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MHD FLOW OF A JEFFREY FLUID IN A POROUS-WALLED RECTANGULAR SQUEEZE FILM

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ABSTRACT

The effect of magnetic field on the electrically conducting flow of a Jeffrey fluid between two infinite strips, where one of the porous strip has a porous bounding surface backed by a solid wall is investigated, the flow in the porous medium is assumed to be described by a modified Darcy law. Expressions for velocity field, load capacity and thickness-time are obtained. It is observed that the magnetic field increases the load capacity and response times of squeeze film.

KEYWORDS: Magnetic field; Jeffrey fluid; Squeeze film; Porous medium

Nomenclature

B_0	impressed uniform magnetic field
E	electric field vector (E_x, E_y, E_z)
H	thickness of porous material
h	thickness of squeeze film
h_0	film thickness at $t=0$
I_n	integrals defined in (39)
J	current density vector (J_x, J_y, J_z)
K	permeability of porous material
l	length of tile strips in z-direction
L	load capacity
m_0	constant defined in (6), $(B_0^2/v_m\mu_f\mu_m)^{\frac{1}{2}}$
M	Hartmann number, $(m_0^2h^2)^{\frac{1}{2}}$
P	pressure distribution in porous material
p	pressure distribution in squeeze film
q	velocity vector (u, v)
t	time
U	stream wise velocity component in porous material
u	stream wise velocity component in the squeeze film
$\bar{u}$	mean velocity in x-direction
u_s	slip velocity
V	transverse velocity component in porous material

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v	transverse velocity component in squeeze film
v_h	value of v at $y=h$
α	constant related to slip coefficient defined in (11)
λ_n	eigen values
μ_f	viscosity
μ_m	magnetic permeability
ρ	density
v_m	magnetic diffusivity, $1/\mu_m\sigma_e$
σ	dimensionless parameter, $h/K^{\frac{1}{2}}$
σ_e	Electrical conductivity
λ_1	Jeffrey parameter

I. INTRODUCTION

In the study of fluid transport in biological organisms, we deal with the flow between permeable walls that may expand or contract. This phenomenon really has a great importance in medical and biological sciences. Oozing through porous walls is an important phenomenon in blood flow, which contribute a lot in inter-body transportation of different substances and it may affect the entire health of the living organism. The flows of such type have also a wide range of industrial applications. Gold miners, use the machinery in which sludge is carried away from the mine to cleansing chambers with the help of vessels which may expand/contract and have the porous walls. The flow through dilating and squeezing permeable gaps has been a research area of many researchers [1, 2, 3, 4]. Many analytical and numerical techniques have been used to determine the flow profile to simulate bio-fluid flow.

In real life, fluids inside living organisms are not Newtonian normally. Si et. al [5] studied the flow of a viscoelastic fluid through a porous channel with expanding and contracting walls. It is worth mentioning that there is no single model available that can incorporate all the properties of every non-Newtonian fluid. Different models have been proposed for different kinds of non-Newtonian fluids [6–8, 9, 10–12, 13, 14]. To understand the transportation of materials inside the body further, we need to examine the flows of non-Newtonian fluids. This is for, here, we present this work. It takes a non-Newtonian fluid model (Jeffery Fluid model) in to consideration. A number of research works have been carried out using the said model [15, 16, 17, 18, 19] dealing with the different kinds of geometries and situations.

Many researchers investigate the action of squeeze films between plane and cylindrical surfaces see for example [20-23]. These studies are devoted to understand the performance of squeeze film bearings which find application in lubrication technology. A squeeze film is a layer of fluid situated between surfaces that are approaching each other. This approaching action of the surfaces forces the fluid in the layer to move towards the less constrained surroundings. If the film or the fluid layer is very thin then the viscous forces become dominant and offer a high resistance to such fluid motion inhibiting the approach of the bounding surfaces. All the previous studies concerning squeeze films relate to impermeable bounding surfaces. Wu [24] and Sparrow et al [25] have considered the situation where one of the bounding surfaces is permeable. In such a situation only part of the fluid will be squeezed out and the remaining part will flow through the porous medium modifying the flow pattern. In this type of coupled flow the fluid motion in the squeeze film, is governed by viscous and pressure forces and by Darcy's Law in the porous regime. The study of Sparrow et al takes account also of the fact that at the porous boundary the no-slip condition is no-longer truly valid. The above fact was demonstrated by the experimental study of Beavers and Joseph [26] and Beavers et al [27]. Beavers and Joseph [26] have also derived a suitable slip condition for the flow. This slip condition has been slightly modified by Sparrow et al [26] in their analysis.

The present investigation is confined to study the interaction of a magnetic flow of a Jeffrey fluid with the coupled flows in a squeeze film and in its porous bounding surface. Expressions for load capacity and thickness-

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time relationship for the squeeze film are obtained. These expressions are numerically evaluated and the results are presented in graphs to indicate the influence of the magnetic field and the slip velocity on the flow.

II. FORMULATION OF THE PROBLEM

The physical model considered is shown in fig. 1. The model consists of Jeffrey fluid passing between two flat plates of the same dimensions separated by a gap, which is filled with a conducting, incompressible fluid of constant properties and of instantaneous height h. The fluid in the gap comprises the squeeze film. The lower plate is impermeable while the upper plate consists in part of a porous material of constant thickness H. A uniform magnetic field B_0 is applied in the transverse direction. Since the analysis is directed to study the combined effect of slip velocity, porous medium and magnetic field on load capacity of the squeeze film it is necessary to study the fluid motion separately in the film and in the porous medium. Then the pressure which determines the load capacity is obtained using the pressure continuity condition at the porous plate-film interface. Hence we begin the analysis with the study of fluid motion in the film.

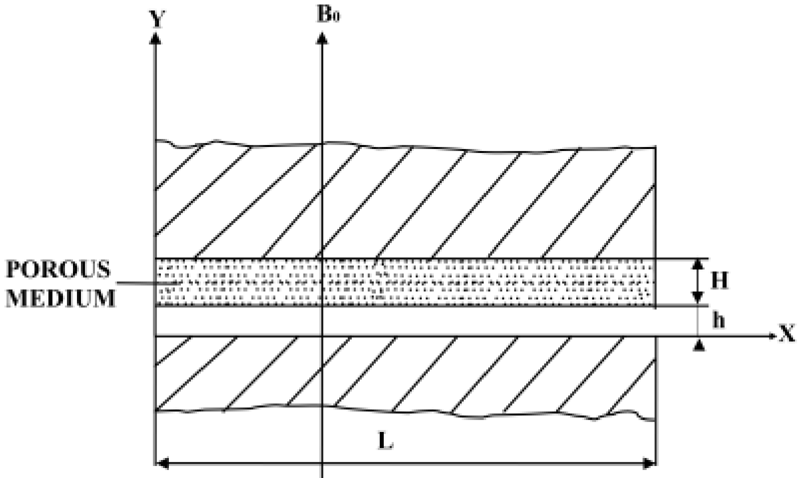

Fig.1. Physical model

Flow in the squeeze film

The equations of motion which describe the fluid motion in the squeeze film are the usual Navier-Stokes equations together with electro-magnetic equations. For quasi-static, laminar, incompressible flow in the film the equations of motion are :

$$\rho(q \cdot \nabla)q = -\nabla p + \frac{\mu_f}{1+\lambda_1}\nabla^2 q + J \times B \tag{1}$$

$$\nabla \cdot q = 0 \tag{2}$$

$$J = \sigma(E + q \times B) \tag{3}$$

$$\nabla \cdot B = 0 \tag{4}$$

$$\nabla \times E = 0 \tag{5}$$

The above equations under the approximations of lubrication theory and the assumption that the induced magnetic field is negligible compared to applied magnetic field B_0, (i.e. the magnetic Reynolds number $R_m \ll 1$) reduce to:

$$\frac{d^2u}{dy^2} - m_0^2 u = \frac{1+\lambda_1}{\mu_f}\left(\frac{\partial p}{\partial x} + E_z H_0 / \nu m\right) \tag{6}$$

for the momentum equation in the x-direction.
Equation (6) can be written in the form

$$\frac{d^2u}{dy^2}-\frac{M^2}{h^2}u=a_0 \tag{7}$$

where $M^2=m_0^2h^2$ (8)

u is the stream wise velocity component in the squeeze film, and

$$a_0=\frac{1+\lambda_1}{\mu_f}\left(\frac{\partial p}{\partial x}+E_zH_0/\nu m\right) \tag{9}$$

E_z which appears in (6) turns out to be constant from (5). In the squeeze film the transverse pressure changes are negligible and hence the pressure p is a function of x only in the film.

Eq. (7) is solved using the boundary conditions:

$$u=0,\quad at\quad y=0 \tag{10}$$

$$-\frac{\partial u}{\partial y}=\frac{\alpha}{\sqrt{K}}u,\quad at\quad y=h \tag{11}$$

The condition (11) is the Beavers and Joseph slip condition, α is the slip parameter and K is the permeability of the porous medium expressed in units of length squared.
The solution of (7) satisfying (10) and (11) is

$$u=-a_0h^2\left[\left\{\frac{M\sinh M+\alpha\sigma(\cosh M-1)}{M^2(M\cosh M+\alpha\sigma\sinh M)}\right\}\sinh\left(\frac{My}{h}\right)-\frac{\cosh\left(\frac{My}{h}\right)-1}{M^2}\right] \tag{12}$$

where $\sigma=h/\sqrt{k}$ is a dimensionless number.

We note that in the limit $M\to 0$, equation (12) using (9) with $B_0=0$, reduces to the Hydrodynamic case, namely

$$u=\frac{h^2(1+\lambda_1)}{2\mu_f}\left[\left(-\frac{\partial p}{\partial x}\right)\left\{\left(\frac{y}{h}-\frac{y^2}{h^2}\right)+\frac{y/h}{1+\alpha\sigma}\right\}\right] \tag{13}$$

The mean velocity $\bar{u}$ in any cross-section $x=$constant, follows as:

$$\bar{u}=\frac{1}{h}\int_0^h u\,dy$$

$$=a_0h^2\left[\frac{M\sinh M(1-\alpha\sigma)-M^2\cosh M+2\alpha\sigma(\cosh M-1)}{M^3(M\cosh M+\alpha\sigma\sinh M)}\right] \tag{14}$$

In the limit $M\to 0$, (14) becomes:

$$\bar{u} = -\frac{h^2(1+\lambda_1)}{12\mu_f}\left[\left(\frac{\partial p}{\partial x}\right)\left(1+\frac{3}{1+\alpha\sigma}\right)\right] \quad (15)$$

The slip velocity u_s is obtained by evaluating (12) at $y = h$. Then the ratio of slip velocity u_s to the mean velocity $\bar{u}$ is written as:

$$\frac{u_s}{\bar{u}} = \frac{M^2(1-\cosh M)}{M\sinh M(1-\alpha\sigma) - M^2\cosh M + 2\alpha\sigma(\cosh M - 1)} \quad (16)$$

Eq. (16) in the limit $M \to 0$ simplifies to:

$$\frac{u_s}{\bar{u}} = \frac{6}{4+\alpha\sigma} \quad (17)$$

The transverse velocity of the fluid at the upper bounding wall $y = h$, is obtained using the equation of continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (18)$$

The transverse velocity v at $y = h$ can be written as

$$v_h = \frac{-h^3(1+\lambda_1)}{\mu_f}[Q]\left(\frac{\partial^2 p}{\partial x^2}\right) \quad (19)$$

where $Q = \dfrac{M\sinh M(1-\alpha\sigma) - M^2\cosh M + 2\alpha\sigma(\cosh M - 1)}{M^3(M\cosh M + \alpha\sigma\sinh M)}$

The pressure $p = p(x)$ appearing in the above equation is still an unknown. To determine $p(x)$ it is necessary to have the knowledge of flow conditions in the porous medium and hence we now study the flow in the porous medium.

Flow in the porous medium

In the porous regime, the velocity components are related to pressure by Darcy's law, which in the presence of a magnetic field can be written in the form:

$$U = -\frac{K(1+\lambda_1)}{\mu_f}\left(\frac{\partial P}{\partial x} - J_z B_0\right) \quad (20)$$

$$V - h = -\frac{K(1+\lambda_1)}{\mu_f}\left(\frac{\partial P}{\partial x}\right) \quad (21)$$

where h refers to the velocity with which the porous medium itself is moving. Capital letters are used in (20) and (21) to denote velocity components and pressure in the porous medium.

Eq. (20) after simplification reduces to:

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$$U=-\frac{a_0}{m} \tag{22}$$

where $a_0=\frac{1+\lambda_1}{\mu_f}\left(\frac{\partial P}{\partial x}+E_z H_0/\nu m\right)$ and $m=m_0^2+1/K$

U and V satisfy the continuity equation in the porous medium and employing the continuity equation:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{23}$$

Eqs. (21) and (22) can be transformed to the form

$$\frac{\partial^2 P}{\partial x^2}+C_0^2\frac{\partial^2 P}{\partial y^2}=0 \tag{24}$$

Where $C_0^2=1+\frac{M^2}{\sigma^2}$

Eq. (24) is a Laplace equation in two dimensions. Using the method of separation of variables, we arrive at the solution of $P(x,y)$ in the form:

$$P(x,y)=\sum_{n=1}^{\infty}\left[A_n e^{\lambda_n y}+B_n e^{-\lambda_n y}\right]\left[C_n\cos C_0\lambda_n x+D_n\sin C_0\lambda_n x\right] \tag{25}$$

The integration constants and eigen values are determined using the boundary conditions on P.

The boundary conditions on P are:

$$\frac{\partial P}{\partial y}=0 \quad at \quad y=h+H \tag{26}$$

$$P=0 \quad at \quad x=0 \text{ and } x=l \tag{27}$$

The above boundary conditions are obtained as follows:

If the porous medium is backed by a solid wall then $V=h$ at the porous-solid interface and hence from (21) the first boundary condition follows. If the boundaries at $x=0$ and $x=1$ are exposed to the atmosphere at uniform pressure, the reference pressure P is taken as zero. Using the above boundary conditions we obtain the expression for the pressure $P(x,y)$ in the form:

$$P(x,y)=\sum_{n=1}^{\infty}E_n e^{\lambda_n y}\left[1+e^{2\lambda_n(h+H-y)}\right]\sin C_0\lambda_n x \tag{28}$$

To determine E_n the pressure continuity condition

$$p(x)=P(x,h) \tag{29}$$

at the interface of film and porous medium is employed. With the aid of (24), (29) can be expressed as:

$$\frac{\partial^2 P}{\partial x^2}=-\left[C_0^2\frac{\partial^2 P}{\partial y^2}\right]_{x,h} \tag{30}$$

Using the continuity of transverse velocity:

$$v_h = V(x,h) \tag{31}$$

Eq. (21) is finally transformed to:

$$\frac{(1+\lambda_1)C_0^2 h^3}{\mu_f}[Q]\left[\frac{\partial^2 P}{\partial y^2}\right]_{x,y} = \dot{h} - \frac{K(1+\lambda_1)}{\mu_f}\left(\frac{\partial P}{\partial y}\right)_{x,h} \tag{32}$$

Eq. (32) with the help of (28) can be written as:

$$\frac{\mu_f \dot{h}}{h^3(1+\lambda_1)} = \sum_{n=1}^{\infty} E_n \frac{n^2\pi^2}{l^2}\exp\left(\frac{n\pi}{C_0 l}\right)\left[\begin{matrix}\left\{1+\exp\left(\frac{2n\pi H}{C_0 l}\right)\right\}Q + \\ \left(\frac{Kl}{h^3}\right)\frac{1}{C_0 n\pi}\left\{1-\exp\left(\frac{2n\pi H}{C_0 l}\right)\right\}\end{matrix}\right]\sin\frac{n\pi x}{l} \tag{33}$$

The constant E_n appearing in (33) is determined by using the orthognality of the eigen functions $\sin\left(\frac{n\pi x}{l}\right)$.

Thus:
$$E_{2n+1} = \frac{4\mu_f \dot{h} l^2}{(2n+1)^3\pi^3 h^3(1+\lambda_1)}\exp(-R)\left[\begin{matrix}\{1+\exp(S)\}Q + \\ \left(\frac{Kl}{h^3}\right)\frac{1}{C_0(2n+1)\pi}\{1-\exp(S)\}\end{matrix}\right]^{-1} \tag{34}$$

where $R = \frac{(2n+1)\pi}{C_0 l}$, $S = \frac{(4n+2)\pi H}{C_0 l}$

E_n vanishes for n =even.

Then the pressure distribution $p(x)$ in the squeeze film using (29) takes the form

$$\frac{h^3(1+\lambda_1)}{\mu_f l^2 \dot{h}} p(x) = \sum_{n=0}^{\infty}\left[\frac{4}{(2n+1)^3\pi^3}\sin\frac{(2n+1)\pi x}{l}\right]\times$$
$$\times\left[Q - \left(\frac{Kl}{h^3}\right)\frac{1}{C_0\pi(2n+1)}\left(\frac{\exp(S)-1}{\exp(S)+1}\right)\right]^{-1} \tag{35}$$

Similarly the pressure in the porous medium $P(x,y)$ is completely determined using (34). Once the pressure fields in the film and the porous medium are known, the respective velocity components are determined completely using (12), (19), (21) and (22).

Load capacity and thickness-time relation

The load capacity per unit length in the z -direction is found by integrating (35):

$$\text{load capacity } L = \int_0^l p(x)\,dx \tag{36}$$

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The non-dimensional load capacity follows as:

$$\frac{h^3 L(1+\lambda_1)}{\mu_f \dot{h} l^3} = \sum_{n=0}^{\infty} \frac{-8}{(2n+1)^4 \pi^4} \left[Q - \left(\frac{Kl}{h^3}\right) \frac{1}{(2n+1)C_0 \pi} \left(\frac{\exp(S)-1}{\exp(S)+1} \right) \right]^{-1} \tag{37}$$

In the limit $M \to 0$, the above expression emerges as:

$$\frac{h^3 L(1+\lambda_1)}{\mu_f \dot{h} l^3} = \sum_{n=0}^{\infty} \frac{96}{(2n+1)^4 \pi^4} \times$$
$$\times \left[1 + \frac{3}{1+\alpha\sigma} + 12\left(\frac{Kl}{h^3}\right) \frac{1}{(2n+1)\pi} \left(\frac{\exp\{(4n+2)\pi H/l\}-1}{\exp\{(4n+2)\pi H/l\}+1} \right) \right]^{-1} \tag{38}$$

An expression for thickness-time relation can be obtained for a constant load by integrating (37).

The non-dimensional thickness-time t is written in the form

$$\frac{(1+\lambda_1) h_0^2 L t}{\mu_f l^3} = \sum_{n=0}^{\infty} F_n I_n \left(h/h_0 \right)$$

(39)

where $F_n = \dfrac{-8}{(2n+1)^4 \pi^4}$ and

$$I_n(h/h_0) = \int_1^{h/h_0} \left[\frac{\xi^3 \left\{ (M \sinh M)\left(1 - \frac{\alpha h_0 \xi}{\sqrt{K}}\right) - M^2 \cosh M + \frac{2\alpha h_0 \xi}{\sqrt{K}} (\cosh M - 1) \right\}}{M^3 \left(M \cosh M + \frac{\alpha h_0 \xi}{\sqrt{K}} \sinh M \right)} - \left(\frac{Kl}{h^3}\right) \frac{1}{(2n+1)C_0 \pi} \left(\frac{\exp(S)-1}{\exp(S)+1} \right) \right]^{-1} d\xi$$

(40)

h_0 is the thickness of the film at time $t = 0$ and h is the thickness of the film at time t.

III. RESULTS AND DISCUSSION:

In this study, $\dfrac{K}{h_0^3} = 0.05, \dfrac{H}{L} = 0.01$ and $\dfrac{\sqrt{K}}{\alpha h_0} = 0.5$ are used for numerical computation.

The dimensionless group $\dfrac{L h_0^2}{\mu_f l^3} t$ is plotted as a function of the ratio of the instantaneous thickness h to the thickness h_0 at time $t = 0$ for different values of Hartmann number M with $\dfrac{K}{\alpha h_0} = 0.5$ and $\dfrac{K}{\alpha h_0} = 0.1$ which are presented in figures 2 and 3 respectively. It is noticed that, for a given value of porous medium group $\dfrac{k\, l}{h_0^3}$

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and slip group $\frac{\sqrt{K}}{\alpha h}$, the thickness time increases with increasing magnetic field. The dimensionless group $\frac{Lh_0^2}{\mu_f l^3}t$ as a function of the ratio of the instantaneous thickness h to the thickness h_0 at time $t=0$ for different values of Jeffrey parameter λ_1 with $\frac{K}{\alpha h_0}=0.5$ is plotted in figure 4. It is observed that with increasing Jeffrey parameter λ_1 the thickness time increases.

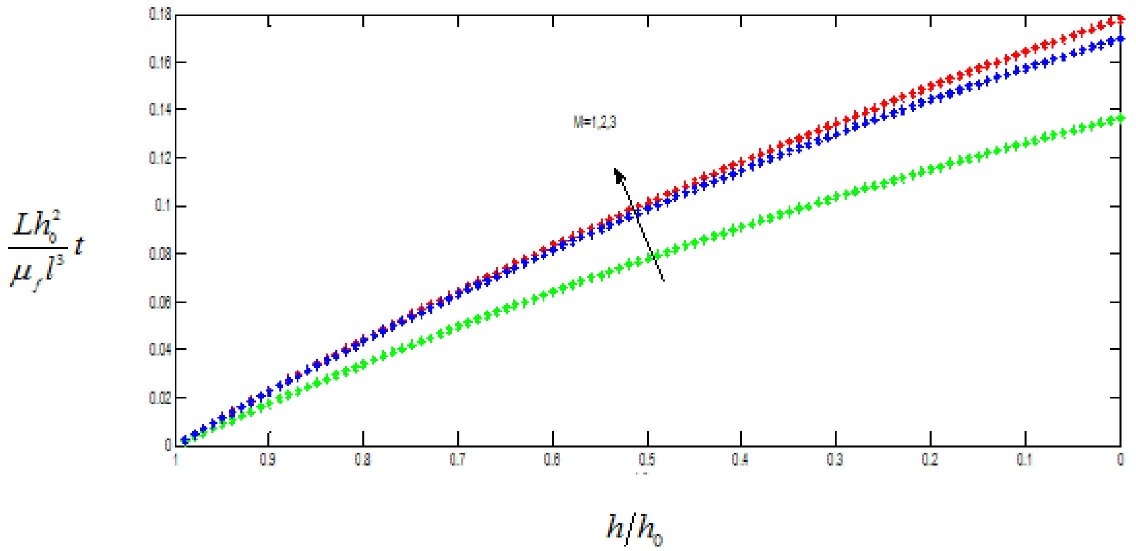

Fig.2. Thickness - time relation for different values of M ***with*** $\frac{K}{\alpha h_0}=0.5$

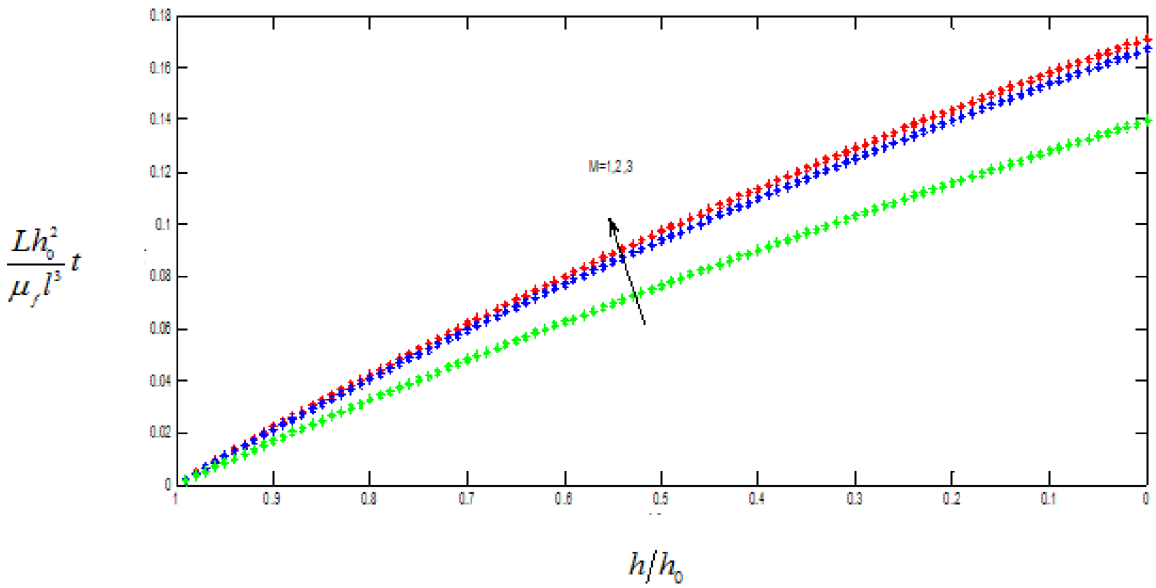

Fig.3. Thickness - time relation for different values of M ***with*** $\frac{K}{\alpha h_0}=0.1$

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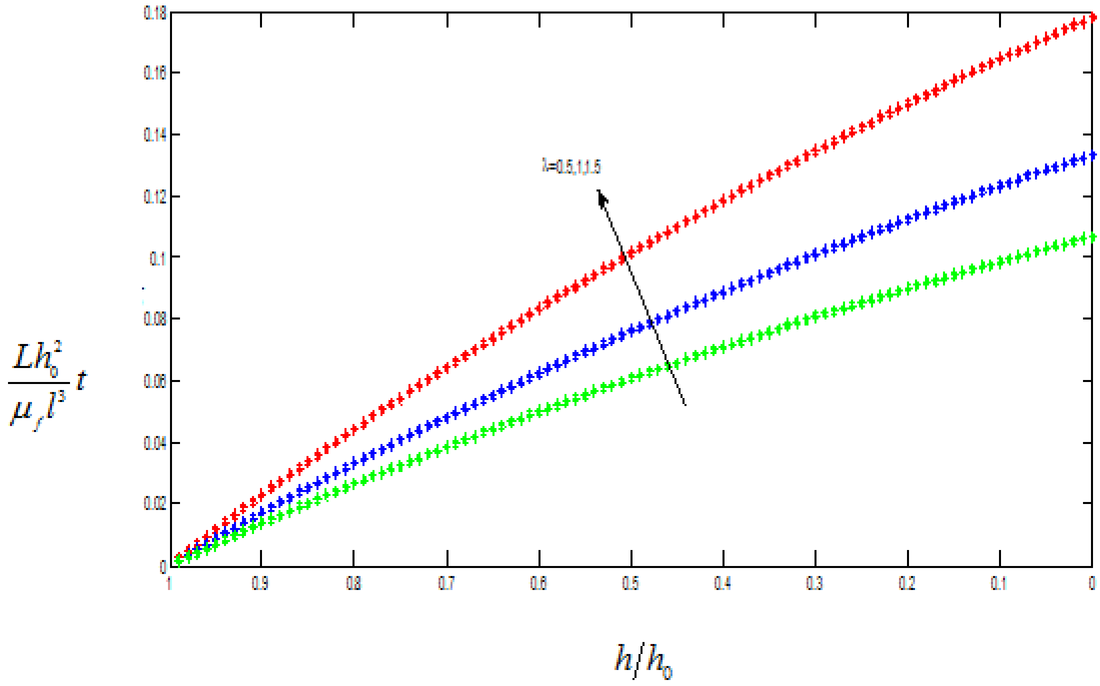

Fig.4. Thickness - time relation for different values of λ_1 ***with*** $\frac{K}{\alpha h_0} = 0.5$

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