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Unsteady heat and/or mass transfer from a fluid sphere in creeping flow

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Abstract

The transient heat and/or mass transfer from a fluid sphere with internal circulation into a flowing fluid are investigated. The temperature and/or concentration inside the sphere are considered uniform. Two cases are studied: the physical mass and/or heat transfer and the mass transfer accompanied by an isothermal, first-order irreversible chemical reaction in the continuous phase. Steady, creeping flow is assumed around and inside the sphere. The problem is solved by a finite difference method in the range of parameters, $10 \leqslant Pe \leqslant 1000$, $0.01 \leqslant H$ $(\Phi_{\mathrm{h}}) \leqslant 100$, $0.1 \leqslant Da \leqslant 1000$. The influence of distribution coefficient (H) or volume heat capacity ratio (Φ_{h}) on the transfer rate and thermal wake phenomenon is analysed. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The phenomena of momentum, heat and mass transport between a translating sphere and its surrounding fluid have been investigated intensively due to a wide range of industrial and scientific applications. The problem is classified as:

"external" – if the transfer resistance is assumed negligible inside the sphere as compared to that of continuous phase;

"internal" – if the transfer resistance is assumed negligible in the continuous phase as compared to that inside the sphere;

"conjugate" – if the transfer resistance in both phases is comparable to each other.

Clift et al. [1], Brauer [2], Brounshtein and Shegolev [3] and Sadhal et al. [4] review the literature in this area. In comparison with the external and internal problems, the conjugate transfer is the subject of relatively few theoretical and experimental studies. For this reason, in the last two decades, the attention was focused on the conjugate problem. The physical conjugate mass and/or heat transfer from a sphere was studied theoretically in [5–16]. Kleinman and Reed [17,18] and Juncu [19–22] theoretically analysed the conjugate transfer from or to a sphere in the presence of a chemical reaction.

In solving the conjugate problem, the reference boundary solutions play an important role. The boundary cases validate the accuracy of the algorithms used to solve the conjugate problem. When the conductivity or diffusivity ratios tend to zero (or infinite) the solution of the conjugate problem should tend to the solution of internal (or external) problem. A careful analysis shows that when the conductivity (diffusivity) ratio tends to infinite, the fair limit of the conjugate problem is the transfer from a sphere with uniform properties (temperature or concentration). Thus, from one point of view, the mass and/or heat transfer from a sphere with uniform concentration and/or temperature is one of the important boundary solutions of the conjugate problem. From another point of view, there are enough real life situations well described by the model of sphere with uniform properties. The condition of *uniform sphere properties* is fulfilled if the diffusivity ratio, the ratio (diffusivity ratio)/(Henry number) and the conductivity ratio take values considerably greater than one. Note that diffusivity and conductivity ratios are defined as (dispersed phase property)/(continuous phase property). Values of the diffusivity ratio considerably greater than one are typical for gas–liquid or supercritical fluid–normal fluid systems. In usual liquid–liquid systems, the ratio (diffusivity ratio)/(Henry number)

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Nomenclature

a	radius of the sphere
c_p	heat capacity
C	concentration
D	diffusion coefficient
Da	Damkholer number, ka^2/D
H	Henry number, C_d/C at $z = 0$
k	chemical reaction rate constant
Pe	Peclet number, $2Ua/D$
r	dimensionless radial distance in spherical coordinate system
Sh	instantaneous Sherwood number
t	time
T	temperature
U	free stream velocity
V_R	dimensionless radial velocity component
V_θ	dimensionless tangential velocity component
z	transformed r-coordinate
Z	continuous phase dimensionless concentration, $(C - C_\infty)/(C_{d,0}/H - C_\infty)$ if $S \equiv 0$, $C/(C_{d,0}/H)$ if $S \neq 0$ (this case $C_\infty \equiv 0$), or temperature, $(T_d - T_\infty)/(T_{d,0} - T_\infty)$
Z_d	dispersed phase dimensionless concentration, $(C_d - HC_\infty)/(C_{d,0} - HC_\infty)$ if $S \equiv 0$, $C_d/C_{d,0}$ if $S \neq 0$ (this case $C_\infty \equiv 0$), or temperature, $(T_d - T_\infty)/(T_{d,0} - T_\infty)$

Greek symbols

Φ_h	volume heat capacity ratio, $\rho_d c_{p,d}/\rho_c c_{p,c}$
μ	viscosity ratio
ρ	density
θ	polar angle in spherical coordinate system
τ	dimensionless time, Dt/a^2

Subscripts

c	continuous phase
d	dispersed phase
0	initial condition
∞	large distance from the sphere

takes values considerably greater than one if Henry number is considerably smaller than one. Values of the conductivity ratio considerably greater than one are not usually encountered in liquid–liquid systems. A dispersed phase that contains mercury should satisfy this condition.

The mass and/or heat transfer from a sphere with uniform concentration and/or temperature has been analysed, from our knowledge, by Ruckenstein et al. [23], Soung and Sears [24], Brauer [2] and Abramzon and Elata [25]. Ruckenstein et al. [23] analysed the mass transfer accompanied by a first-order irreversible chemical reaction from a single component or binary fluid sphere. Based on the Duhamel's theorem, boundary layer theory and extended penetration model, Ruckenstein et al. [23] derived analytical expressions for the *Sh* number and sphere average concentration. The expressions for *Sh* number were deduced assuming constant concentration inside the sphere. Soung and Sears [24] solved numerically the same problems as in [23] assuming negligible diffusion in tangential direction and different orders of chemical reaction. Soung and Sears [24] do not present numerical results for the binary bubble. Brauer [2] presents results about the influence of the distribution coefficient on the physical mass transfer. Two sphere models are considered: the rigid sphere and the fluid sphere with viscosity ratio zero. Abramzon and Elata [25] analysed the physical heat transfer from a sphere in Stokes flow. At different *Pe* numbers, the influence of volume heat capacity ratio on heat transfer is studied. Abramzon and Elata [25] also presented the first detailed investigation of the thermal wake phenomenon.

The aim of this paper is to extend the analysis from [2,25] for the fluid sphere with internal circulation. The problem statement is similar to that of Abramzon and Elata [25] but the range of parameters studied (Henry number or volume heat capacity ratio) is enlarged. In particular, we also investigated the mass transfer accompanied by an isothermal, first-order irreversible chemical reaction in the continuous phase.

2. Mathematical model

Consider a fluid sphere (bubble or drop) with radius a suspended in an unbounded, immiscible, convective environment with uniform velocity U. Assume that the diffusion coefficient (thermal conductivity) of the sphere is so high that there are no gradients within the sphere at each instant of time. The concentration (temperature) of the continuous phase is different from the sphere. Due to the concentration (temperature) difference, mass (heat) will flow from or to the sphere depending on the direction of the concentration (temperature) gradient as depicted by the second law of thermodynamics. Assume also that the flow fields around and inside the sphere are axisymmetric, steady and the particle *Re* number is considerably small compared to unity (creeping flow). Due to the complexities of the problem, we consider also valid the following supplementary assumptions:

- there is no surface active agents;
- constant physical properties and negligible dissipations;
- the size and shape of the sphere remain constant.

Under the scenario outlined previously, the mass (heat) transfer is governed by the following dimensionless balance equation:

$$\frac{\partial Z}{\partial \tau} + \frac{Pe}{2e^{z}}\left(V_{\mathrm{R}}\frac{\partial Z}{\partial z} + V_{\theta}\frac{\partial Z}{\partial \theta}\right) = \frac{1}{e^{2z}}\left(\frac{\partial^2 Z}{\partial z^2} + \frac{\partial Z}{\partial z} + \frac{\partial^2 Z}{\partial \theta^2} + \cot\theta\frac{\partial Z}{\partial \theta}\right) - S. \tag{1}$$

In Eq. (1) the well-known transformation $r = \exp z$ was applied. The term denoted by S is the source term. The creeping flow velocity profiles derived by Hadamard and Rybczynski [1] are used in Eq. (1). The boundary and initial conditions to be satisfied are [2,25]:

- interface $(z = 0)$

heat balance equation

$$Z_{\mathrm{d}} = Z, \quad \frac{\mathrm{d}Z_{\mathrm{d}}}{\mathrm{d}\tau} = \frac{3}{2}\Phi_{\mathrm{h}}^{-1}\int_0^{\pi}\left.\frac{\partial Z}{\partial z}\right|_{z=0}\sin\theta\,\mathrm{d}\theta, \tag{2a}$$

mass balance equation

$$Z_{\mathrm{d}} = Z, \quad \frac{\mathrm{d}Z_{\mathrm{d}}}{\mathrm{d}\tau} = \frac{3}{2}H^{-1}\int_0^{\pi}\left.\frac{\partial Z}{\partial z}\right|_{z=0}\sin\theta\,\mathrm{d}\theta, \tag{2b}$$

- free stream $(z = \infty)$

$$Z = 0.0, \tag{2c}$$

- symmetry axis $(\theta = 0, \pi)$

$$\partial Z/\partial\theta = 0, \tag{2d}$$

- initial conditions

$$\tau = 0.0, \quad Z_{\mathrm{d}} = 1.0, \quad Z\ (z > 0) = 0.0. \tag{3}$$

Relation (2b) shows that when $S \equiv 0$, the mass and heat balance equations are equivalent with the distribution coefficient H playing the role of volume heat capacity ratio, Φ_{h} (or reciprocal). Two cases will be analyzed in this study: the physical mass (heat) transfer, i.e., $S \equiv 0$, and the mass transfer accompanied by a isothermal, first-order irreversible chemical reaction in the continuous phase, i.e., $S \equiv Da\,Z$. In the first case there is no distinction between dimensionless concentration and dimensionless temperature. In the second case, we refer only to mass transfer or dimensionless concentration.

The quantities of interest used to characterize the mass (heat) transfer are:

- sphere dimensionless concentration (temperature), Z_{d};
- overall instantaneous Sh number.

The overall instantaneous Sh number is given by the relation

$$Sh = \frac{-\int_0^{\pi}\partial Z/\partial z|_{z=0}\sin\theta\,\mathrm{d}\theta}{Z_{\mathrm{d}}}. \tag{4}$$

3. Method of solution

The mathematical model of the process analysed in this study is a system formed by a partial differential equation that describes the mass (heat) transfer in the continuous phase and an ordinary differential equation that describes the mass (heat) balance of the sphere. Both equations were solved numerically. The exponentially fitted finite difference scheme [26] was used for the discretization of the partial differential equation. Numerical tests were made with radial step sizes equal to $\Delta z = 1/32, 1/64, 1/128$ and $1/256$. The angular step has the values, $\Delta\theta = \pi/32$, $\pi/64$, $\pi/128$, $\pi/256$. A decomposition procedure of the ADI type is employed. The boundary conditions (2a) or (2b) on the surface of the sphere (the ordinary differential equation) were integrated by an explicit method (modified Euler algorithm). The integral from relations (2a) to (2d) was calculated by the Newton 3/8 rule using the local Sh values available at time τ. The time step was variable and changed from the start of the computation to the final stage. The initial and final values of the time step depend on Da, H and Pe.

To verify the computer coding, the cases worked in [25] were simulated. The agreement between the results (asymptotic values of the Sh number) of Abramzon and Elata [25] and those obtained in this work was better than 1%.

All computations were performed on a HP-9000-715 workstation in HP FORTRAN double precision.

4. Results

For the purpose of illustrating the salient (important) features of the present study, this section is divided into two parts. The first part is dedicated to the analysis of the physical mass (heat) transfer. In the second part the mass transfer accompanied by an isothermal, first-order irreversible chemical reaction is examined.

4.1. Physical transfer

The independent dimensionless parameters in the present system are Pe, H (Φ_{h}) and the viscosity ratio, μ. From these parameters, Pe and H (Φ_{h}) are considered important. In many studies, a modified Pe number that includes the viscosity ratio is defined and used. However, two values viewed as typically for fluid–fluid systems, 1 and 0, were considered in the present study for μ. The values assigned to Pe are: 10, 50, 100, 500 and 1000. These values are similar to those used in [25]. Pe values higher than 1000 are not taken into consideration in order to avoid significant numerical errors. The values considered for H (Φ_{h}), H $(\Phi_{\mathrm{h}}) \in [0.01, 100]$, cover the majority of situations of practical interest.

Table 1
Asymptotic *Sh* values at $\mu = 1$

Pe	H (Φ_h)									External problem
	0.01	0.1	0.2	0.5	1	2	5	10	100	
10	0.019[a]	0.125[a]	0.244[a]	0.576[a]	1.048	1.707	2.558	2.970	3.403	3.424
50	0.060[a]	0.569	1.058	2.144	3.185	4.112	4.857	5.146	5.425	5.512
100	0.113	1.031	1.846	3.424	4.733	5.670	6.372	6.624	6.878	6.893
500	0.435	3.852	6.086	9.074	10.9	11.81	12.41	12.63	12.85	13.06
1000	0.835	6.635	9.802	13.4	15.42	16.28	16.82	17.1	17.29	17.43

[a] Steady-state value not frozen.

For a given H (Φ_h) value, the influence of *Pe* on the transfer rate is easy foreseeable. All the investigations about the *Pe* number effect on the transfer rate, investigations performed for internal, external or conjugate problem with or without chemical reaction, show that the increase in *Pe* increases the transfer rate. For this reason, in this section, the results presentation is focussed on the influence of H (Φ_h) on the mass (heat) transfer. The variable considered adequate to depict the transients of the process is the sphere dimensionless concentration (temperature). For *Sh* number we consider significant the asymptotic values. Special attention receives the thermal wake phenomenon.

Tables 1 and 2 summarize the computations made and present the asymptotic values of the *Sh* number. The values depicted in Table 1 were obtained for a viscosity ratio equal to one. Table 2 shows the asymptotic *Sh* values obtained at a viscosity ratio equal to zero. The last column of Tables 1 and 2 presents the values provided by external problem. Figs. 1–3 plot the influence of H (Φ_h) on the dispersed phase concentration at $Pe = 10$, 100 and 1000, respectively, and $\mu = 1$.

Tables 1 and 2 and Figs. 1–3 show that H (Φ_h) influences significantly the mass (heat) transfer. The increase in the Henry number (volume heat capacity ratio) increases *Sh*. When H (Φ_h) $\to \infty$, *Sh* tends asymptotically to the value provided by external problem. At small values of H (Φ_h), H (Φ_h) < 1, and $Pe = 10$, 50, *Sh* does not tend to a frozen steady-state value (*Sh* decreases continuously in time). The values depicted in Tables 1 and 2 correspond to the integration final when the time variation of *Sh* becomes very low. In heat transfer, the analysis made in [12–15,25] show the same behaviour. In mass transfer, only Brauer [2] presented similar results about the influence of H on sphere concentration and implicitly on *Sh*. However, in [2], the relation used to compute *Sh* is slightly different from that used in this work. For this reason, results concerning the asymptotic *Sh* similar to those presented in Tables 1 and 2 cannot be viewed in [2].

It must be mentioned that in classical theories, i.e., film, penetration and even boundary layer, the continuous phase *Sh* number does not depend on H. Also, the overall mass balance equation for the sphere shows that the time variation of the dispersed phase concentration depends only on products as ShH or ShH^{-1}. The results obtained in this study show a fully different situation. Figs. 1–3 and Tables 1 and 2 show that the solubility of the transferring species has a distinct influence on mass transfer rate.

The variation of the asymptotic *Sh* function of H (Φ_h) can be connected to the thermal wake (TW) phenomenon [25]. The quantity used to describe TW is the thermal inversion point (TIP), [12]. The TIP steady position on the sphere surface, measured from the rear stagnation point, is plotted in Figs. 4 and 5 for viscosity ratios equal to one and zero, respectively. The symbols in Figs. 4 and 5 indicate the *Pe* value. Figs. 4 and 5 show the existence of a critical H (Φ_h) value that depends on *Pe* and viscosity ratio. For H (Φ_h) values greater than

Table 2
Asymptotic *Sh* values at $\mu = 0$

Pe	H (Φ_h)									External problem
	0.01	0.1	0.2	0.5	1	2	5	10	100	
10	0.022[a]	0.153[a]	0.296[a]	0.691[a]	1.231	1.951	2.813	3.215	3.627	3.732
50	0.083[a]	0.775	1.419	2.765	3.931	4.881	5.633	5.920	6.196	6.308
100	0.165	1.470	2.567	4.519	5.910	6.894	7.610	7.872	8.120	8.281
500	0.756	5.969	8.981	12.52	14.25	15.24	15.89	16.12	16.33	16.61
1000	1.277	10.58	14.76	18.89	20.67	21.65	22.27	22.48	22.67	23.03

[a] Steady-state value not frozen.

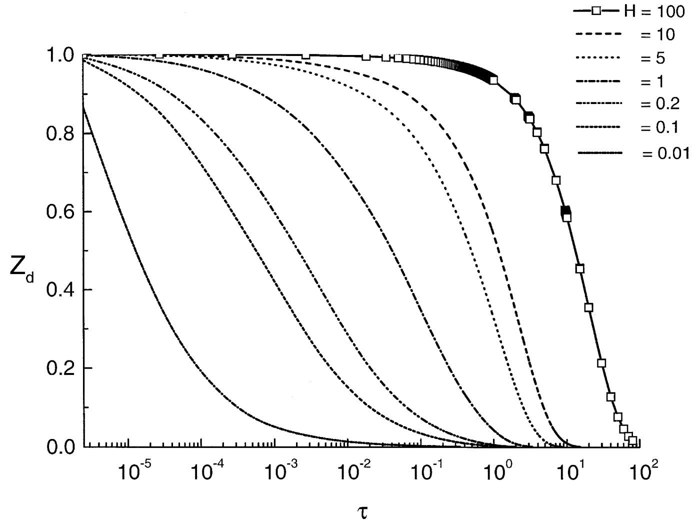

Fig. 1. Variation of the sphere concentration (temperature) with dimensionless time at $Pe = 10$ and viscosity ratio equal to one.

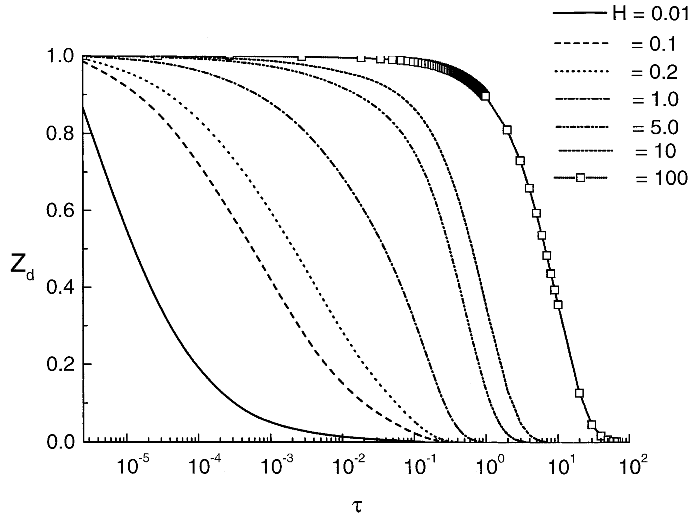

Fig. 2. Variation of the sphere concentration (temperature) with dimensionless time at $Pe = 100$ and viscosity ratio equal to one.

the critical value there is no thermal wake. For H (Φ_h) values smaller than the critical value, TW increases with the decrease in H (Φ_h). The increase in TW coincides to the decrease in *Sh*. Figs. 4 and 5 also confirm the analysis made in [13]. The increase in *Pe* from 10 to 1000 decreases TW. However, the increase in *Pe* does not destroy TW. Figs. 4 and 5 show that at higher *Pe*, TW extends over H (Φ_h) variation domain.

A comparison between Tables 1 and 2 and Figs. 4 and 5 shows that the viscosity ratio influences the mass (heat) transfer. As expected, for a given *Pe* and H (Φ_h), the decrease in μ increases *Sh*. However, the dependence *Sh* versus *Pe* and μ can not be expressed using a modified *Pe* number of the type, $Pe/(1+\mu)$. If we extend the comparison and take into consideration the results obtained in [25] for a rigid sphere in Stokes flow, we can conclude that the velocity fields do not change the important features of the phenomena that accompanied the mass (heat) transfer.

Table 1 also shows a very good agreement between the results obtained in this study and those presented in [15] at high values of conductivity ratio (100) and the same values of the *Pe* number. This way, the present computations confirm the validity of the results obtained in [15]. In addition, the asymptotic values of the *Sh* number obtained in this study are also

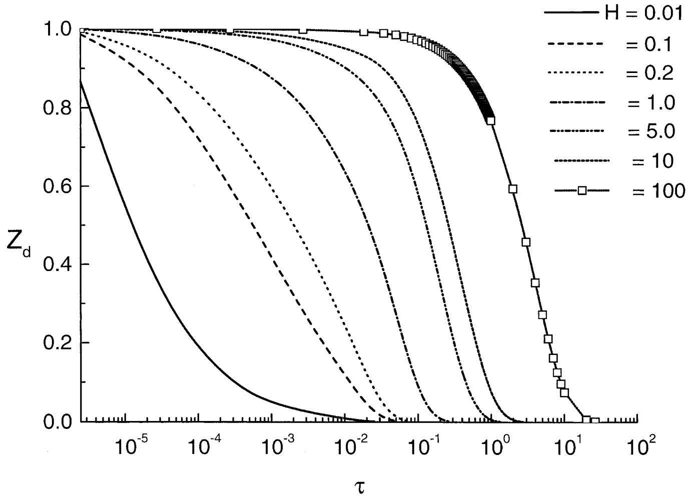

Fig. 3. Variation of the sphere concentration (temperature) with dimensionless time at $Pe = 1000$ and viscosity ratio equal to one.

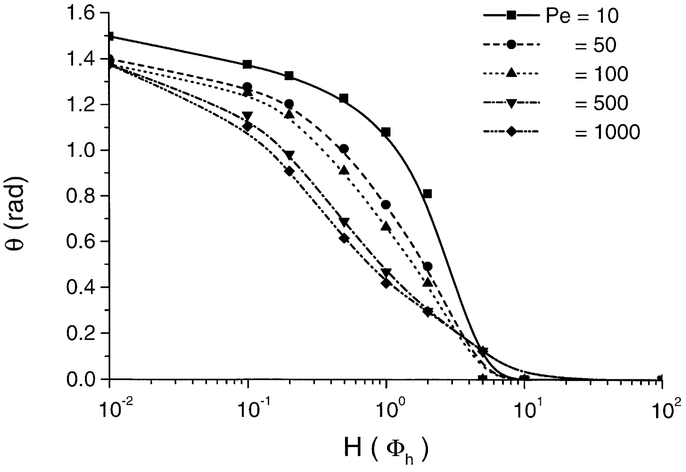

Fig. 4. Steady-state position of the thermal inversion point on the sphere surface function of H (Φ_h) and Pe at viscosity ratio equal to one.

used in [16] in order to verify the accuracy of the computations.

4.2. Mass transfer accompanied by chemical reaction

In the case of mass transfer accompanied by chemical reaction a new parameter, the Damkholer number Da, enters in competition with Pe and H (Φ_h). The results obtained in the previous section show that the variation of Pe with two orders of magnitude does not blur the influence of H on mass transfer. The question that naturally arises is: the presence of chemical reaction changes or perturbs these phenomena? To find the answer of this question, taking also into consideration the results of [21], the following strategy was conceived:

- only the extreme values of Pe, i.e., $Pe = 10$, 1000, were considered;
- for each value of Pe, two Da values were assigned; one considerably smaller than the Pe value and the other equal to the Pe value.

The results obtained are presented in Table 3 and Fig. 6. The computations were performed only for $\mu = 1$. We limit the results presentation only to the asymptotic Sh values and TW. We made this choice because the asymptotic Sh and TW can express synthetically the salient features of the process. At $Da = Pe = 1000$, TW occurs only at $H = 0.01$. For this reason, this case is not plotted in Fig. 6.

Table 3 shows that H influences the mass transfer rate for all Da values or ratios Da/Pe. As expected, at

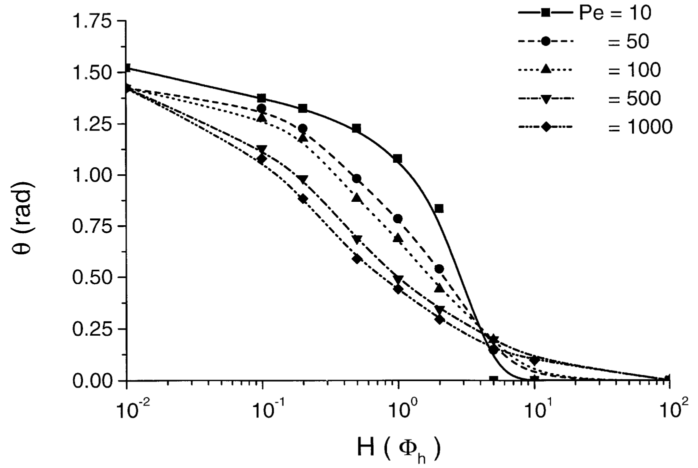

Fig. 5. Steady-state position of the thermal inversion point on the sphere surface function of H (Φ_h) and Pe at viscosity ratio equal to zero.

Table 3
Asymptotic Sh values

Pe	Da	H								
		0.01	0.1	0.2	0.5	1	2	5	10	100
10	0.1	0.02[a]	0.132[a]	0.257[a]	0.607	1.10	1.78	2.65	3.07	3.51
	10	0.115[a]	0.879[a]	1.64[a]	3.46	5.25	6.64	7.64	7.99	8.32
	10	0.944	7.65	11.1	14.7	16.3	17.2	17.7	17.9	18.1
1000	1000	7.412	41.9	55.1	61.1	63.2	64.1	64.7	64.9	65.1

[a] Steady-state value not frozen.

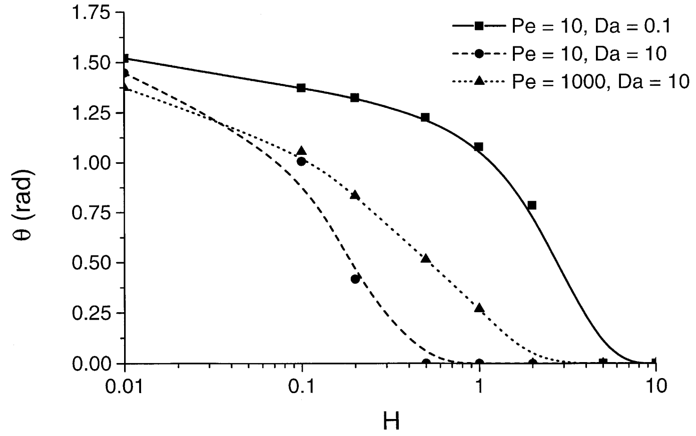

Fig. 6. Steady-state position of the thermal inversion point on the sphere surface function of H, Pe and Da.

small Da values, $Da = 0.1$, the process is similar to the physical transfer. The dimension of TW at $Da = 0.1$ is practically equal to that at $Da = 0$. However, the comparison between Tables 1 and 3 shows an enhancement of the mass transfer rate. This result contradicts the assumptions practiced in classical theories. The increase in Da from 0.1 to 10 reduces the dimension of TW. For $Da = 10$, the decrease in TW dimension is higher at $Pe = 10$. However, the influence of H on Sh remains significant. At $Da = 1000$, even in the condition of TW disappearance, Sh depends on H, especially for $H < 1$. These results lead to the following remark: the influence of H on Sh cannot be explained only in terms of TW.

5. Conclusions

The physical mass and/or heat transfer and the mass transfer accompanied by an isothermal, first-order, irreversible chemical reaction in the continuous phase from a fluid sphere in creeping flow with uniform concentration and/or temperature were investigated. The range of parameters that characterizes the coupling between the two phases, namely H or Φ_h, was much wider than in previous studies of other investigators. The Pe number takes values from 10 to 1000. The main phenomenon studied was the influence of distribution coefficient or volume heat capacity ratio on transfer rate.

The numerical results presented in the previous section show that H or Φ_h affects significantly the physically mass and/or heat transfer. The influence of H or Φ_h on the asymptotic Sh number is related to the thermal wake phenomena. The presence of the chemical reaction in the continuous phase does not change significantly the influence of H on mass transfer. The increase in Da reduces, until disappearance, TW but does not cancel the influence of H on mass transfer rate.

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