Entropy Generation in Couette Flow Through a Deformable Porous Channel

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Abstract

The present study examines the entropy generation on Couette flow of a viscous fluid in parallel plates filled with deformable porous medium. The fluid is injected into the porous channel perpendicular to the lower wall with a constant velocity and is sucked out of the upper wall with the same velocity. The coupled phenomenon of the fluid flow and solid deformation in the porous medium is taken into consideration. The exact expressions for the velocity of fluid, solid displacement, and temperature distribution are found analytically. The effect of pertinent parameters on the fluid velocity, solid displacement, and temperature profiles are discussed in detail. In the deformable porous layer, it is noticed that the velocity of fluid, solid displacement, and temperature distribution are decreases with increasing the suction/injection velocity parameter. The results obtained for the present flow characteristic reveal several interesting behaviors that warrant further study on the deformable porous media. Furthermore, the significance of drag and the volume fraction on entropy generation number and Bejan number are discussed with the help of graphs.

Keywords: Couette flow; deformable porous layer; suction/injection; entropy generation; Bejan number.

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1 Introduction

Viscous flow through deformable porous material along with coupled fluid movements is studied widely by many researchers using analytical and numerical techniques. It has many significant applications such as flow through packed beds and ion-exchange beds, energy extraction from the geothermal regions, solid filtration from liquids. The fluid flows through deformable porous materials are driven by the several biological applications.
like the study of soft tissue, articular cartilage, skin and arterial walls etc. Most of the research works were available in undeformable porous media. Further the work done on deformable porous media is very limited. The coupled phenomenon of fluid flow and solid deformation in permeable materials is classical problems in the fields of geomechanics and biomechanics. The analysis of hemodynamic effect of the endothelial glycocalyx is an important application for interaction of free flow and deformable porous media. In sight of these applications, Terzaghi [1] initiated the study of flow through deformable porous materials. Biot [2] extended the work by considering soil consolidation and acoustic propagation. Atkin [3] and Bowen [4] presented some significant results to the theory of mixture. Later, Jayaraman [5] discussed water transport through the artery wall. Mow et al. [6] analyzed fluid flow with mechanical properties of articular cartilage. Barry et al. [7] investigated fluid flow over a thin deformable porous layer. Klubertanz et al. [8] discussed multiphase flow in deformable porous media. Ranganatha and Siddagamma [9] investigated the flow of Newtonian fluid through a deformable porous channel walls. Wen et al. [10] investigated the characteristics of shear flows in deformable porous surface layer through cylindrical tube. Sreenadh et al. [11] analyzed the MHD free surface flow of a Jeffery fluid through a deformable porous media. Woods [14] studied thermodynamics of fluid systems. Second law analysis in heat transfer energy is explained by Bejan [15]. Paoletti et al. [16] presented calculation of energetic losses in compact heat exchanger passages. Bejan [17] also studied entropy generation through heat and fluid flow. Ajibade et al. [18] analyzed the entropy generation with effect of suction/injection. Makinde et al. [19] analyzed of inherent irreversibility in a variable viscosity of Couette flow through permeable walls with MHD effects. Ramana Murthy et al. [20] made second law analysis for Poiseuille flow of immiscible micropolar fluids in a channel. Rashidi et al. [21] analyzed entropy generation in MHD and slip flow over a rotating porous disk. Das et al. [22] discussed entropy generation in a rotating Couette flow with suction/injection. Vikaskumar et al. [23] investigated entropy generation in Poiseuille flow through a channel partially filled with a porous material. Rashidi et al. [24] studied entropy generation analysis for stagnation point flow through a porous medium over a permeable stretching surface.

Motivated by the above studies, the present paper deals with the entropy generation in Couette flow with suction and injection through a deformable porous channel. The expressions for the fluid velocity, solid displacement and temperature distribution are found analytically. The effect of various physical parameters on flow characteristics are analyzed through graphs and tables.

2 Flow geometry and governing equations

Consider the Couette flow of a viscous fluid bounded by rigid walls through a deformable porous medium. The lower impermeable wall is stationary whereas the upper one is moving with constant velocity $U_0$. The width of the channel is taken as $h$. The fluid is injected into the porous channel perpendicular to the lower wall with a constant velocity $V$ and is sucked out of the upper wall with same velocity $V$. The fluid velocity and the displacement in the porous region are assumed respectively as $(v, 0, 0)$ and $(u, 0, 0)$. The governing equations are

$$
\mu \frac{\partial^2 u}{\partial y^2} - (1 - \phi) \frac{\partial p}{\partial x} + K_v = 0
$$

(1)

$$
\rho^f V \frac{\partial v}{\partial y} = \rho^f g_x + 2\mu_0 \frac{\partial^2 v}{\partial y^2} - \phi \frac{\partial p}{\partial x} - K_v
$$

(2)

$$
K_0 \frac{\partial^2 T}{\partial y^2} + 2\mu_u \left(\frac{\partial v}{\partial y}\right)^2 + Q_0 = 0
$$

(3)
where \( u \) is the solid displacement and \( v \) is the fluid velocity component in the direction. The following non-dimensional quantities are:

\[
y^* = \frac{y}{h}, \quad v^* = \frac{v}{U}, \quad \theta^* = \frac{T - T_0}{T_w - T_0}, \quad p^* = \frac{hP}{\mu a U}, \quad x^* = \frac{x}{h}, \quad u^* = \frac{u}{\mu}, \quad \delta = \frac{Kh}{2}, \quad P = \frac{\partial p}{\partial x},
\]

\[
\beta = \frac{Q_0 h^2}{\kappa_0 (T_w - T_0)}, \quad \text{Re} = \frac{U h}{\nu}, \quad Fr = \frac{U^2}{g h}, \quad Br = \frac{2 \mu U^2}{\kappa_0 (T_w - T_0)}, \quad g_y = \frac{\alpha g_x}{m} = \frac{T_1 - T_0}{T_w - T_0}.
\]

The equations (1) - (4) reduces to the following form. The asterisks (*) are neglected hereafter.

\[
d^2 u \quad dy^2 - (1 - \phi)P + \delta v = 0 \quad (5)
\]

\[
V \text{Re} \frac{dv}{dy} = \frac{Re}{Fr} + \frac{d^2 v}{dy^2} - \phi P - \delta v \quad (6)
\]

\[
\frac{d^2 \theta}{dy^2} + Br \left( \frac{dv}{dy} \right)^2 + \beta = 0 \quad (7)
\]

\[
\frac{dp}{dy} = \frac{Re}{Fr} \quad (8)
\]

The boundary conditions are

\[
\text{At} \quad y = 0 : u = 0, \quad v = 0, \quad \theta = 1 \quad (9)
\]

\[
\text{At} \quad y = 1 : u = 0, \quad v = U_0, \quad \theta = 1 + m \quad (10)
\]

### 3 Solution of the problem

The governing equations (5)-(8) are coupled differential equations that can be solved analytically by using the boundary conditions (9) and (10). The solid displacement, the fluid velocity and the temperature distribution are obtained as

\[
u(y) = \frac{P(1-\phi)y^2}{2} - \delta \left( \frac{c_1 v_{ov}}{a^2} + \frac{c_2 v_{ov}}{b^2} - \frac{\phi P y^2}{2} + \frac{\text{Re} y^2}{Fr} \right) + c_3 y + c_4
\]
\[ v(y) = c_1 e^{ay} + c_2 e^{by} - \frac{\phi P}{\delta} + \frac{\text{Re}}{\delta \text{Fr}} \] (12)

\[ \theta(y) = -\frac{\beta y^2}{2} - Br \left( \frac{c_1^2 e^{2ay}}{4} + \frac{c_2^2 e^{2by}}{4} + \frac{2abc_1 c_2 e^{(a+b)y}}{(a+b)^2} \right) + c_5 y + c_6 \] (13)

where

\[ a = \left( V \text{Re} + \sqrt{V^2 \text{Re}^2 + 4\delta} \right)/2, \quad b = \left( V \text{Re} - \sqrt{V^2 \text{Re}^2 + 4\delta} \right)/2, \quad P = \frac{\partial p}{\partial x} \]

\[ c_1 = \frac{1}{(e^{b} - e^{a})} \left[ -U_0 + \left( \frac{\phi P}{\delta} - \frac{\text{Re}}{\delta \text{Fr}} \right) (e^b - 1) \right], \quad c_2 = \frac{1}{(e^b - e^{a})} \left[ -U_0 + \left( \frac{\phi P}{\delta} - \frac{\text{Re}}{\delta \text{Fr}} \right) (e^a - 1) \right] \]

\[ c_3 = \frac{1}{(e^{b} - e^{a})} \delta \left[ \frac{c_1 e^a}{a^2} + \frac{c_2 e^b}{b^2} - \frac{\phi P}{\delta} + \frac{\text{Re}}{\delta \text{Fr}} \right] - c_4, \quad c_4 = \delta \left( \frac{c_1}{a} + \frac{c_2}{b} \right), \]

\[ c_5 = 1 + m + \frac{\beta}{2} + Br \left[ \frac{c_1^2 e^{2a}}{4} + \frac{c_2^2 e^{2b}}{4} + \frac{2abc_1 c_2 e^{(a+b)}}{(a+b)^2} \right] - c_6, \quad c_6 = 1 + Br \left( \frac{c_1^2}{4} + \frac{c_2^2}{4} + \frac{2abc_1 c_2}{(a+b)^2} \right) \]

4 Mass Flux

The mass flux is given by

\[ M = \int_0^1 v \, dy \] (14)

5 Skin friction

The skin friction at the two vertical walls \( y = 0 \) and \( y = 1 \) are given by

\[ \tau_{0,1} = \left( \frac{du}{dy} \right)_{y=0,1} \] (15)

6 Entropy Generation

The local volumetric rate of entropy generation for a conducting viscous fluid in a deformable vertical porous layer is

\[ E_G = \frac{K_0}{T_0^2} \left( \frac{dT}{dy} \right)^2 + \frac{2\mu_a}{T_0} \left( \frac{dv}{dy} \right)^2 \] (16)

The entropy generation equation (16) consists of two terms, the first term on the right hand side is the entropy generation due to the heat transfer across a finite temperature difference and the second term is the local entropy due to viscous dissipation.

The dimensionless entropy generation number may be determined by the following relationship:

\[ N_S = \frac{T_0^2 h^2 E_G}{K_0(T_w - T_0)^2} \] (17)
In terms of the dimensionless velocity and temperature, the entropy generation number becomes

$$N_S = \left( \frac{d \theta}{d y} \right)^2 + \frac{Br}{\Omega} \left( \frac{d v}{d y} \right)^2$$

(18)

where $Br = \frac{2 \mu U_0^2}{K_0 (T_y - T_0)}$ the Brinkman number and $\Omega = \frac{T_y - T_0}{T_0}$ the non-dimensional temperature.

In view of this Paoletti et al. [16] has defined an alternative irreversibility distribution parameter in terms of Bejan number as

$$Be = \frac{N_1}{N_S} = \frac{1}{1 + \Phi}$$

(19)

where $N_S = N_1 + N_2$ , $N_1 = \left( \frac{d \theta}{d y} \right)^2$ , $N_2 = \frac{Br}{\Omega} \left( \frac{d v}{d y} \right)^2$ and $\Phi = \frac{N_2}{N_1}$ is the irreversibility ratio.

7 Results and discussions

In this section, we analyzed the Couette flow through a horizontal deformable porous layer. The effects of various pertinent parameters such as the volume fraction of the fluid $\phi$ , drag $\delta$ , Brinkman number $Br$ , suction velocity $V$ and heat source parameter $\beta$ on solid displacement, fluid velocity, temperature distribution, entropy generation and Bejan number profiles are discussed through graphs. The numerical computations are carried out by using Matlab software. In this study $P = -8$ , $\phi = 0.6$ , $\delta = 1$ , $\beta = 1$ , $Br = 1$ , $V = 0.5$ , $m = 1$ , $Re = 1$ , $Fr = 1$ and $U_0 = 1$ are used for numerical computation. The variation of solid displacement $u$ with $y$ is calculated from Eq. (11) for different values of $\delta$ , $U_0$ , $\phi$ and $V$ which are represented in figs. 2 - 5. From fig. 2, it is noticed that, an increase in the drag increases the solid displacement in the porous channel.

Figure 3 illustrates that that increasing upper plate velocity causes more solid displacement in the porous channel. It is noticed that the solid displacement reduces with the increasing $\phi$ and $\nu$. That is, the increase in the volume fraction of the fluid and suction/injection velocity decreases the solid displacement in the porous channel which is presented in figs. 4 and 5 respectively. The variation of fluid velocity $v$ with $y$ is calculated from Eq. (12) for various values of $\delta$ , $U_0$ , $P$ , $\nu$ and $V$ is shown in figs. 6 - 10 respectively. It is found that the velocity increases with the increasing $\phi$ , $U_0$ , and $P$. This shows that, the increase in the movement of the upper plate results considerable increase is the fluid velocity in the porous layer along with the favorable pressure gradient. The same phenomenon is noticed even when the volume fraction of the fluid increases in the deformable porous channel. It is found that the velocity reduces with the growing values of $\delta$ and $V$. That is, the fluid velocity gets reduced due to an increase in the drag and suction/injection.

The variation of temperature $\theta$ with $y$ is calculated from Eq. (13) for different values of $U_0$ , $Br$ , $m$ , $\beta$ , $\phi$ and $\nu$ which are shown in figs. 11 - 17. From fig. 11, it is noticed that the temperature profiles increases with increasing upper plate velocity. The temperature increases with increasing Brinkman number $Br$ in porous channel is represented in fig. 12. That is the larger values of Brinkman number $Br$ are indicative of larger frictional heating system so increase in temperature. The effect of $m$ on temperature is shown in fig. 13. The increase in $m$ enhances the temperature in the deformable porous channel i.e., $m = 0$ implies both the plates are maintained at constant temperature, $m = 1$ and $m = 2$ represents heating of the plates $y = 0$. Hence, the temperature increases with increase in due to increase in convection. Figure 14 illustrates that the temperature increases with increasing heat source parameter $\beta$. It is observed from fig. 15 that the increase in volume fraction of the fluid increases the temperature in the deformable porous channel. The decrease in temperature with increasing drag and suction/injection velocity are presented in figs. 16 and 17 respectively.

The effects of the volume fraction of the fluid $\phi$ , viscous dissipation parameter or group parameter $Br/\Omega$ , Brinkmen number $Br$ , drag $\delta$ and suction velocity $V$ on the entropy generation number $N_S$ are shown in figs. 18-22 respectively. In this study $P = -1$ , $\phi = 0.6$ , $\delta = 1$ , $\beta = 1$ , $Re = 1$ , $Fr = 1$ , $m = 1$ , $U_0 = 1$ , $V = 0.5$ , $(Br/\Omega) = 1$
and $Br = 1$ are used for numerical computation. From fig. 18, it is noticed that the entropy generation number $Ns$ enhances near the fixed plate $y = 0$ while it declines near the moving plate $y = 1$ with increase in volume fraction of the fluid $\phi$. Group parameter is an important dimensionless number for entropy generation rate analysis. Figure 19, shows that the entropy generation number increases with growing values of group parameter. The magnitude of entropy generation number takes higher values for larger values of group parameter, since the group parameter determines the relative importance of viscous effects. The increase in entropy generation number with increase in Brinkman number is depicted in fig. 20. The increase in $Br$ enhances fluid frictional heating in the system which enhances the entropy generation. The influence of $Br$ on entropy generation is more pronounced near the channel walls while the effect lessens towards the centerline from both porous plates. It is observed that there exists a fluid section within the channel where the influence of $Br$ on entropy is absent. Figure 21 reveals that the entropy generation number decreases near the stationary plate $y = 0$ where it increases near the moving plate $y = 1$ with increasing drag parameter $\delta$. It is seen from fig. 22 that the entropy generation number decreases near the stationary plate $y = 0$ and increases near the moving plate $y = 1$ with increase suction/injection velocity $V$.

Bejan number profiles for various values of $Br/\Omega$ and $Br$ are presented in figs. 23 - 24 respectively. Figure 23 reveals that the increase in group parameter decreases Bejan number. This figure displays that for moderately small values of $Br/\Omega$, heat transfer irreversibility dominates entropy generation near the stationary porous wall but the dominance is gradually being ceded to the fluid fraction irreversibility as $Br/\Omega$ increases. Near the moving porous wall, fluid fraction irreversibility dominates the entropy generation for all values of the group parameter. It is observed from fig. 24, that the Bejan number increases near the plate $y = 0$ and $y = 1$ decreases near the plate with increase in Brinkman number. That is for relatively small values of $Br$, heat transfer irreversibility dominates entropy generation near the stationary porous wall while fluid friction irreversibility dominates from the centerline to the moving porous wall. For large values of $Br$, heat transfer irreversibility dominates entropy generation near porous walls. The variation of Nusslet number along with volume fraction of the fluid for different values of drag parameter is shown in fig.25. It is noticed that the enhancement of drag parameter reduces the Nusselt number.

From Table I, It is found that the skin friction at both the walls increases with increasing the upper plate velocity $U_0$. We also observed that the skin friction at the stationary plate increases with an increase in $\phi$ whereas it decreases with increasing $\delta$. Further an opposite behavior is noticed at moving plate (upper) of the porous channel.

From Table II, It is noticed that the increase in the volume fraction of the fluid $\phi$ or upper plate velocity $U_0$ increases the mass flux in the deformable porous channel. It is observed that the mass flux in the deformable porous channel decreases with increasing drag. Further the mass flux in the porous channel decreases with increasing suction/injection velocity $V$.

8 Conclusion

In this article, entropy generation analysis for Couette flow through a deformable porous channel is examined. The expressions for the fluid velocity, solid displacement and temperature distribution are obtained analytically. The effects of volume fraction, drag, upper plate velocity and suction/injection velocity on mass flux are studied through tables. The influence of suction/injection velocity is significant on solid displacement, fluid velocity and temperature distribution which transitively affects the entropy generation with in the deformable porous channel. Some of the important observations are summarized as follows

- The increase in upper plate velocity causes more solid displacement in the deformable porous channel. Solid displacement enhances with increasing drag where opposite behavior is observed in the case of increasing volume fraction of the fluid and suction/injection velocity. 
- It is clear that the fluid velocity increases with increasing $\phi, U_0$ and $P$ where the fluid velocity reduced due
to an increase in the drag and suction/injection velocity.

- It is noticed that the temperature increases with increase in $U_0, Br, m, \beta$ and $\phi$ where as an opposite behavior is observed with increase in $\delta$ and $V$.

- It is found that the entropy generation number decreases near the stationary plate $y = 0$ and increases near the moving plate $y = 1$ with increase $\delta$ suction/injection velocity.

- It is observed that the mass flux increases with increase in $\phi$ or $U_0$ where as it decreases with increasing drag or the suction/injection velocity.

Fig. 2 Displacement profiles for different values of $\delta$.

Fig. 3 Displacement profiles for different values of $U_0$. 
Fig. 4 Displacement profiles for different values of $\phi$

Fig. 5 Displacement profiles for different values of $V$

Fig. 6 Velocity profiles for different values of $\phi$

Fig. 7 Velocity profiles for different values of $U_0$
Fig. 8 Velocity profiles for different values of $P$

Fig. 9 Velocity profiles for different values of $\delta$

Fig. 10 Velocity profiles for different values of $V$

Fig. 11 Temperature profiles for different values of $U_0$
Fig. 12 Temperature profiles for different values of $Br$

Fig. 13 Temperature profiles for different values of $m$

Fig. 14 Temperature profiles for different values of $\beta$

Fig. 15 Temperature profiles for different values of $\phi$
Fig. 16 Temperature profiles for different values of $\delta$

Fig. 17 Temperature profiles for different values of $V$

Fig. 18 Entropy generation number profiles for different values of $\phi$

Fig. 19 Entropy generation number profiles for different values of $Br/\Omega$
Fig. 20 Entropy generation number profiles for different values of $Br$

Fig. 21 Entropy generation number profiles for different values of $\delta$

Fig. 22 Entropy generation number profiles for different values of $V$

Fig. 23 Bejan number profiles for different values of $Br/\Omega$
Fig. 24 Bejan number profiles for different values of $Br$

Fig. 25 Variation of Nusslet number along with $\phi$ for different values of $\delta$

Table 1 Effects of $\phi$, $\delta$ and $U_0$ on skin friction $\tau_0$, $\tau_1$, for fixed values of $P = -8$, $Re = 1$, $V = 0.5$ and $Fr = 1$

| $\phi$ | $\delta$ | $U_0$ | $\tau_0$ | $\tau_1$ |
|--------|--------|------|--------|--------|
| 0.2    | 1      | 1    | 1.7616 | 0.2830 |
| 0.4    | 1      | 1    | 2.4418 | -0.5161|
| 0.6    | 1      | 1    | 3.1219 | -1.3151|
| 0.8    | 1      | 1    | 3.8021 | -2.1141|
| 0.6    | 1.5    | 1    | 3.1219 | -1.3151|
| 0.6    | 2      | 1    | 2.8678 | -0.8345|
| 0.6    | 2.5    | 1    | 2.7568 | -0.6167|
| 0.6    | 4      | 1    | 3.1219 | -1.3151|
| 0.6    | 4      | 2    | 3.7782 | 0.2663 |
| 0.6    | 4      | 3    | 4.4345 | 1.8477 |
| 0.6    | 4      | 4    | 5.0907 | 3.4290 |
Table 2 Effect of $\phi$, $\delta$, $V$, and $U_0$ on Mass flux for fixed values of $P = -8$, $Re = 1$ and $Fr = 1$ .

| $\phi$ | $\delta$ | $V$ | $U_0$ | $M$   |
|--------|----------|-----|-------|-------|
| 0.2    | 1        | 0.5 | 1     | 0.6214|
| 0.4    | 1        | 0.5 | 1     | 0.7422|
| 0.6    | 1        | 0.5 | 1     | 0.8630|
| 0.8    | 1        | 0.5 | 1     | 0.9837|
| 0.6    | 1.5      | 0.5 | 1     | 0.8295|
| 0.6    | 2        | 0.5 | 1     | 0.7989|
| 0.6    | 2.5      | 0.5 | 1     | 0.7706|
| 0.6    | 1        | 1   | 1     | 0.8223|
| 0.6    | 1        | 2   | 1     | 0.7388|
| 0.6    | 1        | 3   | 1     | 0.6581|
| 0.6    | 1        | 4   | 1     | 0.5849|
| 0.6    | 1        | 0.5 | 2     | 1.2881|
| 0.6    | 1        | 0.5 | 3     | 1.7132|
| 0.6    | 1        | 0.5 | 4     | 2.1383|

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