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Effects of Suction and Blowing on Heat Transfer between Two Eccentric Rotating Spheres with Sinusoidal Angular Velocities

O. Mahian, A.B Rahimi, A. Kianifar, and A. Jabari Moghadam

Abstract— In this paper, the effects of suction and blowing on the temperature field between two eccentric rotating spheres which rotate about a common axis of rotation are presented. The angular velocity of outer sphere is constant and the angular velocity of inner sphere is considered as sinusoidal function. The Navier-Stokes and energy equations are solved by employing the finite difference method and implicit scheme. The resulting flow patterns and temperature distributions are presented for various values of the flow parameters including rotational Reynolds number Re_r , and a blowing/suction Reynolds number Re_w . In this work, the effect of viscous dissipation is ignored. The eddies created in the flow field are found as preventive means for heat transfer. Also, it is observed, where the distance between two spheres is reduced the diffusion of heat becomes more, because the Coriolis forces are bigger in these regions

Keywords— Eccentric spheres, Heat transfer, numerical solution, sinusoidal angular velocities, suction and blowing.

I. INTRODUCTION

The flow and heat transfer in an annulus between two spheres has been studied in various cases by many researchers. Such studies can be classified into two main groups. In the first group, there is neither suction nor blowing at the spherical walls. Such containers are used in engineering designs like centrifuges and fluid gyroscopes and also are important in geophysics.

Available theoretical works concerning such problems are primarily of a boundary-layer or singular-perturbation

character considered by Howarth [1], Greenspan [2], Carrier [3] and Stewartson [4].

The first numerical study of time-dependent viscous flow between two rotating spheres has been presented by Pearson [5] in which the cases of one (or both)sphere is given an impulsive change in angular velocity starting from a state of either rest or uniform rotation. Munson and Joseph [6] have considered the case of steady motion of a viscous fluid between concentric rotating spheres using perturbation techniques for small values of Reynolds number and a Legendre polynomial expansion for larger values of Reynolds numbers.

Recently a numerical study of flow and heat transfer between two rotating spheres has been done by Jabari Moghadam and Rahimi [7] in which the fluid contained between two vertically eccentric spheres maintained at different temperature and rotating about a common axis with different angular velocities when the angular velocities are arbitrary functions of time. Jabari Moghadam and Rahimi [8] have also studied the similarity solution for spheres rotating with constant angular velocity.

In the second group, the effects of transpiration on flow in an annulus between two spheres have been investigated. The study of flow in a spherical annulus along with transpiration is used in many practical applications, such as rotary machines and spherical heat exchangers and in the design of spherical fluid storage systems. In these applications transpiration is used to regulate the rate of heat transfer.

Effects of transpiration on free convection in an annulus between two stationary concentric porous spheres have been considered by Gulwadi et al. [9]. Gulwadi et al. [10] studied the laminar flow in an annulus between rotating porous spheres and with injection and suction at spherical walls. They used a perturbation technique to solve the steady-state Navier-Stokes equations of motion and also used a finite difference method to validate their analytical results. Their results are valid for small values of the rotational Reynolds number ($Re < 50$) and an injection/suction Reynolds number. A review of the literature reveals that there is no study on the transient motion and heat transfer between two eccentric rotating spheres with uniform transpiration. In the present study, a numerical solution of unsteady momentum and energy equations is presented for eccentric spheres in high Reynolds numbers ($Re = 1000$).

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II. PROBLEM FORMULATION

The geometry of the spherical annulus considered is indicated in Fig.1.

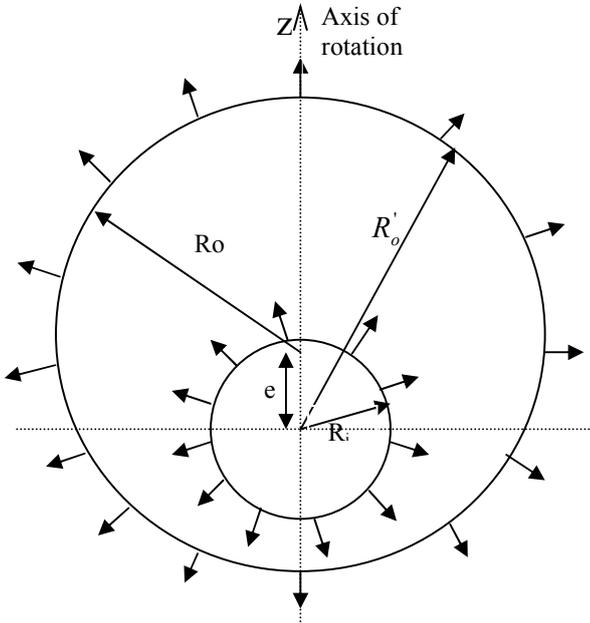


Fig.1: Geometry of problem

The vertical eccentricity of the outer sphere is measured by the distance e . If the outer sphere is placed above the central position, e has a positive value, otherwise it is negative. The origin of the spherical coordinate system is the inner sphere center and the characteristic radius of the outer sphere, R'_o , is a function of θ . A Newtonian, viscous, incompressible fluid fills the gap between the inner and outer spheres, which are of radii R_i and R_o and with constant surface temperatures T_i and T_o and rotate about a common axis with angular velocities Ω_i and Ω_o , respectively. The components of velocity in r, θ and ϕ directions are v_r, v_θ and v_ϕ , respectively. These velocity components for incompressible flow and in meridian plane satisfy the continuity equation and are related to stream function ψ and angular momentum function Ω in the following manner:

$$v_r = \frac{\psi_\theta}{r^2 \sin \theta}, v_\theta = \frac{-\psi_r}{r \sin \theta}, v_\phi = \frac{\Omega}{r \sin \theta} \quad (1)$$

the blowing/suction Reynolds number is defined as:

$$Re_w = \frac{v_{r_o} r_o}{\nu} \quad (2)$$

in which v_{r_o} and r_o are radial velocity and radius reference values, respectively. The blowing/suction Reynolds

number Re_w is positive for blowing at inner sphere and negative for suction. Since the flow is assumed to be independent of the longitude, ϕ , the non-dimensional Navier-Stokes equations and energy equation can be written in terms of the stream function and the angular velocity function as follows:

$$\frac{\partial \Omega}{\partial t} + \frac{\psi_\theta \Omega_r - \psi_r \Omega_\theta}{r^2 \sin \theta} = \frac{1}{(Re)} D^2 \Omega \quad (3)$$

$$\begin{aligned} & \frac{\partial}{\partial t} (D^2 \psi) + \frac{2\Omega}{r^3 \sin^2 \theta} [\Omega_r r \cos \theta - \Omega_\theta \sin \theta] \\ & - \frac{1}{r^2 \sin \theta} [\psi_r (D^2 \psi)_\theta - \psi_\theta (D^2 \psi)_r] \\ & + \frac{2D^2 \psi}{r^3 \sin^2 \theta} [\psi_r r \cos \theta - \psi_\theta \sin \theta] = \frac{1}{(Re)} D^4 \psi \end{aligned} \quad (4)$$

$$\begin{aligned} & \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} = \\ & \frac{1}{(Pe)} \left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\cot \theta}{r^2} \frac{\partial T}{\partial \theta} \right] \end{aligned} \quad (5)$$

in which the non-dimensional quantities Reynolds number (Re), Prandtl number (Pr), Peclet number (Pe) are defined as:

$$Re = \frac{\omega_o r_o^2}{\nu}, Pr = \nu / \alpha, Pe = Re \cdot Pr = \frac{\omega_o r_o^2}{\alpha} \quad (6)$$

The following non-dimensional parameters have been used in the above equations and then the asterisks have been omitted:

$$\begin{aligned} t^* &= t \omega_o, r^* = \frac{r}{r_o}, \psi^* = \frac{\psi}{r_o^3 \omega_o} \\ \Omega^* &= \frac{\Omega}{r_o^2 \omega_o}, T^* = \frac{T - T_i}{T_o - T_i} \end{aligned} \quad (7)$$

in which ω_o is reference value which is selected as Ω_o . The non-dimensional boundary and initial conditions for the above governing equations are:

For $t = 0$:

$$\begin{cases} \psi = 0 \\ \Omega = 0 \\ T = 0 \end{cases} \quad \text{every where}$$

For $t > 0$:

$$\begin{aligned} \theta = 0 &\rightarrow \{\psi_r = 0, \psi_\theta = 0, \Omega = 0\}, \frac{\partial T}{\partial \theta} = 0 \\ \theta = \pi &\rightarrow \{\psi_r = 0, \psi_\theta = 0, \Omega = 0\}, \frac{\partial T}{\partial \theta} = 0 \\ r = R_i / R_o &\Rightarrow \\ &\Rightarrow \left\{ \psi_\theta = \frac{Re_w}{Re} \sin\theta, \psi_r = 0, \Omega = \frac{\Omega_i R_i^2}{\omega_o R_o^2} \sin^2\theta, T = 0 \right. \end{aligned} \quad (8)$$

$$\begin{aligned} r = R'_o / R_o &= e \cos\theta + \sqrt{(1 - e^2 \sin^2\theta)} \Rightarrow \\ &\Rightarrow \left\{ \psi_\theta = \frac{Re_w R'_o{}^2}{Re R_o^2} \sin\theta, \psi_r = 0, \Omega = \frac{\Omega_o R'_o{}^2}{\omega_o R_o^2} \sin^2\theta, T = 1 \right. \end{aligned}$$

where:

$$D^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} - \frac{\cot\theta}{r^2} \frac{\partial}{\partial \theta} \quad (9)$$

III. PROBLEM SOLUTION

In this section, we firstly present the Computational Procedure and discuss then on the obtained results.

A. Computational Procedure

The two equations governing the fluid motion show that each is describing the behavior of one of the dependent variables Ω and ψ . On the other hand, these two equations are coupled only through nonlinear terms. To solve the problem, the momentum equations were discretized by the finite-difference method and implicit scheme. Because of the known velocity field, the energy equation is linear and is solved keeping all its terms.

In each time step (n+1), the value of the dependent variables are guessed from their values at previous time steps (n), (n-1), and (n-2) and after using them in difference equations and repeating it until the desired convergence, will lead to the corrected values at this time step. This procedure is applied for the next time step.

The flow field considered is covered with a regular mesh. To solve the system of linear difference equations, a tridiagonal method algorithm is used in both directions r and θ .

Direct substitution of previous values of dependent variables by new calculated values can cause calculation un-stability in general. To overcome this problem, a weighting procedure is used in which the optimum weighting factor depends on Reynolds number. The mesh size used in numerical solution for equator of the circle is a uniform 40x20, 60x30, 80x40 and 100x50 (θ -direction x r -direction, respectively) with the ratio of $R_{out} / R_{in} = 2$, which all of them show that the problem is

independent of mesh size, but on the one hand by noting to calculations time and on the other hand since a finer mesh size is better we choose the 80x40 mesh size.

In this work, the sphere angular velocity has been considered a function of time (sinusoidal) and to apply this time function to the program, an average value at the beginning of each time step has been calculated and used for the sphere angular velocity function. Therefore, for each considered time step, the sphere velocity is defined and sectionally continues.

B. Results and Discussions

The streamlines and temperature distribution in the meridian plane for $Re = 1000$, $Re_w = -5$, $Pr = 10$

$e = 0.1$, $\Omega_{io} = \frac{\Omega_i}{\Omega_o} = 2 \sin(\pi t / 2)$ in $t = 4.01^{sec}$ are

presented in Fig.2. In Fig.3 the contours of the streamlines and temperature field are presented for the same conditions in Fig.2 except $t = 11.01^{sec}$. As can be seen, the size of the eddies created in flow field comparison with the Fig.2 (a), is smaller. Also Looking at Fig.3 (b), it is found that the diffusion of heat in the vicinity of the poles is less, because the eddies created in the vicinity of the poles are as preventive means for heat transfer.

Fig.4 shows the temperature distribution in the annulus for the same before conditions except $Re_w = -10$. As can be seen, the increase in suction increases the diffusion of heat transfer toward the inner sphere which has less temperature. Finally, in Fig.5 the streamlines and temperature distribution are presented for blowing case ($Re_w = 5$) and two Prandtl numbers $Pr = 1$ and $Pr = 10$. In this case, by considering the flow field, it is found out that the eddies near the outer sphere are the preventive means for transferring the inner sphere coldness toward the outer sphere. Also, the effect of Prandtl number on temperature field is considerable, as is shown in Fig.4, case (b) ($Pr = 1$) and case(c) ($Pr = 10$). In all of the temperature fields, diffusion of heat in lower hemisphere is more visible, because of more Coriolis forces in this hemisphere.

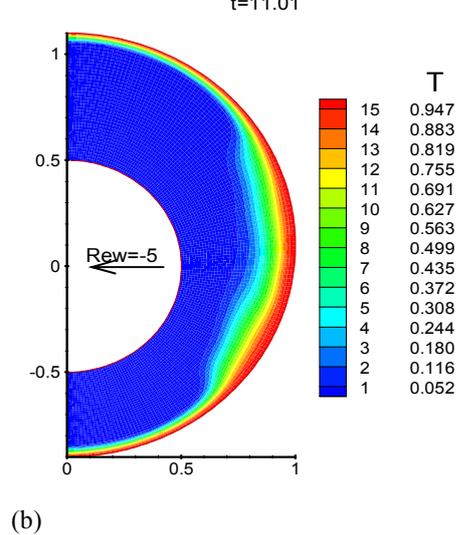
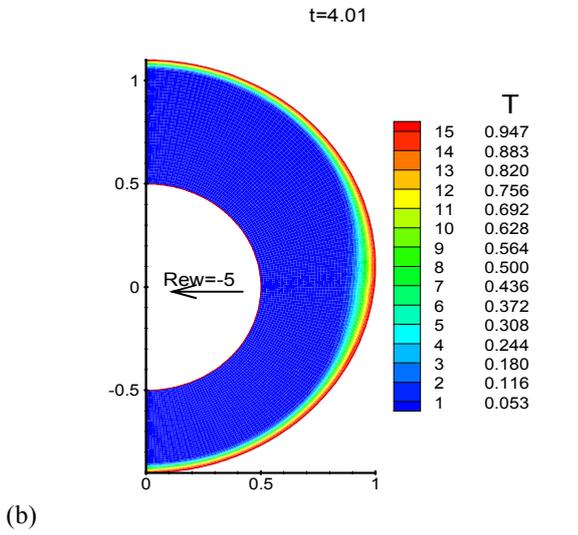
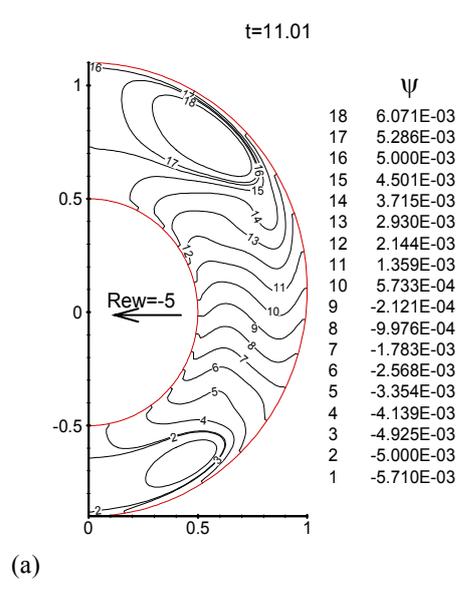
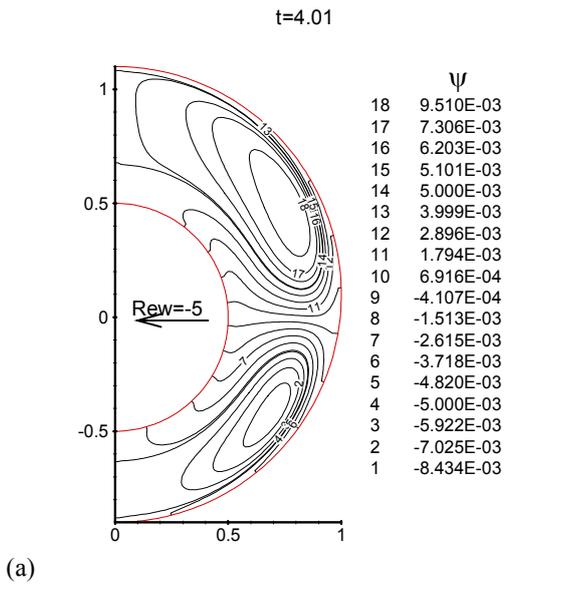


Fig.2: Flow and heat transfer for $Re = 1000$, $Re_w = -5$, $Pr = 10$, $e = 0.1$, $\Omega_{io} = 2 \sin(\pi t / 2)$ at $t = 4.01^{sec}$

Fig.3: Flow and heat transfer for $Re = 1000$, $Re_w = -5$, $Pr = 10$, $e = 0.1$, $\Omega_{io} = 2 \sin(\pi t / 2)$ at $t = 11.01^{sec}$

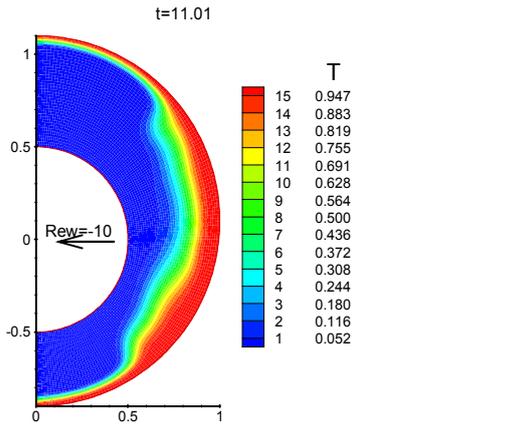
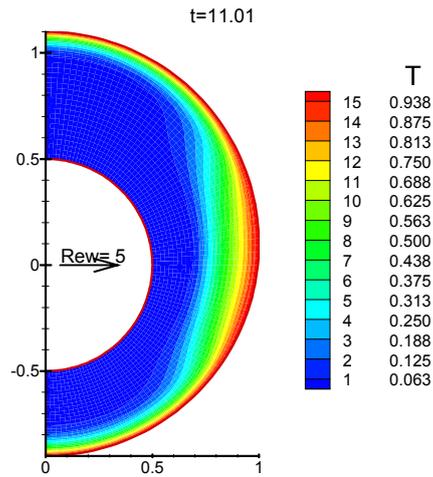
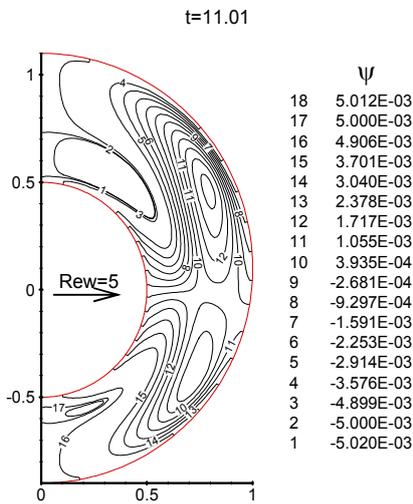


Fig.4: Temperature distribution for $Re = 1000$, $Re_w = -10$, $Pr = 10$, $\Omega_{io} = 2 \sin(\pi t / 2)$ at $t = 11.01^{sec}$

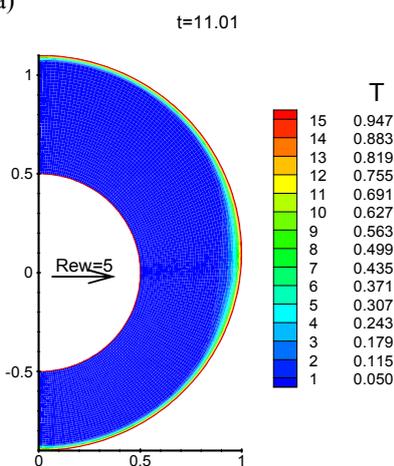


(c)

Fig.5: Flow and heat transfer for $Re = 1000$, $Re_w = 5$, $e = 0.1$, $\Omega_{io} = 2 \sin(\pi t / 2)$ at $t = 11.01^{sec}$, (b) $Pr = 10$, (c) $Pr = 1$



(a)



(b)

IV. CONCLUSION

In this paper, the effects of suction and blowing on flow and especially heat transfer between two vertically eccentric spheres are studied. The angular velocity of the inner sphere was considered as a sinusoidal function while the outer sphere was stationary. The obtained results show that the eddies are as the preventive means for heat transfer so that the diffusion of heat is more in the regions that there are no the eddies. Also it is found; where the distance between two spheres is reduced the diffusion of heat becomes more, because the Coriolis forces are bigger in these regions. Likewise, it is seen that with suction and blowing the rate of heat transfer can be regulated.

ACKNOWLEDGMENT

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