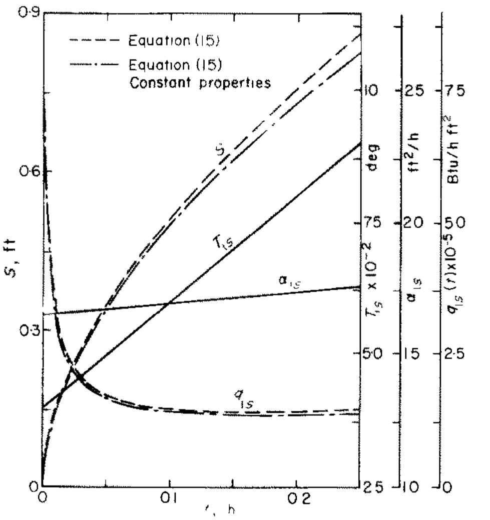

FIG. 1. Melting of copper at $T_{2i} = 0°$ and $T_{1s} = 400 + 2000\,t$.

rather easily by the simpler constant thermal physical property condition for materials having linear thermal conductivity and volumetric specific heat functional relationships with temperature.

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THE INFLUENCE OF ROTATION ON THE HEAT TRANSFER FROM A SPHERE TO AN AIR STREAM

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NOMENCLATURE

- c, specific heat;
- d, duct diameter [m];
- D, sphere diameter [m];
- F, function defined by equation (4) [W/m² K];
- Gr, Grashof number;
- h_c, heat transfer coefficient for convection [W/m² K];
- h_{eff}, effective heat transfer coefficient [W/m² K];
- h_R, heat transfer coefficient for radiation [W/m² K];
- k, thermal conductivity [W/m K];
- Nu, Nusselt number, h_cD/k;
- Pr, Prandtl number;
- Q_c, rate of heat transfer by convection [W];
- Q_{cond}, rate of heat transfer by conduction [W];
- Q_R, rate of heat transfer by radiation [W];
- R, radius of the sphere [m];
- Re, Reynolds number, $(U\rho D/\mu)$;
- R_{eR}, rotational Reynolds number, VD/ν;
- R_{SH}, radius of support shaft [m];
- t_a, air temperature [°C];
- t_m, sphere mean temperature [°C];
- t_s, sphere surface temperature [°C];
- T, absolute temperature of the air in the boundary layer [K];
- T_a, absolute air temperature [K];
- T_m, sphere mean absolute temperature [K];
- T_s, sphere surface absolute temperature [K].

Greek letters

ε, emissivity;

ρ, density [kg/m^3];

σ, Stefan–Boltzmann constant [W/m^2 K^4],

ω, angular velocity of sphere axis [rad/s];

τ, time [s].

INTRODUCTION

THE PROBLEM of heat transfer from a spherical particle to a fluid is of importance in several different applications from combustion of fuel droplets to the formation of hailstones. Many investigators have published papers on the heat transfer from a stationary sphere to a fluid stream. The present note adds some experimental results for the case when a sphere is spinning in a plane at right angles to the flowing fluid, in this case air. Results are also given for a sphere spinning in stationary air.

APPARATUS AND EXPERIMENTAL METHOD

The experimental results of the present investigation were obtained from a solid phosphor-bronze sphere of 50·8 mm diameter attached to a vertical steel shaft of 7·75 mm diameter and mounted in a vertical duct of 610 × 610 mm cross-section, through which air was drawn upwards by a centrifugal fan. A series of meshes and flow straighteners produced a uniform air stream with a free stream turbulence intensity of 0·008.

The experimental technique used to obtain the mean heat transfer coefficient and complete details of the design of the apparatus, are given in [1]. A transient method was used, the temperature of the centre of the sphere being measured as the sphere cooled in an air stream. A carefully devised correction was made for the conduction loss through the steel shaft, based on readings from a series of thermocouples on the shaft. Tests were carried out with the sphere cooling in natural convection and these tests were then repeated with the sphere suspended by a nylon line. Very good agreement was obtained between the corrected results, those from the sphere on the nylon line, and results obtained by other investigators [2–4]. As a further check on the method of correcting for the conduction loss, readings were taken for the sphere stationary in an air stream and compared with correlations of Raithby and Eckert [5], and of Yuge [2]. By analysing the conduction of heat within the sphere and by using the Heisler chart for a sphere [6], it was estimated that the temperature at the sphere centre was within $1\frac{1}{2}$ per cent of the temperature at the sphere surface for sphere centre temperatures up to 80°C. To check this a series of tests was performed with a separate sphere of the same design, with a number of thermocouples mounted on the surface at various stations. From the direct cooling curves obtained, the temperature of the sphere surface was found to be at no point less than about $98\frac{1}{2}$ per cent of the sphere centre temperature over the entire range of Reynolds numbers (see [1]).

The method of calculating the heat transfer coefficient from the cooling curve for the sphere centre thermocouple was as follows: At any instant the sum of the heat losses must equal the rate of loss of energy of the sphere, i.e.

$$Q_c + Q_R + Q_{\text{cond}} = -\rho V_c \, \mathrm{d}T_m/\mathrm{d}\tau \tag{1}$$

Also,

$$Q_c = h_c(4\pi R^2 - \pi R_{SH}^2)(t_s - t_a) \tag{2}$$

$$Q_R = h_R(4\pi R^2 - \pi R_{SH}^2)(t_s - t_a) \tag{3}$$

and

$$Q_{\text{cond}} = F\pi R_{SH}^2 (t_s - t_a). \tag{4}$$

In equation (4) the term F is a function of the thermal conductivity of the shaft material, the length of the shaft, the diameter of the shaft, the heat transfer coefficient from the shaft to the air, and the change of shaft temperature with time; the value of F was carefully calculated as mentioned above, and a detailed account of the method is given in [1]. Substituting equations (2)–(4) in equation (1) and simplifying we have:

$$(t_m - t_a)\left\{\frac{(t_s - t_a)}{(t_m - t_a)}\left[(h_c + h_R)\left(1 - \frac{R_{SH}^2}{4R^2}\right) + \frac{FR_{SH}^2}{4R^2}\right]\right\} = \frac{cR\rho}{3}\frac{\mathrm{d}(t_m - t_a)}{\mathrm{d}\tau} \tag{5}$$

i.e.

$$h_{\text{eff}}(t_m - t_a) = -\frac{\rho c R}{3}\frac{\mathrm{d}(t_m - t_a)}{\mathrm{d}\tau}. \tag{6}$$

If it is assumed that h_{eff} remains constant over a finite time interval $\Delta\tau$ in which the sphere mean temperature falls from t_{m_1} to t_{m_2}, then:

$$h_{\text{eff}} = \frac{\rho c R}{3\Delta\tau}\log_e\frac{(t_{m_1} - t_a)}{(t_{m_2} - t_a)}. \tag{7}$$

Also, by comparing equations (5) and (6) it can be seen that

$$h_{\text{eff}} = \frac{(t_s - t_a)}{(t_m - t_a)}\left[(h_c + h_R)\left(1 - \frac{R_{SH}^2}{4R^2}\right) + \frac{FR_{SH}^2}{4R^2}\right]. \tag{8}$$

Hence,

$$h_c = \left\{\frac{h_{\text{eff}}\left(\dfrac{t_m - t_a}{t_s - t_a}\right) - \dfrac{FR_{SH}^2}{4R^2}}{(1 - R_{SH}^2/4R^2)}\right\} - h_R \tag{9}$$

where

$$h_R = \varepsilon\sigma(T_s^2 + T_a^2)(T_s + T_a).$$

From the sphere cooling curve, values of $(t_m - t_a)$ at various times were measured and a mean effective heat transfer coefficient, h_{eff} calculated using equation (7). After having obtained the appropriate value of F from the conduction correction curves, and a calculated value of h_R for the given surface temperature and air temperatures, equation (9) was used to calculate the heat transfer coefficient for convection, h_c. The surface of the sphere was given a thin bright nickel plating which gave a polished mirror finish at all temperatures, and hence a constant value of emissivity was assumed. The radiation correction, h_R was of the order of 1 per cent of h_c, and the conduction correction F, was never greater than 10 per cent of h_c.

The sphere diameter was sufficiently small compared with the duct cross-section to ensure negligible distortion of the streamlines of the free stream outside the sphere boundary layer. Vliet and Leppert [7] used a corrected free stream velocity by dividing the approach free stream velocity by the factor 12/3 $(D/d)^2$, where D and d represent the sphere and duct diameters respectively. For the present investigation the error in ignoring this correction is about 0·3 per cent.

Pei [8] has shown that for a rear-support shaft the effect of the shaft on the corrected heat transfer coefficient from the sphere, h_c, is negligible when the flow Reynolds number is greater than about 5000.

HEAT TRANSFER RESULTS

Rotating sphere in still air

It has been shown mathematically by Howarth [9] and verified experimentally by Bowden and Lord [10], that as a sphere rotates it draws fluid from each pole, a laminar boundary layer forming on the surface; near the equator the two streams impinge leaving the sphere as a flat radial jet. Dorfman and Mironova [11] have analysed theoretically the case of heat transfer from a rotating sphere in a still fluid. When their results are integrated over the entire sphere surface, the following equation is obtained:

$$Nu = 0{\cdot}252\, Re_R^{\frac{1}{2}}. \qquad (10)$$

Experiments have been performed by Kreith *et al.* [12] and the following correlation suggested

$$Nu = 0{\cdot}43\, Re_R^{\frac{1}{2}} Pr^{0\cdot4} \text{ for } 0{\cdot}7 < Pr < 217 \text{ and } Re < 5 \times 10^4. \qquad (11)$$

For air with $Pr = 0{\cdot}7$ equation (11) becomes

$$Nu = 0{\cdot}373\, Re_R^{\frac{1}{2}}. \qquad (12)$$

In the present investigation a series of tests was undertaken for a sphere rotating in still air, for a Grashof number of $6{\cdot}5 \times 10^5$. When the results are plotted as Nu against $Re_R^{\frac{1}{2}}$ a straight line relationship is found for values of $Re_R > 5800$; this relationship can be expressed as:

$$Nu = 0{\cdot}353\, Re_R^{\frac{1}{2}}. \qquad (13)$$

Below a certain value of Re_R for the given Grashof number free convection effects increase the heat transfer from the sphere. Since only one Grashof number was used for all the tests the exact point at which free convection becomes important is not clearly defined from the present tests. For the present results, when $Gr/Re_R^2 < 0{\cdot}02$ then natural convection effects are negligible.

The present results, together with the mean result for natural convection at $Gr = 6{\cdot}5 \times 10^5$, and the results of Kreith *et al.* [12], are shown in Fig. 1. Also shown on the figure is the correlation of Dorfman and Mironova [11] given by equation (10). The discrepancy between the experiment and the theory may be due to the fact that the

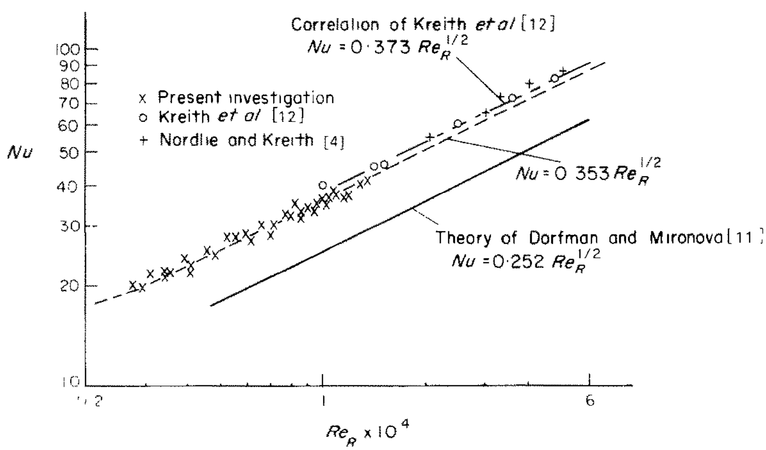

FIG. 1. Heat transfer from a rotating sphere in still air.

theory ignores the effect of the radial jet of fluid leaving the equator, which will considerably increase the heat transfer from the sphere.

Rotating sphere in an air stream

For a given air flow, tests were made at various values of rotational speed and then repeated for a different air flow. It was found that for any given air flow there was a rotational speed below which the heat transfer appeared to be unaffected by the rotation. When the results were plotted as Nusselt number against the ratio of rotational Reynolds number Re_R, to flow Reynolds number, Re, it was found that for all flows the point at which rotation begins to have an influence on the heat transfer, occurs at a fixed value of Re_R/Re of between 0·5 and 0·6.

At zero rotation, the results can be correlated by the equation, $Nu = 0{\cdot}228\, Re^{0\cdot6}$, (1), hence dividing each value of the Nusselt number by the right hand side of this equation reduces the results to a simple correlation for all Reynolds numbers as shown by Fig. 2 in which $Nu/0{\cdot}228\, Re^{0\cdot6}$ is plotted against Re_R/Re. From these results we have:

$$Nu/0{\cdot}228\, Re^{0\cdot6} = 1 + 0{\cdot}167 \left[\frac{Re_R}{Re} - 0{\cdot}54\right] \quad \text{for } Re_R/Re > 0{\cdot}54. \qquad (14)$$

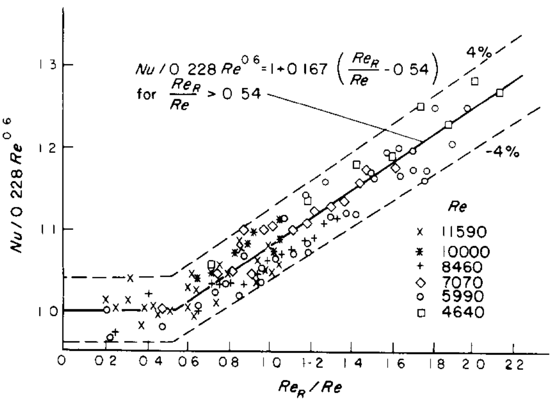

FIG. 2. Heat transfer from a rotating sphere in an air stream.

This equation correlates the results within ±4 per cent. For values of $Re_R/Re < 0{\cdot}54$ rotation does not affect the heat transfer.

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