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An experimental study of forced convective heat transfer from smooth, solid spheres

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ABSTRACT

Forced convective heat transfer from smooth, solid and isothermal spheres of various diameters has been studied experimentally in air flows with various free-stream velocities. The average heat transfer coefficient has been determined from the steady measured power input to a heating element inside the spheres and the steady measured temperatures of the flowing air and of the surface of the spheres, employing corrections to account for heat transfer due to thermal radiation and due to natural convection. The current data for the average heat transfer coefficient, expressed as a relationship between the Nusselt number and the Reynolds number, complement data in literature with respect to the range of large Reynolds numbers that have been considered: here the Reynolds numbers were between 7.8×10^3 and 3.3×10^5. The experimental results show a sudden increase in the Nusselt number above a critical Reynolds number of approximately 2.9×10^5, analogous to the “drag crisis” for the drag force on the sphere. A correlation for the Nusselt number as a function of the Reynolds number has been formulated for air flows that describes these data well for Reynolds numbers below the critical Reynolds number.

1. Introduction

Forced convective heat transfer from spherical objects, or objects that are modelled as spheres, is ubiquitous in many disciplines in engineering and science. The rate of heat transfer $\dot{Q}_{\mathrm{for}}$ due to forced convection is expressed through the average heat transfer coefficient h by

$$\dot{Q}_{\mathrm{for}} = hA_S(T_S - T_\infty) \tag{1}$$

where A_S is the surface area at which convective heat transfer occurs, T_S is the surface temperature of the isothermal sphere and T_∞ is the temperature of the free-stream fluid that is flowing at velocity U_∞. The diameter of the sphere is denoted by D.

Dimensional analysis of the problem of forced convective heat transfer at low fluid speeds (i.e. at low Mach numbers) shows that the Nusselt number Nu is dependent on Reynolds number Re and Prandtl number Pr

$$Nu = f(Re, Pr) \tag{2}$$

These dimensionless numbers are defined by

$$Nu = \frac{hD}{k} \qquad Re = \frac{U_\infty D}{\nu} \qquad Pr = \frac{\nu}{\alpha} \tag{3}$$

Here k is the thermal conductivity, ν is the kinematic viscosity and $\alpha = k/(\rho c_p)$ is the thermal diffusivity with ρ and c_p the density and the specific heat at constant pressure, respectively. All these fluid properties are based here on tabulated values given in Cengel and Ghajar [8]. These are evaluated here at the film temperature $T_f = (T_S + T_\infty)/2$ (as also done by [32,27,14]).

Many experimental studies have been performed of forced convective heat transfer from isothermal spheres, where the average convective heat transfer coefficient h is given in terms of a correlation of the type in Eq. (2). Here an overview is given of the main experimental studies and correlations.

Kramers [20] performed (steady) experiments with Reynolds numbers in the range $0.4 < Re < 2100$ with air, water and an oil that have different Prandtl numbers Pr. Spheres with diameters of 1.26, 0.787 and 0.709 cm were employed. A correlation for the Nusselt number as a function of Reynolds number and Prandtl number was formulated

$$Nu_{\mathrm{Kramers}} = 2 + 1.3Pr^{0.15} + 0.66Pr^{0.31}Re^{0.50} \qquad \begin{array}{l} 0.4 < Re < 2100 \\ 0.71 < Pr < 380 \end{array} \tag{4}$$

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The reported uncertainty of this correlation is about 10% for $10 < Nu < 40$.

Yuge [32] performed (steady as well as unsteady) experiments in air (with $Pr = 0.715$) using spheres of different diameters (2.2 and 6.0 cm for measurements at high Reynolds numbers) and different wind tunnels with different air velocities. In addition, combined heat transfer due to forced and natural convection (in cross, parallel and counterflow) was studied. For heat transfer by forced convection only, the results for air for the Nusselt number as a function of Reynolds number were correlated by

$$\begin{aligned} Nu_{Yuge} &= 2 + 0.493Re^{0.50} \quad 10 < Re < 1.8 \times 10^3 \\ Nu_{Yuge} &= 2 + 0.300Re^{0.57} \quad 1.8 \times 10^3 < Re < 1.5 \times 10^5 \end{aligned} \tag{5}$$

Vliet and Leppert [29] measured the (steady) rate of heat transfer between a sphere (with diameter of 2.2 cm) and flows of water in a (rather small) water tunnel under conditions where a considerable temperature difference exists between the surface of the sphere and the free-stream water (up to 65 K). The range of Reynolds numbers considered in their measurements is $50 < Re < 5 \times 10^4$. As the variation with temperature of the dynamic viscosity of water is significant (in comparison to that of air), this was accounted for in their correlation for water

$$Nu_{Vliet} = \left[2.7 + 0.12Re^{0.66}\right] Pr^{0.5} \left(\frac{\mu_\infty}{\mu_S}\right)^{0.25} \quad 50 < Re < 5 \times 10^4 \tag{6}$$

where μ_S and μ_∞ are the dynamic viscosity of water at the surface temperature and at the temperature of the free stream, respectively.

Raithby and Eckert [27] carefully performed (steady) experiments in air where the Reynolds number was in the range $3.6 \times 10^3 < Re < 5.2 \times 10^4$. Diameters of the spheres were 1.27, 2.54 and 5.08 cm. The influence of the position of the support of the sphere on the rate of heat transfer was also investigated: with a cross-flow support it is about 10% higher than with a rear support. With an increase in turbulence level of the flow (up to about 5%), they observed that the rate of heat transfer increased by 7.5% at $Re = 3.6 \times 10^3$ and by 17.5% at $Re = 5.2 \times 10^4$. Their correlation for air describing these measurements with rear support and with a low turbulence intensity of 0.15% is

$$Nu_{Raithby} = 2 + 0.21Re^{0.61} \quad 3.6 \times 10^3 < Re < 5.2 \times 10^4 \tag{7}$$

The maximum reported deviation between measurements and results of this correlation is 2%.

Eastop and Smith [14] developed a correlation for air that is based on theoretical considerations of laminar boundary layers for the front half of the sphere and data from literature for the heat transfer from the rear half of the sphere where the flow has separated. Their correlation for air for the Nusselt number as a function of the Reynolds number is given by

$$Nu_{Eastop} = 0.42Re^{0.50} + 0.0035Re^{0.92} \quad 3.0 \times 10^3 < Re < 1.0 \times 10^5 \tag{8}$$

where the first and second term on the right-hand side correspond to the heat transfer from the front and rear halves of the sphere, respectively.

Based on experimental data from literature (by Kramers [20], Yuge [32] and Vliet and Leppert [29]), Whitaker [30] proposed a correlation that is given in many textbooks (for example [8,23])

$$\begin{gathered} Nu_{Whitaker} = 2 + \left[0.4Re^{0.50} + 0.06Re^{0.67}\right] Pr^{0.4} \left(\frac{\mu_\infty}{\mu_S}\right)^{0.25} \\ 3.5 < Re < 7.6 \times 10^4 \quad 0.71 < Pr < 380 \end{gathered} \tag{9}$$

where $1 < \mu_\infty/\mu_S < 3.2$. The fluid properties are evaluated at the free-stream temperature T_∞, except that μ_S is the dynamic viscosity at the surface temperature T_S. The maximum deviation reported is 30%.

Ahmed and Yovanovich [4] developed an approximate analytical solution of the energy equation for the limit cases of $Pr \to 0$ and of $Pr \to \infty$. These solutions were combined (using some empirical data), to yield a correlation stated to be valid for all Prandtl numbers

$$Nu_{Ahmed} = 2 + 0.775Re^{0.50} \frac{Pr^{0.33}}{\sqrt{2\gamma+1}\left[1+\frac{1}{(2\gamma+1)^3 Pr}\right]^{0.17}} \quad 1.0 < Re < 1.0 \times 10^5 \tag{10}$$

where $\gamma = Re^{-0.25}$.

It is well-known that the turbulence level Tu of the free-stream influences the heat transfer characteristics from the sphere [6,22,27,16,25,19]. Ahmed et al. [5] incorporated this influence of the turbulence level Tu of the free-stream on the heat transfer characteristics from the sphere. For Tu → 0, their complex relation (represented by their Eqs. (53) and (54)) reduces to the correlation by Ahmed and Yovanovich [4], Eq. (10).

Measurements of local Nusselt numbers in turbulent air flow have been performed by Xenakis et al. [31] for various Reynolds numbers, and by Aufdermauer and Joss [6], Galloway and Sage [16] and Hayward and Pei [17] for various Reynolds numbers and turbulence intensities. In the measurements by Aufdermauer and Joss [6], Galloway and Sage [16] and Hayward and Pei [17] with low turbulence intensity the local Nusselt number in the laminar boundary layer decreases from the stagnation point towards the point of separation. In the wake region the local Nusselt number increases almost monotonically for the Reynolds numbers that have been considered. Measurements by Xenakis et al. [31] (with side support) have been made at very high Reynolds numbers (up to $Re = 4.98 \times 10^5$). From the distribution of the local Nusselt number over the sphere (as represented by Clift et al. [12] on their page 120) for Reynolds numbers of $Re = 2.59 \times 10^5$ and 4.98×10^5 it seems (by the presence of a region with very high local Nusselt numbers) that a turbulent boundary layer is present over part of the rear half of the sphere. These conditions therefore correspond to supercritical values of the Reynolds number.

Experiments on the rate of heat transfer from spheres in the turbulent, outdoor environment have been performed by Kowalski and Mitchell [19], who found that under such conditions the rate of heat transfer is up to twice as large as in low-turbulence laboratory conditions. Experiments on the rate of heat transfer with a fluid with a low Prandtl number of 0.003 have been reported by Melissari and Argyropoulos [24]. Convective heat transfer from rotating spheres in various stationary fluids has been studied experimentally by Kreith et al. [21] and Eastop [15]. An analogy between drag and heat transfer has recently been discussed by Duan et al. [13].

The development of the flow field with changes in Reynolds number is described in detail by Clift et al. [12] in their Section 5.II.A.2. At the front part of the sphere the flow in the boundary layer is laminar. For Reynolds numbers larger than about 20 the flow at the rear part of the sphere has separated. At a Reynolds number of about 400, the flow becomes unsteady and asymmetric, with periodic vortex shedding. At a critical Reynolds number, $Re_{crit} \cong 3 \times 10^5$ for smooth spheres, boundary layer transition occurs. The turbulent boundary layer remains attached over part of the rear half of the sphere, resulting in a narrower wake with corresponding lower pressure drag. Therefore, the drag coefficient shows a pronounced drop, the so-called "drag crisis", at the critical Reynolds number. Analogously, it is expected that there is an increase in the rate of heat transfer.

The experimental study of the rate of heat transfer from spheres has received less attention in the literature than that for cylinders in cross-flow. For cylinders, extensive experimental results for local and total heat transfer rates have been reported for Reynolds