HEAT EXCHANGE OF SPHERE WITH BLOWING FOR SLOW FLOWS

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An analytic solution is given for the problem of convective heat- and mass-exchange of a sphere with transverse flow of matter along the surface for values of Peclet numbers smaller than one and for blowing velocity smaller than that of the incoming gas flow. The solution for velocity field obtained by the authors in a previously published publication is employed on flow past a sphere with blowing; the method of asymptotic expansions of Acrivos and Taylor is also used. Expressions to the second approximation are determined for temperature field and for the values of local and averaged Nusselt numbers. It is shown that blowing reduces the temperature gradient or the concentrations at the surface.

In [1] the formulation was given of a flow past a sphere together with its heat- and mass-exchange in the presence of a transverse flow of matter across the surface; solutions were obtained in the second approximation for the velocity profile and the resistance coefficient by using the method of Pearson and Proudman [2].

The second half of the overall problem, namely the determination of temperature field or concentrations around the sphere, reduces to the solving of the following heat-balance equation in its dimensionless form:

$$\nabla^2 h = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial h}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \mu}\left[(1-\mu^2)\frac{\partial h}{\partial \mu}\right] = \frac{P}{2}\left[V_r\frac{\partial h}{\partial r} - \frac{V_\theta}{r}(1-\mu^2)^{1/2}\frac{\partial h}{\partial \mu}\right] \tag{1}$$

where $h = (T-T_\infty)/(T_a-T_\infty)$ is the dimensionless temperature (or concentration), T_a is the temperature of the sphere surface, T_∞ is the temperature of the oncoming flow, V_r and V_θ are the radial and tangential velocity components, respectively, $\mu \equiv \cos\theta$, $\theta = 0$ is the direction of the oncoming flow, $P = 2aU_\infty/D$, a is the sphere radius, and D is the diffusion coefficient.

Our aim in this work is to solve Eq. (1) by using the method of Acrivos and Taylor [3] in the case of a slow flow past a sphere with constant blowing intensity and with the same temperature on the entire surface if

$$R = \frac{aU_\infty}{\nu} < 1, \quad S = \frac{\nu}{D} \approx 1, \quad k = \frac{R_1}{R} < 1 \tag{2}$$

where $R_1 = aV/\nu$, V is the radial blowing velocity on the surface, and ν is the coefficient of kinematic viscosity.

If the method of [3] or of [2] is used in a hydrodynamic problem, then the solution of Eq. (1) is sought in the form of two different expansions of the same function which is uniformly valid in the entire flow region.

For the first expansion, which is valid only in the inner region close to the sphere, one has to substitute in Eq. (1) the velocity components obtained in [1] for the same inner region; these are equal to

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$$V_r = \left(1 - \frac{3}{2r} + \frac{1}{2r^3}\right)\mu + \frac{k}{r^2} + R\left[\frac{3}{8}\left(1 - \frac{3}{2r} + \frac{1}{2r^3}\right)\mu + \right.$$
$$\left. + \frac{3}{16}\left(1 - \frac{3}{2r} + \frac{1}{2r^2} - \frac{1}{2r^3} + \frac{1}{2r^4}\right)(1 - 3\mu^2) - \frac{9k}{16}\left(\frac{1}{r} - \frac{2}{r^2} + \frac{1}{r^3}\right)\mu\right] + \ldots \tag{3}$$
$$V_\theta = -\left(1 - \frac{3}{4r} - \frac{1}{4r^3}\right)(1 - \mu^2)^{1/2} + R\left[-\frac{3}{8}\left(1 - \frac{3}{4r} - \frac{1}{4r^3}\right)(1 - \mu^2)^{1/2} + \right.$$
$$\left. + \frac{3}{8}\left(1 - \frac{3}{4r} + \frac{1}{4r^3} - \frac{1}{2r^4}\right)(1 - \mu^2)^{1/2}\mu + \frac{9k}{32}\left(\frac{1}{r} - \frac{1}{r^3}\right)(1 - \mu^2)^{1/2}\right] + \ldots \tag{4}$$

Then Eq. (1) is transformed into the following:

$$\nabla_r^2 h = \frac{\sigma}{r^2}\frac{\partial h}{\partial r} + \left[\left(1 - \frac{3}{2r} + \frac{1}{2r^3}\right)\left(\varepsilon + \frac{3\varepsilon^2}{8S}\right)\mu + \right.$$
$$+ \frac{3\varepsilon^2}{16S}\left(1 - \frac{3}{2r} + \frac{1}{2r^2} - \frac{1}{2r^3} + \frac{1}{2r^4}\right)(1 - 3\mu^2) -$$
$$\left. - \frac{9\sigma\varepsilon}{16S}\left(\frac{1}{r} - \frac{2}{r^2} + \frac{1}{r^3}\right)\mu + \ldots\right]\frac{\partial h}{\partial r} + \left\{\left[\left(\frac{1}{r} - \frac{3}{4r^2} - \frac{1}{4r^4}\right)\left(\varepsilon + \frac{3\varepsilon^2}{8S}\right) - \right.\right.$$
$$\left.\left. - \frac{3\varepsilon^2}{8S}\left(\frac{1}{r} - \frac{3}{4r^2} + \frac{1}{4r^4} - \frac{1}{2r^5}\right)\mu - \frac{9\sigma\varepsilon}{32S}\left(\frac{1}{r^2} - \frac{1}{r^4}\right)\right](1 - \mu^2) + \ldots\right\}\frac{\partial h}{\partial \mu} \tag{5}$$

where $\varepsilon = {}^1/_2\ P$, $\sigma = SR_1$.

In view of (2) a solution of this equation can be represented as a series of powers of the small parameter ε,

$$h(r, \mu) = \sum_{n=0}^{\infty} f_n(\varepsilon)\, h_n(r, \mu), \quad f_0(\varepsilon) = 1 \tag{6}$$

under the assumption that $f_{n+1}/f_n \to 0$ if $\varepsilon \to 0$.

The corresponding boundary conditions on the sphere surface are

$$h_0(1, \mu) = 1, \quad h_n(1, \mu) = 0 \ \text{ for } n \geqslant 1 \tag{7}$$

For the second expansion, which is valid only in the outer region, i.e., at large distance from the sphere, one has to use the velocity components obtained in [1] for that region, which in the standard r and μ coordinates are given by

$$V_r = \mu + \frac{3}{2r^2R} - \frac{3}{2}\left(\frac{1}{r^2R} + \frac{1+\mu}{r}\right)\exp\left[-{}^1/_2 Rr(1 - \mu)\right]$$
$$V_\theta = \left\{-1 + \frac{3}{4r}\exp\left[-{}^1/_2 Rr(1 - \mu)\right]\right\}(1 - \mu^2)^{1/2} \tag{8}$$

The insertion of (8) and a change of variables yields

$$\rho = \varepsilon r, \qquad H = h \tag{9}$$

Equation (1) for the outer expansion is transformed for the heat problem into the following:

$$\nabla_\rho^2 H = \left\{\mu + \frac{3\varepsilon S}{2\rho^2} - \frac{3\varepsilon}{2}\left(\frac{S}{\rho^2} + \frac{1+\mu}{\rho}\right)\exp\left[-\frac{\rho}{2S}(1 - \mu)\right] + \ldots\right\}\frac{\partial H}{\partial \rho} +$$
$$+ \left\{\left[\frac{1}{\rho} + \frac{3\varepsilon}{4\rho^2}\exp\left(-\frac{\rho(1-\mu)}{2S}\right)\right](1 - \mu^2) + \ldots\right\}\frac{\partial H}{\partial \mu} \tag{10}$$

The solution is also given in a series form

$$H(\rho, \mu) = \sum_{n=0}^{\infty} F_n(\varepsilon)\, H_n(\rho, \mu) \tag{11}$$

where $F_{n+1}/F_n \to 0$ for $\varepsilon \to 0$ and the boundary conditions at infinity are

$$H(\infty, \mu) = 0 \tag{12}$$

This missing boundary conditions for the inner as well as outer expansion follow, similarly as in the hydrodynamic problem, from the continuation of both asymptotic expansions into the intermediary region

$$h(r \to \infty, \mu) = H(\rho \to 0, \mu) \tag{13}$$

The solution is constructed as follows. Since in the inner expansion (6) one has $f_0(\varepsilon) = 1$, it is obvious that in Eq. (5) for h_0 only the leading term is left

$$\nabla_r^2 h_0 = \frac{\sigma}{r^2}\frac{\partial h_0}{\partial r} \tag{14}$$

It also follows from the condition (2) that $\sigma < 1$; therefore it is expedient to expand the leading term of h_0 as well as the subsequent terms into power series in the small parameter σ,

$$h_n = \sum_{m=0}^{\infty} \sigma^m \varphi_{n,m}(r, \mu) \tag{15}$$

Then Eq. (14) becomes

$$\nabla_r^2 \varphi_{0,m} = \frac{1}{r^2}\frac{\partial \varphi_{0,m-1}}{\partial r} \tag{16}$$

with boundary conditions on the surface

$$\varphi_{00} = 1, \quad \varphi_{0,m} = 0 \quad \text{for} \quad m \geqslant 1 \tag{17}$$

By solving the equations by the method of the variation of parameters step by step for m = 0, 1, 2, ... and by satisfying every time the boundary conditions (17) one can obtain the following general solution:

$$\begin{aligned} h_0 = {} & \frac{1}{r} + \sigma\left(\frac{1}{2r} - \frac{1}{2r^2}\right) + \sigma^2\left(\frac{1}{12r} - \frac{1}{4r^2} + \frac{1}{6r^3}\right) + \\ & + \sigma^3\left(\frac{-1}{24r^2} + \frac{1}{12r^3} - \frac{1}{24r^4}\right) + \ldots + \sum_{q=0}^{\infty}\Big\{(B_{00q} + \sigma B_{01q} + \sigma^2 B_{02q} + \ldots) \times \\ & \times \Big[\left(\frac{-1}{r^{q+1}} + r^q\right) + \sigma\left(\frac{1}{2r^{q+2}} - \frac{1}{2}r^{q-1}\right) + \sigma^2\left(\frac{2q+1}{4(2q+3)(2q-1)r^{q+1}} - \right. \\ & \left. - \frac{q+2}{4(2q+3)r^{q+3}} + \frac{q-1}{4(2q-1)}r^{q-2}\right) + \sigma^3\left(-\frac{2q+1}{8(2q+3)(2q-1)r^{q+2}} + \right. \\ & \left. + \frac{q+3}{24(2q+3)r^{q+4}} - \frac{q-2}{24(2q-1)}r^{q-3}\right) + \ldots\Big]\Big\} P_q(\mu) \end{aligned} \tag{18}$$

where $P_q(\mu)$ is the Legendre spherical function of the first kind.

The expression can be rewritten as

$$\begin{aligned} h_0 = {} & \frac{\sigma}{1 - e^{-\sigma}} \sum_{i=0}^{\infty} \frac{(-1)^i \sigma^i}{(1+i)!\, r^{i+1}} + \sum_{q=0}^{\infty}\Big\{\sum_{i=0}^{\infty} \sigma^i B_{0iq}\Big[\left(\frac{-1}{r^{q+1}} + r^q\right) + \\ & + \sigma\left(\frac{1}{2r^{q+2}} - \frac{1}{2}r^{q-1}\right) + \sigma^2\left(\frac{2q+1}{4(2q+3)(2q-1)r^{q+1}} - \frac{q+2}{4(2q+3)r^{q+3}} + \right. \\ & \left. + \frac{q-1}{4(2q-1)}r^{q-2}\right) + \sigma^3\left(-\frac{2q+1}{8(2q+3)(2q-1)r^{q+2}} + \right. \\ & \left. + \frac{q+3}{24(2q+3)r^{q+4}} - \frac{q-2}{24(2q-1)}r^{q-3}\right) + \ldots\Big]\Big\} P_q(\mu) \end{aligned} \tag{19}$$

which can easily be seen by expanding the leading term into a Maclaurin series.

To find the first approximation for the inner expansion only terms of zero degree in ε are left in (10). The general solution of the corresponding equation can be found in [3]; it is

$$H_0 = \left(\frac{\pi}{\rho}\right)^{1/2} \exp\left(\tfrac{1}{2}\rho\mu\right) \sum_{k=0}^{\infty} C_k K_{k+1/2}\left(\frac{\rho}{2}\right) P_k(\mu) \tag{20}$$

where

$$K_{n+1/2}\left(\frac{\rho}{2}\right) = \left(\frac{\pi}{\rho}\right)^{1/2} \exp\left(-\tfrac{1}{2}\rho\right) \sum_{m=0}^{n} \frac{(n+m)!}{(n-m)!\, m!\, \rho^m}$$

is the modified Bessel function.

If the solution (19) is written in the coordinates (9) and the higher terms are retained in it and also in (20) with $r \to \infty$ and $\rho \to 0$, then the matching condition (13) becomes in this case

$$\underset{r\to\infty}{\frac{\sigma}{1-e^{-\sigma}}\frac{\varepsilon}{\rho}+\sum_{q=0}^{\infty}\sum_{i=0}^{\infty}\sigma^i B_{0iq}\frac{\rho^q P_q(\mu)}{\varepsilon^q}} = \underset{\rho\to 0}{\frac{\pi F_0(\varepsilon)}{\rho}[1+\ldots]\sum_{k=0}^{\infty}C_k\frac{(2k)!\,P_k(\mu)}{k!\,\rho^k}} \tag{21}$$

It follows directly that the above equality takes place if and only if

$$B_{0iq}=0,\quad C_k=0 \quad \text{for} \quad k\geqslant 1,\quad C_0=\sigma/\pi(1-e^{-\sigma}),\quad F_0(\varepsilon)=\varepsilon$$

One thus obtains for the first approximation of the solution in the inner and outer regions

$$h_0=\frac{\sigma}{1-e^{-\sigma}}\sum_{i=0}^{\infty}\frac{(-1)^i\sigma^i}{(1+i)!\,r^{i+1}}=\frac{1-e^{-\sigma/r}}{1-e^{-\sigma}} \tag{22}$$

$$H_0=\frac{\sigma}{1-e^{-\sigma}}\frac{1}{\rho}\exp\left[-{}^1\!/_2\rho(1-\mu)\right],\quad F_0(\varepsilon)=\varepsilon \tag{23}$$

It is noted that the expression (22) is identical with that obtained in [4]; it is the exact solution for a sphere with blowing in a medium at rest. It is thus valid for any blowing intensities; the latter was experimentally verified (see [5]).

The second approximation h_1 is obtained in a similar manner. If one assumes $f_1(\varepsilon)=\varepsilon$ then Eqs. (5), (6), and (15) imply the following:

$$\begin{aligned}\nabla_r^2\varphi_{1,m}&=\frac{1}{r^2}\frac{\partial\varphi_{1,m-1}}{\partial r}+\left(1-\frac{3}{2r}+\frac{1}{2r^3}\right)\mu\frac{\partial\varphi_{0,m}}{\partial r}-\\&-\frac{9}{16S}\left(\frac{1}{r}-\frac{2}{r^2}+\frac{1}{r^3}\right)\mu\frac{\partial\varphi_{0,m-1}}{\partial r}\end{aligned} \tag{24}$$

since after matching (21) the derivatives of all $\varphi_{0,m}$ with respect to μ vanish. By using the previously obtained values of $\varphi_{0,0}$, $\varphi_{0,1}$, and $\varphi_{0,2}$ one can obtain the following general solution which satisfies the boundary conditions $\varphi_{1,m}(1,\mu)=0$

$$\begin{aligned}h_1&=\Big[\left(\frac{1}{2}-\frac{3}{4r}+\frac{3}{8r^2}-\frac{1}{8r^3}\right)+\sigma\left(\frac{1}{4}-\frac{7}{8r}+\frac{63}{80r^2}+\frac{\ln r}{4r^2}-\frac{1}{4r^3}+\frac{7}{80r^4}\right)+\\&+\sigma^2\left(\frac{1}{24}-\frac{5}{16r}+\frac{247}{480r^2}+\frac{\ln r}{8r^2}-\frac{149}{480r^3}-\frac{\ln r}{8r^3}+\frac{1}{10r^4}-\frac{1}{30r^5}\right)+\ldots\Big]\mu+\\&+\frac{9}{16S}\Big[\sigma\left(\frac{-1}{2r}+\frac{1}{4r^2}+\frac{2\ln r}{3r^2}+\frac{1}{4r^3}\right)+\\&+\sigma^2\left(\frac{-1}{4r}+\frac{7}{40r^2}+\frac{\ln r}{2r^2}+\frac{1}{4r^3}-\frac{\ln r}{3r^3}-\frac{7}{40r^4}\right)+\ldots\Big]\mu+\\&+\sum_{q=1}^{\infty}\Big\{\sum_{i=0}^{\infty}\sigma^i B_{1iq}\Big[\left(\frac{-1}{r^{q+1}}+r^q\right)+\sigma\left(\frac{1}{2r^{q+2}}-\frac{1}{2}r^{q-1}\right)+\\&+\sigma^2\left(\frac{2q+1}{4(2q+3)(2q-1)r^{q+1}}-\frac{q+2}{4(2q+3)r^{q+3}}+\frac{q-1}{4(2q-1)}r^{q-2}\right)\Big]+\ldots\Big\}P_q(\mu)\end{aligned} \tag{25}$$

To match this solution with the outer solution by using the condition (13) only higher terms in $r\to\infty$ must be left in (25), the solution must be represented in the coordinates (9), and one must eliminate from (23) the previously matched highest term in $\rho\to 0$. This yields

$$\begin{aligned}&\underset{r\to\infty}{f_1(\varepsilon)\left(1+\frac{\sigma}{2}+\frac{\sigma^2}{12}+\ldots\right)\frac{\mu}{2}+f_1(\varepsilon)\sum_{i=1}^{\infty}\sigma^i B_{1i0}}+\\&+f_1(\varepsilon)\sum_{q=1}^{\infty}\sum_{i=0}^{\infty}\sigma^i B_{1iq}\frac{\rho^q P_q(\mu)}{\varepsilon^q}=\underset{\rho\to 0}{\frac{\varepsilon\sigma}{1-e^{-\sigma}}\frac{1}{\rho}\left[-\frac{\rho}{2}(1-\mu)+\ldots\right]}\end{aligned} \tag{26}$$

Since

$$1 + \frac{\sigma}{2} + \frac{\sigma^2}{12} + \ldots = \frac{\sigma}{1 - e^{-\sigma}}$$

one can see by comparing the terms that the equality is satisfied if

$$B_{1iq} = 0 \quad \text{for} \quad q \geqslant 1, \quad \sum_{i=0}^{\infty} \sigma^i B_{1i0} = -\frac{1}{2}\frac{\sigma}{1 - e^{-\sigma}}, \quad f_1(\varepsilon) = \varepsilon$$

that is, the previously assumed form of the function $f_1(\varepsilon)$ is simultaneously confirmed.

In this case the term with the summation sign in (25) is equal to

$$-\frac{\sigma}{1 - e^{-\sigma}}\frac{1}{2}\left[\left(1 - \frac{1}{r}\right) + \sigma\left(\frac{-1}{2r} + \frac{1}{2r^2}\right) + \sigma^2\left(\frac{-1}{12r} + \frac{1}{4r^2} - \frac{1}{6r^3}\right) + \ldots\right]$$

and the polynomial in the square brackets can also be written as $1-(1-e^{-\sigma/r})/(1-e^{-\sigma})$.

Thus the final form of the solution for h in the second approximation, which is the one we are seeking, is given by

$$\begin{aligned} h = h_0 + \varepsilon h_1 = \frac{1 - \exp(-\sigma/r)}{1 - \exp(-\sigma)} - \frac{\varepsilon\sigma}{2[1 - \exp(-\sigma)]}\left[1 - \frac{1 - \exp(-\sigma/r)}{1 - \exp(-\sigma)}\right] + \\ + \varepsilon\left[\left(\frac{1}{2} - \frac{3}{4r} + \frac{3}{8r^2} - \frac{1}{8r^3}\right) + \sigma\left(\frac{1}{4} - \frac{7}{8r} + \frac{63}{80r^2} + \frac{\ln r}{4r^2} - \frac{1}{4r^3} + \frac{7}{80r^4}\right) + \right. \\ + \sigma^2\left(\frac{1}{24} - \frac{5}{16r} + \frac{247}{480r^2} + \frac{\ln r}{8r^2} - \frac{149}{480r^3} - \frac{\ln r}{8r^3} + \frac{1}{10r^4} - \frac{1}{30r^5}\right) + \ldots \\ + \frac{9\sigma}{16S}\left(\frac{-1}{2r} + \frac{1}{4r^2} + \frac{2\ln r}{3r^2} + \frac{1}{4r^3}\right) + \\ \left. + \frac{9\sigma^2}{16S}\left(\frac{-1}{4r} + \frac{7}{40r^2} + \frac{\ln r}{2r^2} + \frac{1}{4r^3} - \frac{\ln r}{3r^3} - \frac{7}{40r^4}\right) + \ldots\right]\mu \end{aligned} \tag{27}$$

with an accuracy up to the terms of the order of ε.

If by local or averaged Nusselt numbers one understands in this case their standard definition, namely,

$$\mathrm{Nu}^* = -2\left(\frac{\partial h}{\partial r}\right)_{r=1}, \quad \mathrm{Nu} = -\int_{-1}^{+1}\left(\frac{\partial h}{\partial r}\right)_{r=1} d\mu$$

then their values in terms of the more usual notation $R_1^* = 2R_1$ are

$$\begin{aligned} \mathrm{Nu}^* = \frac{SR_1^*}{\exp(\frac{1}{2}SR_1^*) - 1} + \frac{P(SR_1^*)^2 \exp(-\frac{1}{2}SR_1^*)}{8[1 - \exp(-\frac{1}{2}SR_1^*)]^2} + \\ + \frac{3P}{8}\left[-1 + \frac{SR_1^*}{15} + \frac{(SR_1^*)^2}{80} + \frac{R_1^*}{16} - \frac{S(R_1^*)^2}{160}\right]\mu + \ldots \end{aligned} \tag{28}$$

$$\mathrm{Nu} = \frac{SR_1^*}{\exp(\frac{1}{2}SR_1^*) - 1} + \frac{P(SR_1^*)^2 \exp(-\frac{1}{2}SR_1^*)}{8[1 - \exp(-\frac{1}{2}SR_1^*)]^2} + \ldots \tag{29}$$

respectively.

By using (2) the latter expression can be expressed in series form

$$\mathrm{Nu} = 2 - \frac{SR_1^*}{2} + \frac{(SR_1^*)^2}{24} + \ldots + \frac{P}{2} - \frac{5P(SR_1^*)^2}{288} + \ldots \tag{30}$$

It is much more difficult to obtain higher approximations; for small P and $\frac{1}{2}SR_1^*$ improved results are hardly possible.

It can be seen by comparing (30) with the expression obtained in [4] that the leading terms are the same; the second-degree terms, however, have become slightly modified in the more accurate solution (30).

The analysis has shown that blowing reduces the gradient temperatures or the concentrations at the surface and smoothes out the irregularities of the transfer coefficient in the frontal and rear regions of the sphere.

Strictly speaking, the derived formulas are only valid if the conditions (2) are satisfied. However, as previously stated, for P = 0 the expression (22) is valid for any blowing intensity.

In conclusion, it should be recalled that an actual enthalpy flow inside the material of the sphere itself in the presence of blowing could be given by the formula

$$q_s = \frac{\mathrm{Nu}\,\lambda_0}{2a}(T_\infty - T_a) - \rho c_p V T_a \tag{31}$$

where Nu is calculated by the formula (29), λ_0 is the gas heat-conduction coefficient, and ρc_p is the heat capacity of the blown-in matter. The last term takes into account the loss of heat enthalpy due to the matter reaching the sphere; in the case of a heated sphere it reduces q_s even further, but cooling increases the absolute value of the flow of heat enthalpy.

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