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THREE DIMENSIONAL FLUCTUATING FLOW AND HEAT TRANSFER THROUGH A POROUS MEDIUM

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This paper reports an analytical study of an unsteady flow of a viscous incompressible fluid through a highly porous medium bounded by an infinite porous plate. The plate is subjected to a transverse sinusoidal suction velocity distribution fluctuating with time and thus generating a three-dimensional flow of the fluid through the porous medium. The wall shear stress and the rate of heat transfer are obtained for asymptotic flow conditions. During the course of discussion, it is found that the amplitude, $|F|$, in main flow direction decreases with the increase of the frequency, 'ω', of the fluctuation, however, for very large values of the Reynolds number the frequency has no effect on the amplitude.

Key Words: Three Dimensional; Fluctuating; Transverse Sinusoidal; Suction; Porous Medium; Permeability

Introduction

In the recent years, the problem of flow through a porous medium has attracted the attention of a number of scholars because of its possible application to several geophysical applications, viz., in the fields of agricultural engineering to study the underground water resources, seepage of water in riverbeds; in petroleum technology to study the movement of natural gas, oil and water through the oil reservoir. In view of these applications, a series of investigations have been made by Raptis *et al.*[1-3] into the steady flow past a vertical wall. Raptis[4] studied the unsteady flow through a porous medium bounded by an infinite porous plate subjected to a constant suction and variable temperature. Raptis and Perdikis[5] further studied the problem of free convective flow through a porous medium bounded by a vertical porous plate with constant suction when the free stream velocity oscillates in time about a constant mean value.

In most of the studies mentioned above the infinite surface bounding the porous medium is subjected to a constant suction and thus the problem remains two-dimensional. Varshney[6] used the equations of motion derived by Ahmadi and Manvi[7] to study an oscillatory two-dimensional flow through a porous medium bounded by a porous plate subjected to a suction velocity which varies in magnitude. The problem of laminar flow control (LFC) is gaining considerable importance in engineering and technology because of its application to reduce drag. The boundary layer suction is one of the effective methods of reducing the drag coefficient which entails large energy losses. The transition from laminar to turbulent flow which causes increase of drag coefficient may also be prevented by applying suction at the surface. In order to obtain any desired reduction in the drag, the effects of different arrangements and configurations of the suction holes and slits on the drag coefficients have been studied extensively both experimentally and theoretically. The development, since World War-II, on this subject has been compiled by Lachmann[8]. Singh *et al.*[9] investigated the effect of periodic variation of suction velocity given by Gerston and Gross[10] on the three-dimensional convective flow and heat transfer through a porous medium. Singh *et al.*[11] further extended the problem in an ordinary medium by varying the suction velocity distribution on the plate with time also. By assuming sinusoidal suction velocity distribution at the horizontal surface, Singh[12] studied an oscillatory flow through a highly porous medium. Recently, Singh and Rana[13] further studied the effect of periodic suction velocity on the heat transfer and the flow through highly porous medium bounded by a flat surface at constant temperature. The object of the present paper is to study the effect of permeability on the flow of a viscous incompressible fluid through a highly porous medium bounded by an infinite porous plate which is subjected to a transverse sinusoidal suction velocity distribution fluctuating with time.

Nomenclature

t^*	time;
t	dimensionless time;
x^*, y^*, z^*	coordinates along the main flow direction, perpendicular to the plate, transverse to the main flow direction respectively;
y, z	dimensionless coordinates perpendicular to the plate, dimensionless coordinates transverse to the main flow direction;
u^*, v^*, w^*	velocity components along $x^* y^* z^*$-axis respectively;
u, v, w	dimensionless velocity component along x, y, z axis respectively;
T^*	fluid temperature;
θ	dimensionless fluid temperature;
T^*_a	free stream temperature;
T^*_w	temperature at the plate;
l	wave length of the periodic suction;
$V > 0$	constant suction velocity;
p^*	pressure;
p	dimensionless pressure;
ρ	density;
ν	kinematic viscosity;
U	free stream velocity;
k	thermal conductivity;
C_p	specific heat at constant pressure;
K^*	permeability of porous medium;
K	dimensionless permeability of the porous medium;
P	Prandtl number;
ω^*	frequency;
ω	dimensionless frequency;
$\varepsilon(<<1)$	amplitude of the suction velocity distribution;

R	Reynolds number;
τ_x	skin friction along main flow;
τ_z	skin friction transvetse to the main flow;
q^*_w	heat transfer at the plate;
Nu	Nusselt number.

Mathematical Analysis

We consider the flow of an incompressible viscous fluid through a porous medium bounded by an infinite porous plate lying horizontally on $x^* - z^*$ plane. The x^*-axis is taken along the plate, being the direction of the flow, and the y^*-axis is taken normal to the plate directed into the fluid flowing laminarly. Since the plate is considered infinite in x^*-direction, all physical quantities will be independent of x^*, however, the flow remains three-dimensional due to the variation of the suction velocity which is of the form:

$$V^*(z^*,t^*) = -V\left[1+\varepsilon\cos\left(\frac{\pi z^*}{l} - w^* t^*\right)\right], \qquad \ldots(1)$$

Eq. (1) consists of a basic steady distribution $V>0$ with a superimposed weak time varying distribution $\varepsilon V \cos\left(\frac{\pi^*_z}{l} - w^* t^*\right)$ The negative sign in eq. (1) indicates that the suction is towards the plate. The permeability K^* of the porous medium is assumed to be $\geqslant 1$. This is a valid assumption for a highly porous medium such as an air filter. The porosity of such filter is close to unity as these are made of fibrous material. Thus, the flow in the highly porous medium is governed by the following equations:

$$V^*_y + w^*_z = 0, \qquad \ldots(2)$$

$$u^*_t + v^* u^*_y + w^* u^*_z = -p^*_x/\rho + \nu(u^*_{yy} + u^*_{zz}) - \nu u^*/K^*, \qquad \ldots(3)$$

$$v^*_t + v^* v^*_y + w^* v^*_z = -p^*_y/\rho + \nu(v^*_{yy} + v^*_{zz}) - \nu v^*/K^*, \qquad \ldots(4)$$

$$w^*_t + v^* w^*_y + w^* w^*_z = -p^*_z/\rho + \nu(w^*_{yy} + w^*_{zz}) - \nu w^*/K^* \qquad \ldots(5)$$

and

$$T^*_t + v^* T^*_y + w^* T^*_z = k(T^*_{yy} + T^*_{zz})/\rho C_p. \qquad \ldots(6)$$

The last terms on the right-hand sides of eqs. (3) to (5) account for the pressure drop across the porous material. The boundary conditions of the problem are:

$$\left.\begin{aligned} &y^*=0;\ u^*=0,\ v^* = -V[1+\varepsilon\cos(\pi^*_z z^*/l - w^* t^*)],\ w^*=0,\ T^* = T^*_w,\\ &y^*\to \alpha;\ u^* = U,\ w^*=0,\ p^* = p^*_\alpha,\ T^* = T^*_\alpha \end{aligned}\right\} \qquad \ldots(7)$$

In the free stream from eqs. (3), we get

$$-p^*_x/\rho = \nu U/K^* \qquad \ldots(8)$$

Eliminating $-p^*_x/\rho$ between (3) and (8), we get

$$u^*_t + v^*u^*_y + w^*u^*_z = \nu(u^*_{yy} + u^*_{zz}) - \nu(u^* - U)/K^* \quad \ldots (9)$$

We now introduce the following non-dimensional quantities

$$\left.\begin{array}{l} y = y^*/l,\ z = z^*/l,\ t = w^*t^*,\ w = w^*l^2/\nu,\ u = u^*/U \\ v = v^*/V,\ w = w^*/V,\ R = Vl/\nu,\ P = \mu C_p/k,\ K = K^*v^2/\nu^2, \\ \theta = (T^* - T^*_a)/(T^*_w - T^*_a),\ p = p^*/\rho V^2 \end{array}\right\} \quad \ldots (10)$$

in eqns (2), (9), (4), (5) and (6), we get

$$v_y + w_z = 0, \quad \ldots (11)$$

$$wu_t/R + vu_y + wu_z = (u_{yy} + u_{zz})/R - R(u-1)/K, \quad \ldots (12)$$

$$wv_t/R + vv_y + wv_z = -p_y + (v_{yy} + v_{zz})/R - Rv/K, \quad \ldots (13)$$

$$ww_t/R + vw_y + ww_z = -p_z + (w_{yy} + w_{zz})/R - Rw/K \quad \ldots (14)$$

and

$$w\theta_t/R + v\theta_y + w\theta_z = (\theta_{yy} + \theta_{zz})/RP. \quad \ldots (15)$$

The corresponding boundary conditions reduce to

$$\left.\begin{array}{l} y = 0;\ u = 0,\ v = -[1 + \varepsilon\cos(\pi z - t)],\ w = 0,\ \theta = 1, \\ y \to \alpha;\ u = 1\ \ w = 0,\ p = p_a,\ \theta = 0. \end{array}\right\} \quad \ldots (16)$$

When the amplitude, $\varepsilon(<<1)$, of the suction velocity distribution is small, we assume the solution in the neighbourhood of the plate as

$$u(y,z,t) = u_0(y) + \varepsilon u_1(y,z,t) + \ldots \quad \ldots (17)$$

Similar expressions hold for v, w, p and θ. When $\varepsilon = 0$, the problem reduces to the steady two-dimensional flow through a highly porous medium with constant suction at the plate and the solution of this basic steady flow is given as

$$u_0(y) = 1 - e^{-my}, \quad \ldots (18)$$

$$\theta_0(y) = e^{-RPy} \quad \ldots (19)$$

with $\quad v_0 = -1, \quad w_0 = 0 \quad$ and $\quad p_0 = p_a, \quad \ldots (20)$

where $\quad m = R[1 + (1 + 4/K)^{1/2}]/2$

When $\varepsilon \neq 0$, substituting (17) in eqs. (11) to (15) and comparing the coefficients of identical powers of ε, neglecting those of ε^2, we get following equations as the coefficients of ε with the help of eq. (20):

$$v_{1y} + w_{1z} = 0, \quad \ldots (21)$$

$$wu_{1t}/R - u_{1y} + v_1 u_{0y} = (u_{1yy} + u_{1zz})/R - Ru_1/K, \quad \ldots (22a)$$

$$wv_{1t}/R - v_{1y} = -p_{1y} + (v_{1yy} + v_{1zz})/R - Rv_1/K, \quad \ldots (22b)$$

$$ww_{1t}/R - w_{1y} = -p_{1z} + (w_{1yy} + w_{1zz})/R - Rw_1/K \quad \ldots (22c)$$

and

$$w\theta_{1t}/R - \theta_{1y} + v_1\theta_{0y} = (\theta_{1yy} + \theta_{1zz})/RP, \quad \ldots (22d)$$

with corresponding boundary conditions as:

$$\left.\begin{array}{l} y=0;\ u_1=0,\ v_1=-\cos(\pi z - t),\ w_1=0,\ \theta_1=0, \\ y\to\alpha;\ u_1=0,\ w_1=0,\ p_1=0,\ \theta_1=0. \end{array}\right\} \quad \ldots (23)$$

This is the set of linear partial differential equations which describe the unsteady three-dimensional flow through a highly porous media.

The solutions will be obtained in terms of complex notations, the real part of which will have physical significance. Thus, we write u_1, v_1, w_1, p_1 and θ_1 as

$$u_1(y,z,t) = u_{11}(y)e^{i(\pi z - t)}, \quad \ldots (24a)$$

$$v_1(y,z,t) = v_{11}(y)e^{i(\pi z - t)}, \quad \ldots (24b)$$

$$w_1(y,z,t) = -v'_{11}(y)e^{i(\pi z - t)}/i\pi, \quad \ldots (24c)$$

$$p_1(y,z,t) = p_{11}(y)e^{i(\pi z - t)}, \quad \ldots (24d)$$

and

$$\theta_1(y,z,t) = \theta_{11}(y)e^{i(\pi z - t)}, \quad \ldots (24e)$$

where the prime in eq (24c) denotes the differentiation with respect to y.

The forms of the cross flow velocity profiles in the above equations are so chosen that the equation of continuity (21) is satisfied. Substitution of expressions (24) in equation (22) reduce them to ordinary differential equations:

$$u''_{11} + Ru'_{11} - (\pi^2 + R^2/K - iw)u_{11} \equiv Rv_{11}u'_0, \quad \ldots (25)$$

$$v''_{11} + Rv'_{11} - (\pi^2 + R^2/K - iw)v_{11} = Rp'_{11}, \quad \ldots (26)$$

$$v'''_{11} + Rv''_{11} - (\pi^2 + R^2/K - iw)v'_{11} = \pi^2 Rp_{11} \quad \ldots (27)$$

and

$$\theta''_{11} + RP\theta'_{11} - (\pi^2 - iwp)\theta_{11} = RPv_{11}\theta'_0. \quad \ldots (28)$$

Solving these equations under the corresponding transformed boundary conditions, we get the expressions for u_1, v_1, w_1, p_1 and θ_1 as

$$u_1 = \frac{Rm}{(\lambda - \pi)}\left[\frac{\pi(e^{-(m+\lambda)y} - e^{-\lambda y})}{2m\lambda + R^2/K} - \frac{\lambda(e^{-(m+\pi)y} - e^{-\lambda y})}{(2m - R) + iw}\right]e^{i(\pi z - t)}, \quad \ldots (29)$$

$$v_1 = \frac{1}{(\lambda-\pi)}\left[\pi e^{-\lambda y}\lambda e^{-\pi y}\right] e^{i(\pi z - t)}, \qquad \dots (30)$$

$$w_1 = \frac{\lambda}{i(\lambda-\pi)}\left[e^{-\lambda y} - e^{-\pi y}\right] e^{i(\pi z - t)}, \qquad \dots (31)$$

$$p_1 = N_1\left(\frac{\lambda}{\pi-\lambda}\right) e^{-\pi y} e^{i(\pi z - t)} \qquad \dots (32)$$

$$\theta_1 = \frac{R^2P^2}{(\lambda-\pi)}\left[\frac{\pi}{f_1}\left(e^{-\bar{\lambda} y} - e^{-(\lambda - RP)y}\right) - \frac{\lambda}{f_2}\left(e^{-\bar{\lambda} y} - e^{-(\pi + RP)y}\right)\right]\cdot e^{i(\pi z - t)}, \qquad \dots (33)$$

where $\lambda = A - iB$ and $\bar{\lambda} = \bar{A} - i\bar{B}$ are respectively the positive roots of the equations:

$$\lambda^2 - R\lambda - \left(\pi^2 + \frac{R^2}{K} - iw\right) = 0$$

and

$$\bar{\lambda}^2 - RP\bar{\lambda} - (\pi^2 - iwp) = 0,$$

with A, B, $\bar{A}$ and $\bar{B}$ given by

$$A = R/2 + \sqrt{\left[\sqrt{\left\{\pi^2 + R^2\left(\frac{1}{4} + \frac{1}{K}\right)\right\}^2 + w^2} + \left\{\pi^2 + R^2\left(\frac{1}{4} + \frac{1}{K}\right)\right\}\right]\Big/ 2},$$

$$B = \sqrt{\left[\sqrt{\left\{\pi^2 + R^2\left(\frac{1}{4} + \frac{1}{k}\right)\right\}^2 + w^2} - \left\{\pi^2 + R^2\left(\frac{1}{4} + \frac{1}{K}\right)\right\}\right]\Big/ 2},$$

$$\bar{A} = RP/2 + \sqrt{\left[\sqrt{\left(\pi^2 + \frac{R^2P^2}{4}\right)^2 + w^2p^2} + \left(\pi^2 + \frac{R^2P^2}{4}\right)\right]\Big/ 2}$$

and

$$\bar{B} = \sqrt{\left[\sqrt{\left(\pi^2 + \frac{R^2P^2}{4}\right)^2 + w^2p^2} + \left(\pi^2 + \frac{R^2P^2}{4}\right)\right]\Big/ 2}.$$

In the above equations, f_1, f_2 and N_1 has also been defined as

$$f_1 = R\lambda(P+1) + iw(P-1) + R^2/K,$$

$$f_2 = P(\pi R - iw)$$

and

$$N_1 = \left[1 + \frac{P}{\pi K} - \frac{iw}{\pi R}\right]$$

Results and Discussion

The important characteristics of the problem, we are interested in, are the plate shear stress and the rate of heat transfer at the plate. Knowing the velocity profile we can obtain the components of the shear stress in the dimensionless form along and perpendicular to the main flow directions as

$$\tau_x = \frac{\tau_x^*}{\rho U V} = \frac{\nu}{v l}\left(\text{Real of } \frac{\partial u}{\partial y}\right)_{y=0} = \frac{m}{R} + \varepsilon\,|F|\cos(\pi z - t + \phi_1) \qquad \ldots (34)$$

and

$$\tau_z = \frac{\tau_z^*}{\mu v/\lambda} = \left(\text{Real of } \frac{\partial w}{\partial y}\right)_{y=0} = \varepsilon |G| \cos(\pi z - t + \phi_2), \qquad \ldots (35)$$

where

$$|F| = (F_r^2 + F_i^2)^{1/2}, \qquad |G| = (A^2 + B^2)^{1/2},$$

$$\tan \phi_1 = F_i/F_r \qquad \text{and } \tan \phi_2 = A/B$$

and

$$F_r = \frac{m[(A-\pi)\{\pi(2m-R)(A(m+\pi-A)+B^2)+w(AB-B(m+\pi-A))\}]}{[(A-\pi)^2+B^2][\{\pi(2m-R)\}^2+w^2]}$$

$$- mB\frac{[\pi(2m-R)\{AB-B(m+\pi-A)\}-w\{A(m+\pi-A)+B^2\}]}{[(A-\pi)^2+B^2][\{\pi(2m-R)\}^2+w^2]}$$

$$- \pi m^2 \frac{[(A-\pi)(2mA+R^2/K)-2mB^2]}{[(A-\pi)^2+B^2][(2mA+R^2/K)^2+(2mB)^2]}$$

and

$$F_i = m\frac{[B\{\pi(2m-R)(A(m+\pi-A)+B^2)+w(AB-B(m+\pi-A))\}]}{[(A-\pi)^2+B^2][\{\pi(2m-R)\}^2+w^2]}$$

$$+ m(A-\pi)\frac{[\pi(2m-R)\{AB-B(m+\pi-A)\}-w\{A(m+\pi-A)+B^2\}]}{[(A-\pi)^2+B^2][\{\pi(2m-R)\}^2+w^2]}$$

$$- \pi m^2 \frac{[2mB\,(A-\pi)+B(2mA+R^2/K)]}{[(A-\pi)^2+B^2][(2mA+R^2/K)^2+(2mB)^2]}.$$

The amplitude, $|F|$, of the skin friction components in the main flow direction is shown in Fig. 1. It is interesting to note that by increasing the permeability, the amplitude, $|F|$, decreases for small values but increases for large values of the Reynolds number. For very large values of the Reynolds number, $|F| \to 1$.

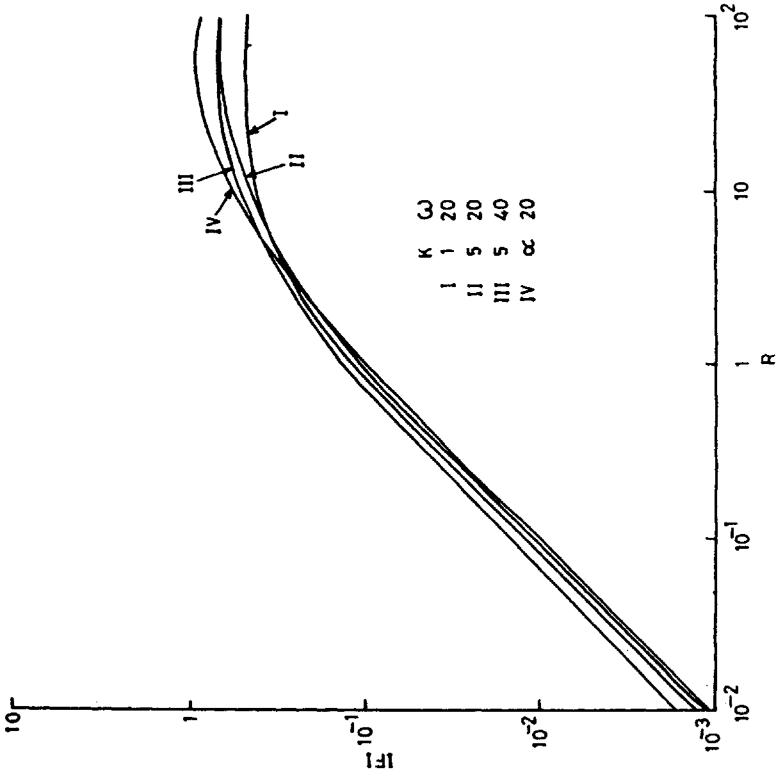

Fig 1 The amplitude, |F|, of the skin friction in the main flow direction

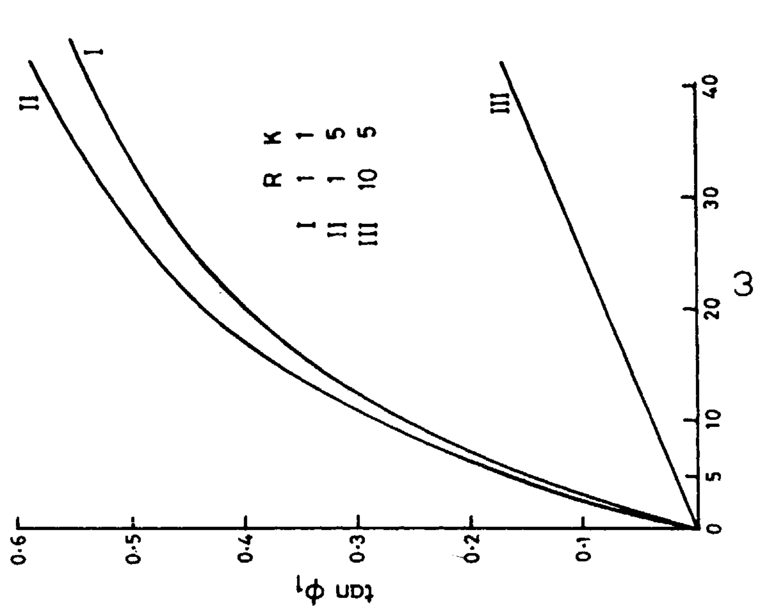

Fig 2 The tangent of phase angle tan ϕ_1 of the main flow skin friction

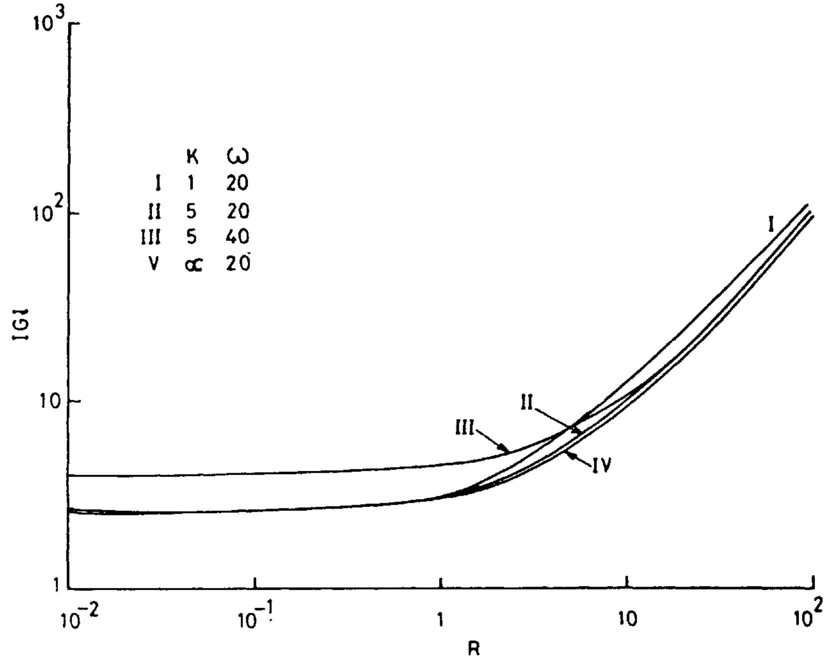

Fig 3 The amplitude, IGI,of the skin friction in the transverse direction

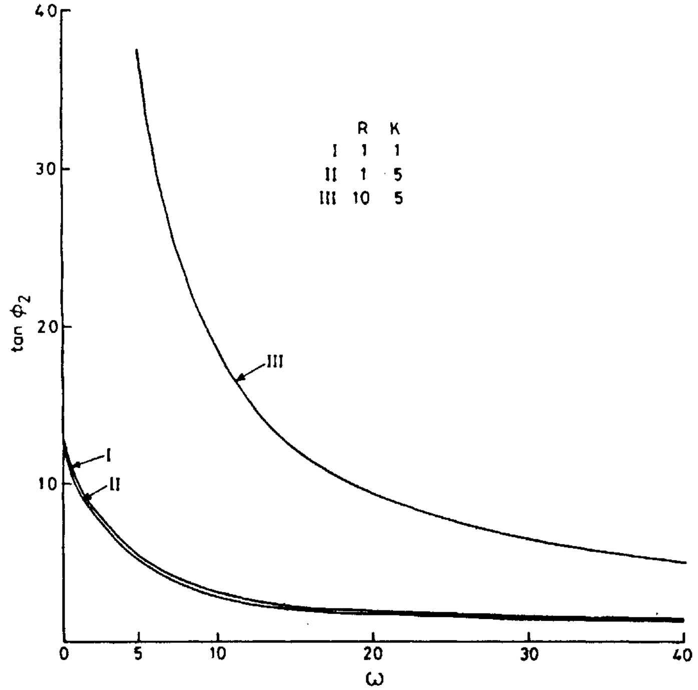

Fig 4 The tangent of phase angle tan ϕ_2 of the skin friction in the transverse direction

The amplitude decreases with the increase of the frequency, w, however, for very large values of the Reynolds number, the frequency has no effect on the amplitude.

The amplitude, $|G|$, of the skin friction component in the direction perpendicular to the main flow has also been shown graphically in Fig. 2. It is observed that with the increase of the frequency the amplitude increases, however, the frequency has no influence on the amplitude for large values of the Reynolds number. It is also evident from this figure that with the increase of permeability of the porous medium the amplitude $|G|$ decreases, but the permeability has no effect on $|G|$ for very small values of R. The tangents of the phase angles of the skin friction components in the main flow direction, $\tan \phi_1$, and normal to it, $\tan \phi_2$ are presented respectively in Figures 3 and 4. It is found that with the increase of the permeability the phase along the main flow direction increases but the phase in the direction perpendicular to the main flow decreases. It is also inferred that the phase in the main flow direction decreases and in the direction normal to it increases considerably with the increase of the Reynolds number. There is always a phase lead in both the components of the skin friction. It is also found that when the frequency $w \to 0$ the phase lead ϕ_2 of the skin in the direction perpendicular to the main flow is $\pi/2$.

Similarly, the rate of heat transfer can be obtained from the temperature field in terms of the Nusselt number as

$$N_u = \frac{q^*_w}{\rho V Cp(T^*_w - T^*_a)} = -\frac{k}{\rho V l Co}\left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$= 1 + \varepsilon |H| \cos(\pi z - t + \phi_3), \qquad \ldots (36)$$

where

$$|H| = (H_r^2 + H_i^2)^{1/2} \qquad \text{and } \tan \phi_3 = H_i/H_r$$

and

$$H_r = \pi RP(A-\pi)$$

$$\frac{[(\bar{A}-A-RP)\{R(P+1)A+R^2/K\}+(\bar{B}-B)\{R(P+1)B-w(P-1)\}]}{[(A-\pi)^2+B^2][\{R(P+1)+R^2/K\}^2+\{R(P+1)B-w(P-1)\}^2]}$$

$$-\pi RPB\frac{[(\bar{A}-A-RP)\{R(P+1)B-w(P-1)\}-(\bar{B}-B)\{R(P+1)A+R^2/K\}]}{[(A-\pi)^2+B^2][\{R(P+1)+R^2/K\}^2+\{R(P+1)B-w(P-1)\}^2]}$$

$$-R(A-\pi)\frac{[\pi R\{A(\bar{A}-\pi-RP)-B\bar{B}\}-w\{B(\bar{A}-\pi-RP)+A\bar{B}\}]}{[(A-\pi)^2+B^2][\pi^2R^2+w^2]}$$

$$-RB\frac{[\pi R\{B(\bar{A}-\pi-RP)+A\bar{B}\}+w\{A(\bar{A}-\pi-RP)-B\bar{B}\}]}{[(A-\pi)^2+B^2][\pi^2R^2+w^2]},$$

$$H_i = \pi RP(A-\pi)\frac{[(\bar{A}-A-RP)\{R(P-1)B-w(P-1)\}-(\bar{B}-B)\{R(P+1)A+R^2/K\}]}{[(A-\pi)^2+B^2][\{R(P+1)A+R^2/K\}^2+\{R(P+1)B-w(P-1)\}^2]}$$

$$+\pi RPB\frac{[(\bar{A}-A-RP)\{R(P+1)A+R^2/K\}+(\bar{B}-B)\{R(P+1)B-w(P-1)\}]}{[(A-\pi)^2+B^2][\{R(P+1)A+R^2/K\}^2+\{R(P+1)B-w(P-1)\}^2]}$$

$$-RB\frac{[\pi R\{A(\bar{A}-\pi-RP)-B\bar{B}\}-w\{B(\bar{A}-\pi-RP)+A\bar{B}\}]}{[(A-\pi)^2+B^2][\pi^2R^2+w^2]}$$

$$+R(A-\pi)\frac{[\pi R\{B(\bar{A}-\pi-RP)+A\bar{B}\}+w\{A(\bar{A}-\pi-RP)-B\bar{B}\}]}{[(A-\pi)^2+B^2][\pi^2R^2+w^2]}.$$

Table I

The amplitude $|H|$ of the rate of heat transfer

P	K	ω	$R/10^{-2}$	10^{-1}	1	10	10^2
0.71	1	20	0.0013	0.0131	0.1237	0.6801	0.9687
0.71	5	20	0.0013	0.0131	0.1244	0.6941	0.9718
0.71	5	40	0.0011	0.0105	0.1004	0.6515	0.9717
0.71	10	20	0.0013	0.0131	0.1238	0.6968	0.9725
7.00	1	20	0.0056	0.0552	0.4554	0.9884	0.9990
7.00	5	20	0.0056	0.0552	0.4555	0.9903	0.9992
7.00	5	40	0.0045	0.0398	0.3481	0.9866	0.9990

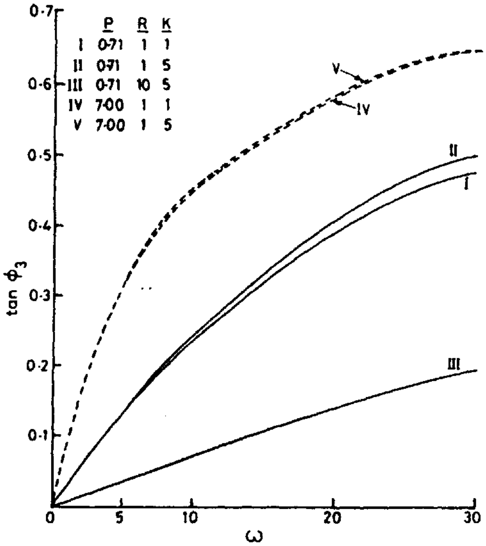

Fig 5 The tangent of phase angle tan ϕ_3 of the rate of heat transfer

The numerical values of the amplitude $|H|$ of the rate of heat transfer have been listed in Table I. This table shows that the amplitude decreases, with the increase of the frequency, w but for large values of R the frequency has no influence on the amplitude. It is also noticed that with the increase of the permeability, K the amplitude increases for $R \geqslant 1$. It is also clear from the values in the table that $|H| \to 0$ for $R \to 0$ and when $R \to \alpha$, $|H| \to 1$. The values of the amplitude are large in water ($P=7$) than in air ($P=0.71$). The tangent of the phase angle, tan ϕ_3, of the rate of heat transfer is presented in Fig. 5. This figure clearly shows that the phase increases with increase of the permeability of the medium but decreases considerably with the increase of the Reynolds number. The phase of the rate of heat transfer is more in water ($P=7$) than in air ($P=0.71$). The figure shows that there always remains a phase lead.

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