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Low Prandtl number heat transfer to fluids flowing past an isothermal spherical particle

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An analytical solution to the forced convective heat and mass transfer across a laminar incompressible boundary layer, over the surface of a stationary isothermal spherical particle was obtained. An inviscid flow was assumed outside the viscous boundary layer. The solution is confined to low Prandtl number fluids. New relations for the forward and rear stagnation points, local and overall heat and mass transfer rates for the forward and wake regions of the sphere were derived. These compared well with the available experimental results and other theories.

Keywords: convective heat transfer; external flow; sphere; boundary layer; separation angle

Introduction

Convective heat and mass transfer from an isothermal spherical particle surrounded by a flowing fluid occurs in many engineering industries. Among these are: drying, adsorption, extraction, fixed and fluidized beds, cooling of airplane components, cooling of spherical fuel elements in certain types of nuclear reactors.

The complex nature of the fluid flow around the sphere rendered the mathematical treatment of the heat or mass transfer rather difficult. For a steady and uniform fluid flow at Reynolds number (Re) greater than 20, the transfer rate from the forward region of the sphere is different and independent from that at the rear region (Garner and Grafton, 1954). A hydrodynamic boundary layer is formed at the forward surface of the sphere. This layer gets separated from the surface, and reverse flow is immediately established at the rear of the sphere with the development of a rear boundary layer.

Clift et al. (1978) made an extensive survey of available information on the subject. However, Frossling (1938) and Linton and Sutherland (1960) solved Navier–Stokes, continuity and mass concentration equations by expanding the fluid velocity function as a power series in distance along the surface from the front pole of the sphere.

Others such as Levich (1962), Hamielec (1961), Graner and Keey (1958) and Akselrud (1953) have used the boundary-layer theory to get the following expression for the overall Nusselt number:

$$\mathrm{Nu} = A\mathrm{Re}^{1/2}\mathrm{Sc}^{1/3} \tag{1}$$

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Received 11 November 1994; accepted 23 March 1995

Int. J. Heat and Fluid Flow 16: 291–297, 1995

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for Re > 100, where Sc is the Schmidt number, and the constant A has been found to lie between 0.55 and 0.94, which is quite a wide range.

Inadequate methods were reported for calculating the heat or mass transfer rates from the wake region of the sphere; e.g., the assumption of a constant local mass transfer after the separation ring (Askelrud 1953) and negligible skin friction in the wake (Garner and Keey 1958).

The work of this paper is prompted by the consideration of a need for a unified theory for the convective heat and mass transfer over a submerged isothermal spherical particle, particularly in the wake region. The present technique of solution is based upon an assumption of the potential flow in the energy conservation equation with utilization of boundary-layer approximations. The solution is limited to low (not as low as the liquid metals domain) Prandtl number (Pr < 1) fluids and for laminar flow with Re > $O(10^2)$. This flow limit was indicated by Bejan (1993).

Forward region of sphere

Consider a solid stationary isothermal sphere of radius a (see Figure 1) in an infinite flowing medium. The uniform velocity of the fluid at infinity is represented by U_∞. The center of the sphere is taken as the origin of the spherical system of coordinates r, Θ. The heat exchange between the sphere and the fluid takes place within a thin upstream laminar boundary layer over the forward surface of the sphere, whose thickness is δ_1.

The upstream laminar boundary layer separates from the forward sphere surface at Θ_s because of the deceleration of the fluid and the consequent increase in its local pressure. The fluid flow beyond this layer is assumed inviscid and irrotational, which can be represented by the following stream function

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(Milne-Thomson 1972)

$$\psi = \tfrac{1}{2}U_\infty[1 - (a/r)^3]r^2 \sin^2\Theta \quad (2)$$

The inviscid flow assumption was used by Merk (1959), Acrivos (1962) and Chen (1974) among others.

The angular U and radial V velocity components of the main flow around the sphere can be obtained from the following:

$$(\mathbf{U}, \mathbf{V}) = -\nabla\psi \quad (3)$$

as

$$U = U_\infty \sin\Theta[1 + 1/2(a/r)^3] \quad (4)$$

and

$$V = -U_\infty \cos\Theta[1 - (a/r)^3] \quad (5)$$

The steady-state energy conservation equation in spherical coordinates for an incompressible flow with negligible heat generation and no viscous dissipation is as follows:

$$V\frac{\partial T}{\partial r} + U\frac{\partial T}{r\partial\Theta} = \alpha\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial\Theta}\left(\sin\Theta\frac{\partial T}{\partial\Theta}\right)\right] \quad (6)$$

where T is the temperature, and α is the thermal diffusivity.

If we assume that the heat conduction in the angular direction is small in comparison with that in the radial direction, then we get the following

$$V\frac{\partial T}{\partial r} + U\frac{\partial T}{r\partial\Theta} = \alpha\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right] \quad (7)$$

If the thickness of the upstream laminar boundary layer is (δ_1), then the right side of Equation 7 is further approximated as follows:

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} \simeq \frac{\partial^2 T}{\partial r^2} \quad (8)$$

because if $(2/r)\partial T/\partial r$ is $O(2/a\delta_1)$, then

$$\frac{1}{\delta_1^2} + \frac{2}{a\delta_1} \simeq \frac{1}{\delta_1^2} \quad (9)$$

Now we transfer the origin of the r, Θ coordinates from the center of the sphere to its surface with the introduction of a new radial variable y, so that $y = O$ at $r = a$, and $-\Theta_s \le \Theta \le \Theta_s$.

Assuming

$$(r - a)/a = y/a \ll 1 \quad (10)$$

allows us to say that

$$\frac{\mathrm{U}}{\mathrm{r}}\frac{\partial \mathrm{T}}{\partial\Theta} \simeq \frac{\mathrm{U}}{\mathrm{a}}\frac{\partial \mathrm{T}}{\partial\Theta} \quad (11)$$

Utilizing the binomial theorem and retaining the first two terms with Equation 10 in mind, we get the following:

$$(a/r)^3 = (1 - y/r)^3 = 1 - 3y/r - \ldots \quad (12)$$

therefore, Equations 4 and 5 become as follows:

$$U \simeq 3/2U_\infty \sin\Theta \quad (13)$$

and

$$V \simeq -3U_\infty(y/a)\cos\Theta \quad (14)$$

Substituting Equations 8, 10, 11, 13, and 14 into Equation 7, we get the following:

$$\sin\Theta\frac{\partial T}{\partial\Theta} - 2y\cos\Theta\frac{\partial T}{\partial y} = \lambda\frac{\partial^2 T}{\partial y^2} \quad (15)$$

where

$$\lambda = 2a\alpha/3U_\infty \quad (16)$$

The boundary conditions are as follows:

$$T = 0 \quad \text{at} \quad y = \infty \quad \text{and} \quad \pi \ge \Theta \ge 0 \quad (17)$$

$$T = T_a \quad \text{at} \quad y = 0 \quad \text{and} \quad \Theta_s \ge \Theta \ge 0 \quad (18)$$

$$T = 0 \quad \text{at} \quad \infty > y > 0 \quad \text{and} \quad \Theta_s \ge \Theta \ge 0 \quad (19)$$

The independent variables y and Θ of Equation 15 are

Notation

A	constant, Equation 1
A_f	surface area of the forward region of the sphere
A_w	surface area of the wake region of the sphere
a	sphere radius
D	diffusion coefficient
h	average heat transfer coefficient
h_Θ	local heat transfer coefficient
J	Colburn J-factor
k	thermal conductivity of fluid
Nu	overall Nusselt number, $h\,(2a)/k$
N*u	Nusselt number based on radius, ha/k
$[\mathrm{Nu}(\Theta)]_f$	local Nusselt number at the forward region of the sphere, $h_\Theta\,(2a)/k$
$[\mathrm{Nu}(\Theta)]_w$	local Nusselt number at the wake region of the sphere, $h_\Theta\,(2a)/k$
$[\mathrm{Nu}(O)]_f$	local Nusselt number at the forward stagnation point of the sphere
$[\mathrm{Nu}(\pi)]_w$	local Nusselt number at the rear stagnation point of the sphere
Pe	Peclet number, $U_\infty(2a)/\alpha$
$(\mathrm{Pe})_w$	Peclet number at the wake, $U_w\,(2a)/\alpha$
Pr	Prandtl number, ν/α
q	overall rate of heat transfer
$(q_\Theta)_f$	rate of heat transfer from the forward surface of the sphere
r	polar coordinate
Re	Reynolds number, $U_\infty(2a)/\nu$
Re*	Reynolds number based on radius, $U_\infty a/\nu$
Sc	Schmidt number, ν/D
T	absolute temperature
U	angular component of fluid velocity
U_∞	uniform velocity of the flow at infinity
U_w	reverse velocity of the wake at the edge of the boundary layer
V	radial component of fluid velocity
y	radial distance from sphere surface
Greek	
α	thermal diffusivity
Θ	polar coordinate
Θ_s	separation angle
Ψ	stream function at the forward region of the sphere
Ψ_w	stream function at the wake region of the sphere
ω, ϕ	functions defined by Equations 20 and 21
ν	kinematic viscosity
λ	constant, Equation 16

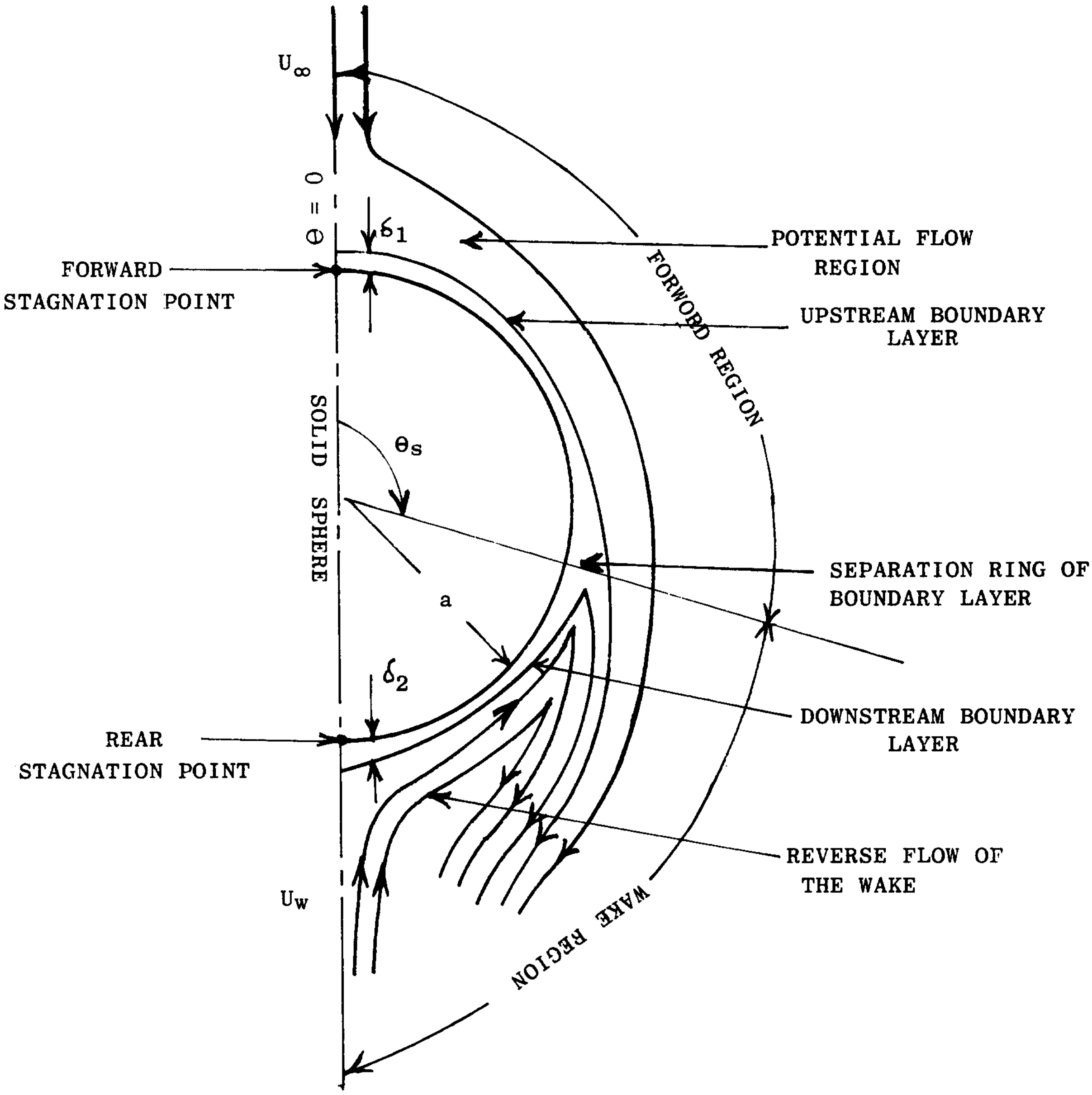

Figure 1 Geometry of the problem

transformed into the following:

$$\omega = y \sin^2\Theta \tag{20}$$

$$\phi = \tfrac{1}{3}\cos^3\Theta - \cos\Theta + 2/3 \tag{21}$$

so that Equation 15 becomes the following:

$$\frac{\partial T}{\partial \phi} = \lambda \frac{\partial^2 T}{\partial \omega^2} \tag{22}$$

which is a parabolic partial differential equation analogous to the diffusion equation. The new boundary conditions are as follows:

$$T = O \text{ at } \omega = \infty \quad \text{and} \quad \phi \geq 0 \tag{23}$$

$$T = T_a \text{ at } \omega = 0 \quad \text{and} \quad \phi \geq 0 \tag{24}$$

The solution of Equation 22 is (Carslaw and Jaeger 1959)

$$T = T_a \operatorname{erfc}[\omega/2(\lambda\phi)^{1/2}] \tag{25}$$

Substituting the values of ω and ϕ into the above equation gives the temperature distribution over the forward region of the sphere, as follows:

$$T = T_a \operatorname{erfc}\{y \sin^2\Theta/2[\lambda(1/3 \cos^3\Theta - \cos\Theta + 2/3)]^{1/2}\} \tag{26}$$

The local convective rate of heat transfer per unit area of the forward surface of the sphere is given by the following:

$$(q_\Theta)_f = -k(\partial T/\partial y)_{y=0} = kT_a \sin^2\Theta/(\pi\lambda\phi)^{1/2} \tag{27}$$

where k is the thermal conductivity of the fluid, but

$$(q_\Theta)_f = h_\Theta T_a \tag{28}$$

where h_Θ is the convective heat transfer coefficient. Therefore, the local Nusselt number $[\mathrm{Nu} = h_\Theta(2a)/k]$ for the forward region of the sphere is given by the following:

$$[\mathrm{Nu}(\Theta)]_f = 1.693\, g^1(\Theta)\mathrm{Pe}^{1/2} \tag{29}$$

where

$$g^1(\Theta) = \sin^2\Theta/(2 + \cos^3\Theta - 3\cos\Theta)^{1/2} \tag{30}$$

and

$$\mathrm{Pe} = 2aU_\infty/\alpha = \text{Peclet number} \tag{31}$$

Also Pe = (Re) (Pr) where Re is the Reynolds number of the flow, and Pr is the Prandtl number ($\mathrm{Pr} = v/\alpha$) where v is the kinematic viscosity.

At the forward stagnation point of the sphere (i.e., at $\Theta = 0$), we get

$$[\mathrm{Nu}(0)]_f = 1.955\,\mathrm{Pe}^{1/2} \tag{32}$$

Noting that

$$\lim_{\Theta\to 0} g1(\Theta) = 1.155 \tag{33}$$

Wake region of the sphere

Consider the reverse flow around the rear surface of the sphere to be similar in pattern and streamlines to that around the forward surface of the sphere, particularly in the vicinity of the surface. This assumption is not far from reality if we examine the photographs of the streamlines for the flow past a sphere taken by Taneda (1956) and shown in Batchelor (1967, Plate 3).

The same method of solution used in the previous section is employed here by starting from the rear stagnation point and working forward to the separation ring. The above assumptions mean that $\Theta = O$ will be at the rear stagnation point, and the origin of the r, Θ coordinate is still at the center of the sphere.

Batchelor (1967, p. 348) and Lee and Barrow (1965) indicated that boundary-layer approximations are applicable in the wake region of spherical particles. The stream function that represents the flow of the wake above the edge of the downstream laminar boundary layer (see Figure 1) is as follows:

$$\psi_w = (1/2)U_w[1 - (a/r)^3]r^2\sin^2\Theta \tag{34}$$

where U_w represents the reverse velocity of the wake at the edge of the downstream boundary layer.

Lee and Barrow (1965) found experimentally that the ratio of $U_w/U_\infty = 0.077$ for the Reynolds number range of $10 < \mathrm{Re} < 1000$. Accordingly, the local Nusselt number for the wake region of the sphere will be the following:

$$[\mathrm{Nu}(\Theta)]_w = 1.693\, g1(\Theta)(\mathrm{Pe}^{1/2})_w \tag{35}$$

where

$$(\mathrm{Pe})_w = 2aU_w/\alpha = 0.077\,\mathrm{Pe} \tag{36}$$

The transformation to the original r, Θ coordinates requires the replacement of every angle Θ in $g1$ (Θ) by ($\pi - \Theta$), so that we get the following:

$$g2(\Theta) = \sin^2\Theta/(2 - \cos^3\Theta + 3\cos\Theta)^{1/2} \tag{37}$$

Therefore, the final form of Equation 35 becomes the following:

$$[\mathrm{Nu}(\Theta)]_w = 0.4698\, g2(\Theta)\mathrm{Pe}^{1/2} \tag{38}$$

with the

$$\lim_{\Theta\to\pi} g2(\Theta) = 1.155$$

Therefore, the rear stagnation point heat transfer is

$$[\mathrm{Nu}(\pi)]_w = 0.543\,\mathrm{Pe}^{1/2} \tag{39}$$

Clift et al. (1978, p. 121) indicated that $\mathrm{Nu}(\Theta) = f(\mathrm{Re}^{1/2})$ for laminar boundary layers; whereas, $\mathrm{Nu}(\Theta) = f(\mathrm{Re}^{0.8})$ for turbulent boundary layers. This is consistent with the results above.

Overall Nusselt number

To derive the Nusselt number averaged over the entire surface of the sphere, we say

$$q = \frac{1}{4\pi a^2}\left[\int_0^{\theta_s}(q_\theta)_f\,\mathrm{d}A_f + \int_\pi^{\theta_s}(q_\theta)_w\,\mathrm{d}A_w\right] \tag{40}$$

where

$$4\pi a^2 = \int_0^{\theta_s}\mathrm{d}A_f + \int_\pi^{\theta_s}\mathrm{d}A_w$$

A_f and A_w are the surface areas of the forward and wake regions of the sphere, respectively. The above gives the overall Nusselt number as

$$\mathrm{Nu} = \mathrm{Pe}^{1/2}[0.564\,H1(\Theta_s) + 0.156\,H2(\Theta_s)] \tag{41}$$

where

$$H1(\Theta_s) = (2 + \cos^3\Theta_s - 3\cos\Theta_s)^{1/2} \tag{42}$$

and

$$H2(\Theta_s) = (2 - \cos^3\Theta_s + 3\cos\Theta_s)^{1/2} \tag{43}$$

As $\Theta_s \to \pi$ in Equation 41, we get the Boussinesq (1905) solution for the heat transfer to the single sphere; namely,

$$\mathrm{Nu} = 1.13\,\mathrm{Pe}^{1/2} \tag{44}$$

The proportionality to the separation angle Θ_s in Equation 41 does not seem to have been previously suggested as a general law for the calculation of the convective rate of heat or mass transfer over the surface of a spherical particle. However, the separation angle can be obtained from the correlations of Linton and Sutherland (1960), as follows:

$$\Theta_s = 83 + 660\,\mathrm{Re}^{-1/2} \quad \text{for} \quad \mathrm{Re} > 100 \tag{45}$$

and

$$\Theta_s = 83 + 191\,\mathrm{Re}^{-1/3} \quad \text{for} \quad 15 < \mathrm{Re} < 1000 \tag{46}$$

The ratio of the heat transferred from the forward flow region of the spherical particle to that from the wake region may be written as follows:

$$\mathrm{Ratio} = 3.615\,H1(\Theta_s)/H2(\Theta_s) \tag{47}$$

This ratio is plotted in Figure 2, where the effect of the wake

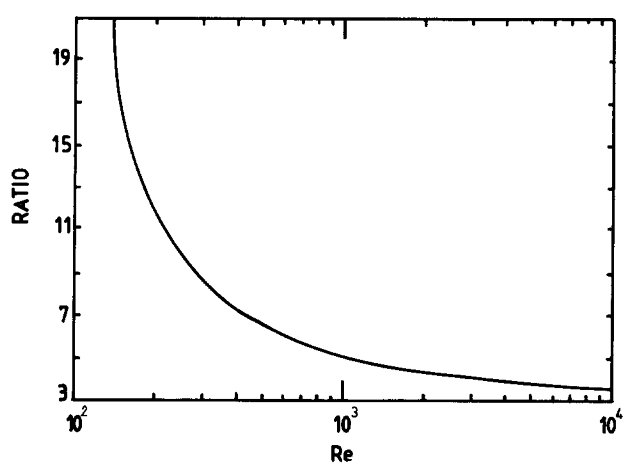

Figure 2 Ratio of heat transfer from forward to wake

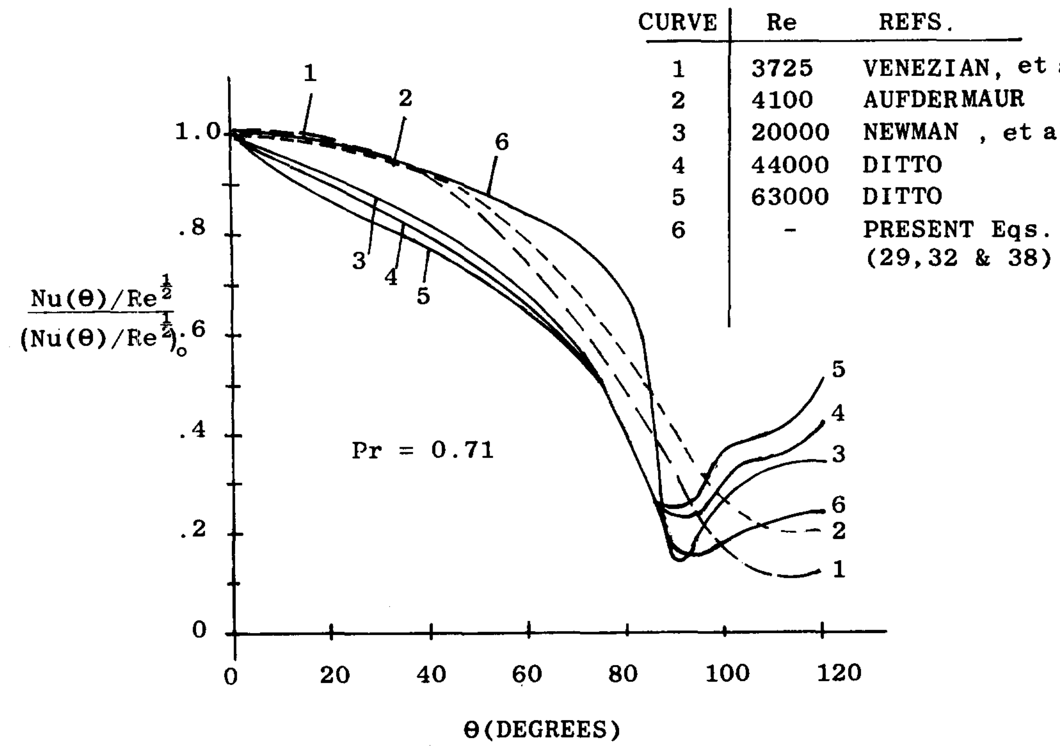

Figure 3 Comparison of local distributions of Nusselt number from several sources

is clearly demonstrated. At the lower end of the range, at Re = 200, and $\Theta_s = 130°$, the wake contributes about 8% of the total transfer; whereas, at Re = 4000, and $\Theta_s = 93°$, the wake contributes about 20% of the total.

Mass transfer

The corresponding problem in mass transfer can be stated in an analogous method to the previously discussed heat transfer, particularly when viscous heating is ignored in the latter. We need only to replace temperature by concentration, the thermal boundary layer by concentration boundary layer, the Nusselt number by Sherwood number, and the Prandtl number by Schmidt number.

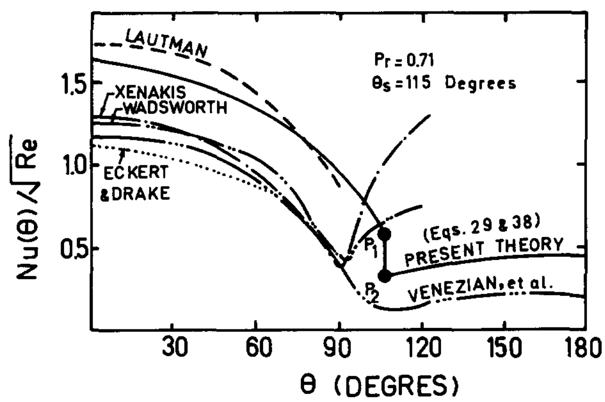

Figure 4 Comparison of local heat transfer from several sources

Verification of the theory

The present theory has been tested by comparing it with other theories and the available experimental results. Figures 3 and 4 show fair agreement for the local rates of heat transfer from a single solid sphere (i.e., Equations 29, 32, and 38) with the measured values of Newman et al. (1972), Venezian et al. (1962), Aufdermauer and Joss (1967), Lautman and Droege (1950), Xenakis et al. (1953), and Wadsworth (1958).

In Figure 3, note that $(Nu/Re^{1/2})_o$ means that the quantity was evaluated at the forward stagnation point, therefore

$$[Nu(\Theta)/Re^{1/2}]/(Nu/Re^{1/2})_o = 0.875\, g1(\Theta) \tag{48}$$

for the forward stagnation region of the sphere and

$$[Nu(\Theta)/Re^{1/2}]/(Nu/Re^{1/2})_o = 0.243\, g2(\Theta) \tag{49}$$

for the wake region of the sphere.

The variation of the function $[Nu(\Theta)_{f,w}/Pe^{1/2}]$ of Equations 29 and 38 around the separation angle Θ_s was not specified in the present study (see Figure 4). A smoothing function is required to join the two different values of P_1 and P_2 at Θ_s. The analytical solution of the energy equation at Θ_s is rather complex to obtain the smoothing function caused by the nonexistence of the boundary layer there. An average value between points P_1 and P_2 would be sufficient for the completion of this presentation.

Figure 5 represents a comparison between the present work and the theories of Sibulkin (1952) and Short (1960) and the experimental results of the authors indicated. Note that the dimensionless numbers in Figure 5 were based on the radius of the sphere, so Equation 32 becomes as follows:

$$[Nu^*(O)]_f = 1.38\,(Re^*\,Pr)^{1/2} \tag{50}$$

The equation above is identical to that derived by Short (1960).

Figures 6 and 7 show a fair agreement between the experimental and theoretical results of various investigators

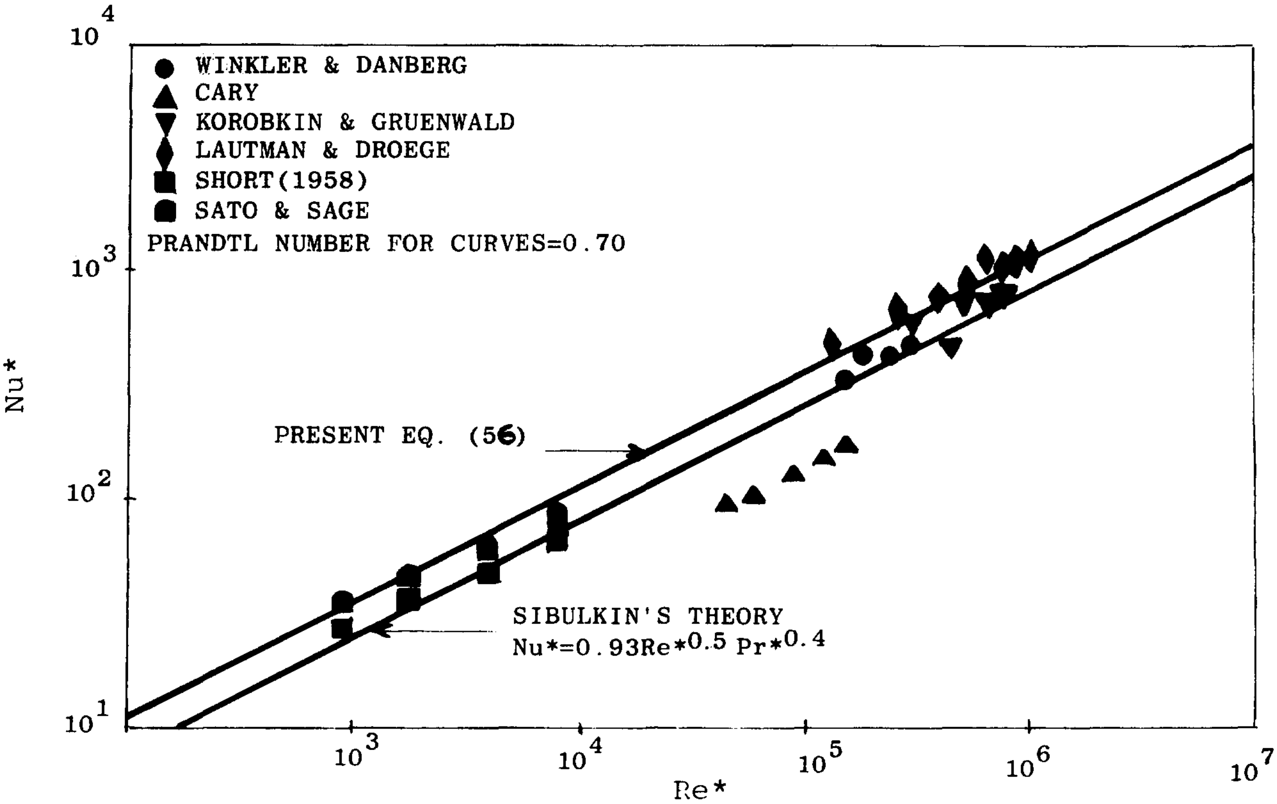

Figure 5 Heat transfer at stagnation point of a sphere

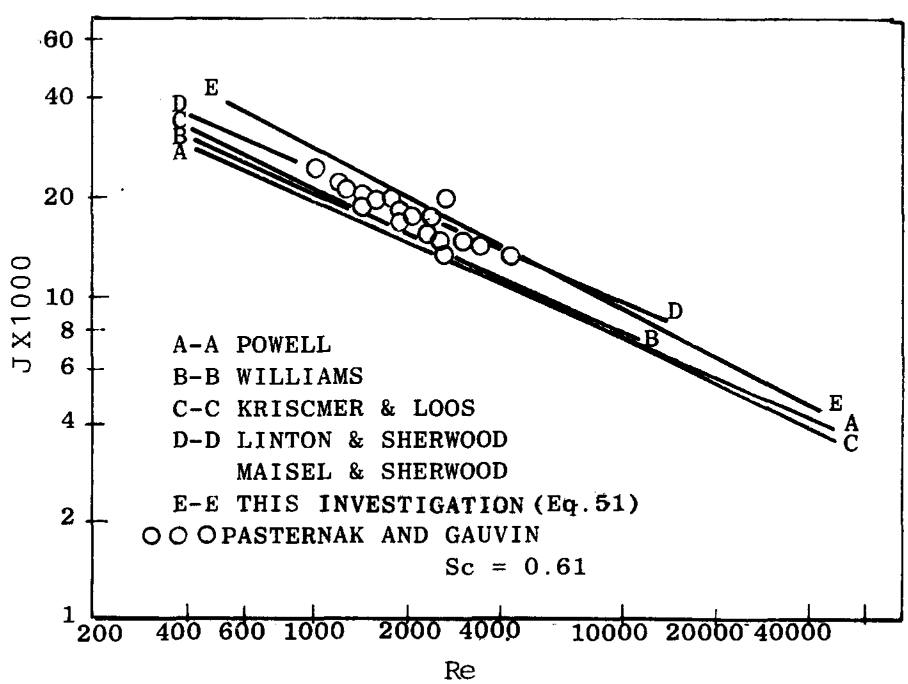

Figure 6 Data for spheres

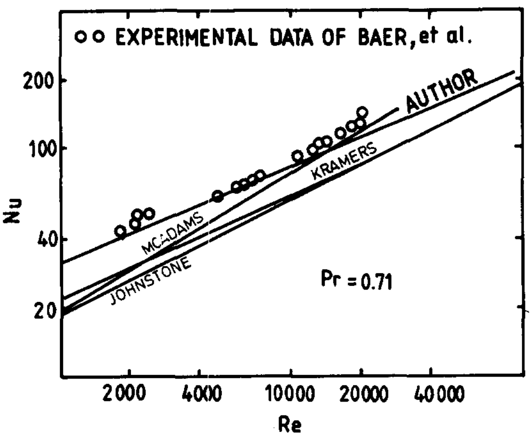

Figure 7 Variation of overall Nusselt number with Reynolds number

for the overall Nusselt number for the flow of fluid past a spherical particle and the present theory (i.e., Equation 41). The ordinate of Figure 6 represents the Colburn J-factor defined as $J = (St)(Sc)^{2/3}$, where St = Sh/Re Sc = Stanton number, so our Equation 41 for Sc = 0.61 becomes

$$J = 0.921\ Re^{-1/2}[0.564\ H1(\Theta_s) + 0.156\ H2(\Theta_s)] \qquad (51)$$

The potential flow assumption outside the viscous boundary layer makes the present solution suitable for large Reynolds number flows of small viscosity, therefore, the present solution was found to give fair agreement with the experimental results of fluids with low Prandtl numbers (e.g., gases and light liquids).

Conclusions

The new theory developed in this paper for the convective heat and mass transfer over the surface of the spherical particle has been successful in calculating the local heat and mass transfer, the transfer coefficients at the forward and rear stagnation points, and the overall transfer rates. The present analytical results compared well with the available experimental results and other theories.

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