interval D/d = 0.7–1.0 the heat transfer is somewhat less than in the previous cases, as mentioned above in connection with Fig. 2. This may be attributable to a reduction in the velocity gradient on the forward half of the sphere and insufficient development of the flow velocity over its surface (as compared with cases D/d < 0.7). This is clear from a comparison of the curves in Fig. 1a corresponding to the designations 1, 2, and 3.

With further increase in D/d two different flow and hence heat transfer regimes are possible. If the flow is supercritical, the heat transfer coefficient is higher than for the homogeneous flow. If the flow is subcritical, the heat transfer rate approaches its value in the homogeneous flow.

The dependence of the heat transfer of the sphere on Reynolds number on the initial section of the jet was investigated in the interval $20 \cdot 10^3 \leq Re_0 \leq 320 \cdot 10^3$ for all values of D/d. At D/d ⩽ 0.4, when the greater part of the boundary layer on the surface of the sphere is turbulent, on average the heat transfer is proportional to $Re_0^{0.75}$. In these circumstances the quantity $Nu/Nu_{\infty,0}$ will increase somewhat with Re_0 according to the law $Nu/Nu_{\infty,0} \sim Re_0^{0.11}$. As D/d increases, almost all the forward half of the sphere is covered by a laminar boundary layer, as in the homogeneous flow. However, at D/d ⩾ 0.4 heat transfer in the jet is proportional to $Re_0^{0.56}$ and $Nu/Nu_{\infty,0} \sim Re_0^{-0.08}$. The decrease in $Nu/Nu_{\infty,0}$ to a certain limit as Re_0 increases is due to the different dependence on the Reynolds number of the heat transfer coefficient for the forward and rear halves of the sphere. It is known [1] that the mean heat transfer coefficient for the forward half of the sphere is proportional to $Re^{0.5}$ and for the rear half to $Re^{0.7-0.8}$. Consequently, as the Reynolds number increases the contribution of the rear half of the sphere to the over-all heat transfer increases and that of the forward half decreases. This leads to a decrease in $Nu/Nu_{\infty,0}$ with increase in Re_0, since the deviation of Nu from $Nu_{\infty,0}$ is chiefly attributable to the strong influence of the high level of flow turbulence in the jet on the heat transfer of the forward half of the sphere, where the boundary layer is predominantly laminar.

On the principal section of the jet, where $l/D \geq 8$, the heat transfer coefficients for the forward and rear halves of the sphere depend on the Reynolds number in much the same way, since in these cases the boundary layer on the forward half of the sphere is now turbulent. This makes it possible to neglect the dependence of $Nu/Nu_{\infty,0}$ on the Reynolds number remote from the nozzle at all values of D/d.

Moreover, remote from the nozzle the diameter ratio also has only a slight influence on the heat transfer coefficient. It is clear from Fig. 3 that the value of D/d, starting from which an increase in nozzle diameter does not affect heat transfer, decreases sharply with distance from the nozzle. At $l/D = 20$ it may be assumed that, for all practical purposes, the nozzle diameter does not affect the heat transfer of the sphere at D/d ≥ 0.3. In Fig. 2 almost all the data corresponding to heat transfer remote from the nozzle lie on a single curve irrespective of the value of D/d. Correct to ±5% this curve can be approximated by the following equation:

$$\frac{Nu}{Nu_{\infty,0}} = 1.39\left(\frac{0.96}{0.29+0.14 \cdot l/D)}\right)^{0.64}. \qquad (3)$$

Using (1) and (2), we can rewrite Eq. (3) in the form

$$Nu = 1.39 \cdot 0.147 Re_l^{0.64} \quad \text{or} \quad Nu = 1.39 Nu_{\infty,l}. \qquad (4)$$

Hence it is clear that given the same free-stream velocity the heat transfer coefficient of the sphere on the principal section of the jet, where the flow can be assumed unrestricted, is approximately 40% higher than in the undistrubed homogeneous flow.

The graph in Fig. 4 shows the variation along the axis of the jet of the ratio of the heat transfer coefficient of the sphere in the jet to its value for a homogeneous flow with velocity equal to the maximum jet velocity at distance l from the nozzle.

Here, we have plotted the experimental data for values D/d greater than a certain limiting value starting from which the rate of heat transfer ceases to depend on the flow width (see Fig. 3). The same figure also shows the variation of the relative intensity of turbulence along the jet axis for D = 15, 40, 62 mm. A certain difference in the variation of the level of turbulence observed for different nozzles is apparently attributable to the different values of the level of turbulence at the nozzle exit. It is clear from an analysis of the figure than an increase in the level of turbulence to 15% causes a 40% increase in the heat transfer coefficient of the sphere.

NOTATION

D is the diameter of nozzle exit section
d is the sphere diameter
l is the distance along jet axis from nozzle exit to the forward stagnation point of the sphere
u_m and u_0 are the maximum velocity of jet at distance l and at nozzle exit, respectively
Re is the Reynolds number referred to sphere diameter
Nu is the Nusselt number
Re_m and Re_0 are the Reynolds numbers determined from the maximum velocity in the jet at distance l and at the nozzle exit, respectively
Nu_∞ is the Nusselt number calculated from the heat transfer coefficient of the sphere in an unbounded flow
$Nu_{\infty,0}$ and $Nu_{\infty,l}$ are the Nusselt numbers corresponding to heat transfer in a homogeneous flow whose velocity is equal to the maximum jet velocity at the nozzle exit and at distance l
ε is the relative intensity of the longitudinal component of the turbulent fluctuations of the flow
ε_0 is the intensity of turbulent fluctuations at nozzle exit
Θ is the angle reckoned from the forward stagnation point of the sphere
$\overline{P} = 2(P - P_\infty)/\rho u_m^2$ is the pressure coefficient
P_∞ is the dynamic pressure
$\rho u_m^2/2$ is the dynamic pressure of jet at forward stagnation point.

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