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Entropy generation in thermal radiative oscillatory MHD couette flow in the influence of heat source

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Abstract. Entropy generation and their minimization for magnetohydrodynamic oscillatory couette flow through a vertical channel, soaked with a porous medium in the existence of heat source and thermal radiation has been deliberated. In the present analysis, flow governing equations are elucidated and extricated with the help of analytical technique for the fluid velocity profile, temperature field, irreversibility distribution and Bejan number. Also, the numerical value of dimensionless shearing stress and heat transfer coefficient are obtained and presented through tables with reference to flow governing parameters. It has noticed that entropy generation can be regulated or minimized with the change in the applied magnetic field and thermal radiation, and this result is useful in several thermodynamic industries and engineering field for attaining the high performance of devices with minimum heat loss.

Keywords: Entropy Generation, Bejan number, Heat Source, MHD, Thermal Radiation, Heat Source, Couette Flow

1. Introduction

The Entropy generation in convective Magnetohydrodynamic Couette flows through the porous material has a wide range of applications in numerous disciplines, like cooling of electronic components of heat-generating devices, ground hydrology, storage of nuclear wastes, polymer industries, petroleum industries, purification of crude oil, and many more. Katagiri [1], Drake [2], Gupta and Arora [3], Singh and Ram [4] are the few researchers who made significant contributions in this area. Sengupta and Ray [5] considered the oscillatory Couette flow through the rotating channel in the impact of the magnetic field.

Magnetohydrodynamic oscillatory flow through a horizontal channel was discussed by Makinde and Mhone [6] by considering the heat source effect. Further, Singh and Okwoya [7] examined the effect of the uniform magnetic field during the flow-through channel. The effect of radiation due to natural convective couette flow through a parallel plate channel was discussed by Narhari [8]. Later, Raju and Verma [9] expanded the work with periodic wall temperature. In the recent years, Chand et al. [10], Pal and Talukdar [11], Devika et al. [12], Gul et al. [13], Jha et al. [14], Sharma and Choudhary [15] are the few researchers who have also extended the earlier research work and explored the oscillatory flow with different geometrical conditions. In the same time, Narayana et. al. [16] explained the MHD oscillatory flow in asymmetry channel with the heat source and mass transfer effect. Falade et. al. [17] considered the MHD oscillatory flow through the vertical channel with suction and injection.
In the literature, we have noticed that MHD oscillatory flow through the porous material occupied channel has been discussed extensively by several researchers due to its useful practical applications in medical (arterial blood flow) and industrial fields.

In the present study, we have made an attempt to fill the literature gap and analyze the MHD free convective, oscillatory couette flow through a vertical channel with the impact of thermal radiation, heat source and strong magnetic field, and also explored the total entropy generation/irreversibility and their minimization with reference to the flow parameters. The main concern of the present analysis is to find the suitable parameters that can optimize the irreversibilities in the specified flow conditions.

2. Mathematical Formulation and Physical Model

In the present paper, we have considered the time-dependent natural convective oscillatory flow due to viscous incompressible electrically and thermally conducting fluid through a channel.

This channel is occupied with a saturated porous material and bounded by non-conducting vertical plates of infinite length in the existence of heat source and magnetic field. The magnetic field $B_0$ is working in the normal direction of the flow. Suppose, the plate at $y^* = 0$ starts suddenly with the velocity:

$$U^*(t^*) = U_0 (1 + \varepsilon e^{i\omega t^*}).$$

and its temperature fluctuates with time which is denoted by $T_m$. Where $U_0$ is the mean velocity, $\varepsilon << 1$ is the amplitude of the velocity variation, $\omega$ represents the frequency of oscillations and $t^*$ is given for time.

The plate lying in the plane $y^* = d$ is considered stationary with the temperature $T^* = T_s$ as displayed in Fig. 1. In the present flow scheme, the flow variables do not depend on $x^*$, therefore the derivative $\frac{d(\cdot)}{dx^*} = 0$.

Under the discussed conditions, the governing equations for present fluid flow configurations are defined as:

$$\frac{\partial u^*}{\partial t^*} = \frac{\partial U^*}{\partial t^*} + \nu \frac{\partial^2 u^*}{\partial y^*^2} + g\beta(T^* - T_s)\left(U^* - U_s\right) - \frac{\sigma B_0^2}{\rho}(u^* - U^*),$$

$$\frac{\partial T^*}{\partial t^*} = \frac{\kappa}{\rho C_p}\left(\frac{\partial^2 T^*}{\partial y^*^2}\right) + \frac{\mu}{\rho C_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \frac{Q}{\rho C_p}\left(T^* - T_s\right) - \frac{1}{\rho C_p}\left(\frac{\partial q^*}{\partial y^*}\right)^2 + \frac{\sigma B_0^2}{\rho C_p}(u^* - U^*)^2.\tag{3}$$

The consistent boundary conditions are:

$$y^* = 0: \quad u^* = U^*(t^*) = U_0 (1 + \varepsilon e^{i\omega t^*}), \quad T^* = T_m + \varepsilon (T_m - T_s) e^{i\omega t^*};$$

$$y^* = d: \quad u^* = 0, \quad T^* = T_s;$$

The flux of radiative heat is defined by Cogley et. al. [18], which is written as
\[ \frac{\partial T}{\partial y} = 4(T' - T_s) \int_0^\infty K_{M i} \left( \frac{\partial T_{M i}}{\partial T} \right)_W d\lambda = 4T' \left( T' - T_s \right), \] (5)

where \( T' = \frac{1}{\kappa} K_{M i} \left( \frac{\partial T_{M i}}{\partial T} \right)_W d\lambda. \)

In the above-discussed relations, \( u' \) represent velocity component in the \( x' \) direction. \( \beta \) denotes the thermal expansion, \( g \) for the gravity \( T' \) represents fluid temperature, \( T_m \) is the temperature of moving plate, \( T_s \) denotes the temperature of stationary plate, \( \rho \) stands for fluid density, \( \nu \) denotes the kinematic viscosity, \( K' \) defines the permeability parameter, \( \sigma \) and \( \kappa \) show the thermal and electrical conductivity, and \( Q' \) explain heat source.

### 3. Method and Solution

The dimensionless parameters are listed as:

\[ y = \frac{y'}{d}, \quad u = \frac{u'}{U_0}, \quad t = \frac{t'}{d'}, \quad \omega = \frac{\omega d^2}{\nu}, \quad U = \frac{U'}{U_0}, \quad M = \frac{\sigma B_0^2 d^2}{\rho \nu}, \quad T = \frac{T' - T_s}{T_m - T_s}, \quad \text{Pr} = \frac{\mu C_p}{\kappa}, \]

\[ Gr = \frac{g \beta d^2 (T_m - T_s)}{\nu U_0}, \quad K = \frac{K'}{d^2}, \quad Ec = \frac{U_0^2}{C_p (T_m - T_s)}, \quad Q = \frac{Q' d^2}{\mu C_p}, \quad R = \frac{4T' d^2}{\mu C_p}. \] (6)

Using (6), the equations (2) and (3) are reduced to:

\[ \frac{\partial u}{\partial \tau} = \frac{dU}{dt} + \frac{\partial^2 u}{\partial y^2} + GrT - \left( M + \frac{1}{K} \right) (u - U), \] (7)

\[ \frac{\partial T}{\partial \tau} = \frac{1}{Pr} \frac{\partial^2 T}{\partial y^2} + Ec \left( \frac{\partial u}{\partial y} \right)^2 + (Q - R)T + EcM (u - U)^2. \] (8)

The dimensionless boundary conditions are:

\[ at: \quad y = 0; \quad u = U = 1 + \varepsilon e^{i\omega t}, \quad T = 1 + \varepsilon e^{i\omega t}. \] (9)

\[ at: \quad y = 1; \quad u = 0, \quad T = 0. \]

Where \( Gr \) stand for buoyancy force, \( M \) shows the magnetic field, \( Ec \) for the dissipation parameter, \( K \) represents the permeability, \( Pr \) the Prandtl number, \( u \) represents the dimensional velocity, \( U \) stand for the velocity of moving plate, \( Q \) is the heat source and \( R \) explains the thermal radiation.

The solution of equations (7) and (8) are not possible at this stage, due to non-linear and coupled nature. For the solution of these equations, we have taken the velocity and temperature distribution in the vicinity of the plate (Raju and Verma, [9]) as:

\[ F(y, \tau) = F_0(y) + e^{i\omega \tau} F_1(y) + O(\varepsilon^2), \] (10)

Where \( F \) stand for the \( u \) and \( T \) respectively. Substituting (10) in the equations (7) to (9) and comparing the like terms, the succeeding differential equations with the reduced boundary conditions are obtained as:

#### 3.1. Zeroth order equations

\[ \frac{d^2 u_0}{dy^2} - \left( M + \frac{1}{K} \right) u_0 = -GrT_0 - \left( M + \frac{1}{K} \right), \] (11)

\[ \frac{1}{Pr} \frac{d^2 T_0}{dy^2} + (Q - R)T_0 = -Ec \left( \frac{du_0}{dy} \right)^2 - EcM (1 - u_0)^2. \] (12)

#### 3.2. First-order equations

\[ \frac{d^2 u_1}{dy^2} - \left( M + \frac{1}{K} + i\omega \right) u_1 = -GrT_1 - \left( M + \frac{1}{K} + i\omega \right), \] (13)
\[ \frac{1}{Pr} \frac{d^2 T}{dy^2} + (Q - R - i\omega)T_i = -2Ec \left( \frac{du_0}{dy} \right) \left( \frac{du_1}{dy} \right) - 2EcM \left( 1 + u_0u_i - u_0 - u_i \right), \] (14)

The reduced form of boundary conditions are:
\[ y = 0; \quad u_0 = 1, \quad u_i = 1, \quad T_0 = 1, \quad T_i = 1; \]
\[ y = 1; \quad u_0 = 0, \quad u_i = 0, \quad T_0 = 0, \quad T_i = 0; \] (15)

The equations (11) to (14) are still coupled ordinary second-order differential equations. Since Eckert number \( Ec \ll 1 \) for the incompressible fluid flow, therefore, \( u_0, u_i, T_0, T_i \) can be expressed as:
\[ F_0(y) = F_{00}(y) + Ec F_{01}(y) + O(Ec^2); \]
\[ F_1(y) = F_{10}(y) + Ec F_{11}(y) + O(Ec^2). \] (16)

Now, substituting (16) into (11) to (14) and comparing the coefficient of Eckert number \( Ec \) and desertsing the term of \( O(Ec^2) \), we have:

### 3.3. Zeroth order equations
\[ \frac{d^2 u_{00}}{dy^2} - \left( M + \frac{1}{K} \right) u_{00} = -GrT_{00} - \left( M + \frac{1}{K} \right), \] (17)
\[ \frac{d^2 u_{01}}{dy^2} - \left( M + \frac{1}{K} + i\omega \right) u_{01} = -GrT_{01} - \left( M + \frac{1}{K} + i\omega \right), \] (18)
\[ \frac{1}{Pr} \frac{d^2 T_{00}}{dy^2} + (Q - R)T_{00} = 0, \] (19)
\[ \frac{1}{Pr} \frac{d^2 T_{01}}{dy^2} + (Q - R - i\omega)T_{01} = 0, \] (20)

### 3.4. First-order equations
\[ \frac{d^2 u_{10}}{dy^2} - \left( M + \frac{1}{K} \right) u_{10} = -GrT_{10}, \] (21)
\[ \frac{d^2 u_{11}}{dy^2} - \left( M + \frac{1}{K} + i\omega \right) u_{11} = -GrT_{11}, \] (22)
\[ \frac{1}{Pr} \frac{d^2 T_{10}}{dy^2} + (Q - R)T_{10} = -\left( \frac{du_{00}}{dy} \right)^2 - M \left( 1 - u_{00} \right)^2, \] (23)
\[ \frac{1}{Pr} \frac{d^2 T_{11}}{dy^2} + (Q - R - i\omega)T_{11} = -2 \left( \frac{du_{00}}{dy} \right) \left( \frac{du_{10}}{dy} \right) - 2M \left( 1 + u_0u_i - u_0 - u_i \right), \] (24)

The reduced form of boundary conditions are:
\[ y = 0; \quad u_{00} = 1, \quad u_{01} = 0, \quad u_{10} = 1, \quad T_{00} = 1, \quad T_{01} = 0, \quad T_{10} = 1, \quad T_{11} = 0; \]
\[ y = 1; \quad u_{00} = 0, \quad u_{01} = 0, \quad u_{10} = 0, \quad u_{11} = 0, \quad T_{00} = 0, \quad T_{01} = 0, \quad T_{10} = 0, \quad T_{11} = 0; \] (25)

Equations (17) to (24) are the set of second-order coupled differential equations. These equations are solved by the usual algebraic method with the help of boundary conditions (25).

### 4. Coefficient of Skin Friction
The dimensionless form of the coefficient of skin friction at both the plates of the channel is given as:

#### 4.1. Coefficient of skin friction at the moving plate for \( y = 0 \)
\[ C_e = \left( \frac{\tau_y}{\rho U_0^2} \right)_{y=0} = \frac{2}{\text{Re}} \left( \frac{\partial u}{\partial y} \right)_{y=0} = \frac{2}{\text{Re}} \left\{ \left( \frac{\partial u}{\partial y} \right)_{y=0} + \varepsilon e^{i\omega t} \left( \frac{\partial u}{\partial y} \right)_{y=0} \right\}, \]  
\[ (26) \]

4.2. Coefficient of skin friction at the stationary plate for \( y=1 \)

\[ C_f = \left( \frac{\tau_y}{\rho U_0^2} \right)_{y=d} = \frac{2}{\text{Re}} \left( \frac{\partial u}{\partial y} \right)_{y=1} = \frac{2}{\text{Re}} \left\{ \left( \frac{\partial u}{\partial y} \right)_{y=1} + \varepsilon e^{i\omega t} \left( \frac{\partial u}{\partial y} \right)_{y=1} \right\}, \]  
\[ (27) \]

Where shear stress \( \tau_y \) at the wall of plates (Moving and Stationery) are presented by \( \tau_y = \mu \left( \frac{\partial u}{\partial y} \right)_{y=0} \) and \( \tau_y = \mu \left( \frac{\partial u}{\partial y} \right)_{y=d} \) respectively.

5. Nusselt Number/ Coefficient of Heat Transfer

The rate of heat transfer at the wall of the plates of the channel is given as:

5.1. Coefficient of heat transfer (Nusselt number) at the moving plate for \( y=0 \)

\[ N_{u_0} = \left( \frac{\partial T}{\partial y} \right)_{y=0} = \left\{ \left( \frac{\partial T}{\partial y} \right)_{y=0} + \varepsilon e^{i\omega t} \left( \frac{\partial T}{\partial y} \right)_{y=0} \right\}, \]  
\[ (28) \]

5.2. Coefficient of heat transfer (Nusselt number) at the stationary plate for \( y=1 \)

\[ N_{u_1} = \left( \frac{\partial T}{\partial y} \right)_{y=1} = \left\{ \left( \frac{\partial T}{\partial y} \right)_{y=1} + \varepsilon e^{i\omega t} \left( \frac{\partial T}{\partial y} \right)_{y=1} \right\}, \]  
\[ (29) \]

Where \( q_{o,0} = -\kappa \left( \frac{\partial T^*}{\partial y} \right)_{y=0} \) and \( q_{o,1} = -\kappa \left( \frac{\partial T^*}{\partial y} \right)_{y=1} \) are the coefficient of heat transfer for both the plates respectively.

6. Entropy Generation

The work efficiency of the thermal systems or devices needs to be maintained in all the thermal industries, where entropy generation is encountered due to friction and heat transfer. In the thermodynamics, entropy generation is referred to as irreversibility distribution. In the present case, the volumetric rate of entropy generation is given due to the magnetic field, thermal radiation and friction. Following Wood [19] and Bejan [20], the entropy generation is given as:

\[ S_{gen}^* = \kappa \left( \frac{\partial T^*}{\partial y} \right)^2 + \mu \left( \frac{\partial u^*}{\partial y} \right)^2 + \left( \frac{u^* - U^*}{K^*} \right)^2 + \sigma B_0^2 \left( \frac{u^* - U^*}{T_0^*} \right)^2, \]  
\[ (30) \]

Where \( T_0^* \) denotes the reference temperature and \( S_{gen}^* \) the dimensional entropy generation term. Using (30), the entropy generation in dimensionless form as:
\[ N_s = \frac{S_{enm}}{S_0} = \left[ \frac{dT}{dy} \right]^2 + \text{Pr} \text{Ec}T_0 \left\{ \frac{du}{dy} \right\}^2 + \frac{(u - U)^2}{K} + \text{Pr} \text{Ec}T_0 M \left( u - U \right)^2 \right]. \quad (31) \]

Where \( T_0 = \frac{T_0}{(T_m - T)} \) is the dimensionless temperature and \( S_0 = \frac{\kappa}{T_0^2 d^2} \).

In equation (31), the irreversibility due to friction, magnetic field and heat transfer has been obtained and presented as:

\[ N_H = \left( \frac{dT}{dy} \right)^2, \quad (32) \]

\[ N_F = \text{Pr} \text{Ec}T_0 \left\{ \frac{du}{dy} \right\}^2 + \frac{(u - U)^2}{K}, \quad (33) \]

\[ N_M = \text{Pr} \text{Ec}T_0 M \left( u - U \right)^2, \quad (34) \]

The Bejan number is also defined for the stated flow configuration, and it is expressed as

\[ Be = \frac{N_H}{N_s} = \frac{\text{Entropy generation due to heat transfer}}{\text{Total entropy generation (friction + heat transfer + magnetic field)}} \]

7. Results and Discussion

The fluid velocity profile, temperature field, entropy generation and Bejan number are obtained for the distinct flow parameters by using MATLAB software. The positive values of buoyancy force parameter (\( Gr > 0 \)) represent the cooling of plates while negative values (\( Gr < 0 \)) stand for heating of plates.

**Velocity distribution profiles**

The velocity distribution profiles for the various physical parameter are shown in Figure. 2 to Figure. 8. Figure 2 depicts that the cooling of plates accelerates the fluid motion, and increase in the magnetic field enhance the fluid motion when the plates are hot as noticed from Figure 3.

Figure 4 reflects that an upsurge in the Eckert number promotes the fluid flow for \( (Gr < 0) \), whereas adverse behavior is seen for the cooling of plates \( (Gr > 0) \). Figure 5 depicts the effect of permeability parameter with fluid velocity, and it is observed that fluid flow reduces with the improvement in the permeability parameter.

The rise in the Prandtl number, heat source, and thermal radiation, deaccelerates the fluid flow when plates are taken hot for \( (Gr < 0) \), and boosts the fluid motion when plates are cool \( (Gr > 0) \) as presented through Figures 6, 7 and 8.
**Figure 2.** Velocity distribution profile for $M = 2.0, Ec = 0.01, K = 0.5, Pr = 1.0, Q = 0.5,$ and $R = 1.0$

*Graph showing velocity distribution profile for different values of $Gr$. The graph includes curves for $Gr = -5.0, 0, 5.0, 10.0$. The x-axis represents $y$, and the y-axis represents $u(y,t)$. The figure includes a legend with curves for $Gr = -5.0$ and $Gr = 15.0$.*

**Figure 3.** Velocity distribution profile for $Ec = 0.01, K = 0.5, Pr = 1.0, Q = 0.5,$ and $R = 1.0$

*Graph showing velocity distribution profile for different values of $M$. The graph includes curves for $M = 2.0, 4.0, 6.0$, and $Gr = -5.0$ and $Gr = 15.0$. The x-axis represents $y$, and the y-axis represents $u(y,t)$. The figure includes a legend with curves for $Gr = -5.0$ and $Gr = 15.0$.*

**Figure 4.** Velocity distribution profile for $M = 2.0, K = 0.5, Pr = 1.0, Q = 0.5,$ and $R = 1.0$

*Graph showing velocity distribution profile for different values of $Ec$. The graph includes curves for $Ec = 0.01, 0.04, 0.10$, and $Gr = -5.0$ and $Gr = 5.0$. The x-axis represents $y$, and the y-axis represents $u(y,t)$. The figure includes a legend with curves for $Gr = -5.0$ and $Gr = 5.0$.***
Figure 5. Velocity distribution profile for $M = 2.0, Ec = 0.01$, $Pr = 1.0, Q = 0.5$, and $R = 1.0$.

Figure 6. Velocity distribution profile for $M = 2.0, Ec = 0.01$, $K = 0.5, Q = 0.5$, and $R = 1.0$.

Figure 7. Velocity distribution profile for $M = 2.0, Ec = 0.01$, $K = 0.5, Pr = 1.0$, and $R = 1.0$. 
Temperature distribution profiles

The temperature distribution profiles for the various physical parameter are shown in Figures 9 to 15. In Figures 9 to 11, we have noticed that fluid temperature declines, due to escalation in the buoyancy force, magnetic field and Eckert number, whereas fluid temperature props up with the increment in the permeability, Prandtl number, heat source and thermal radiation as reported from Figures 12 to 15.
Figure 10. Temperature distribution profile for $Ec = 0.01$, $K = 0.5$, $Pr = 4.0$, $Q = 0.5$, and $R = 1.0$

Figure 11. Temperature distribution profile for $M = 2.0$, $K = 0.5$, $Pr = 4.0$, $Q = 0.5$, and $R = 1.0$

Figure 12. Temperature distribution profile for $M = 2.0$, $Ec = 0.01$, $Pr = 4.0$, $Q = 0.5$, and $R = 1.0$
Figure 13. Temperature distribution profile for $M = 2.0$, 
$Ec = 0.01, K = 0.5, Q = 0.5$, and $R = 1.0$

Figure 14. Temperature distribution profile for $M = 2.0$, 
$Ec = 0.01, K = 0.5, Pr = 4.0$, and $R = 1.0$

Figure 15. Temperature distribution profile for $M = 2.0$, 
$Ec = 0.01, K = 0.5, Pr = 4.0$, and $Q = 0.5$
Entropy generation profiles
The irreversibility distributions in terms of entropy generations profiles are presented from Figures 16 to 23 for various flow governing parameters. From Figures 16 to 19, it is noticed that total entropy generation declines near the moving plate when the intensity of the applied magnetic field, heat source, thermal radiation and Prandtl number increase, although it props up with the increase of permeability and Eckert number as observed from Figure 20 and 21. The reverse effect is seen near the stationary plate as compared to the moving plate. It is also depicted that the rate of entropy generation near the moving plate for the heating case ($Gr < 0$) is higher than the cooling case ($Gr > 0$), while the adverse phenomenon is reported near the stationary plate as shown in Figure 22 and 23.

In the analysis of entropy generation profiles, it is found that external applied magnetic field and thermal radiation play an important role for regulating the entropy generation in the fluid slow system.

*Figure 16.* $Ns$ distribution profile for $Ec = 0.10$, $K = 0.5, Pr = 0.71, Q = 1.0$, and $R = 0.5$

*Figure 17.* $Ns$ distribution profile for $Ec = 0.10$, $K = 0.5, Pr = 0.71, M = 2.0$, and $R = 0.5
Figure 18. $N_s$ distribution profile for $Ec = 0.10,$ $K = 0.5, Pr = 0.71, M = 2.0,$ and $Q = 1.0$

Figure 19. $N_s$ distribution profile for $Ec = 0.10,$ $K = 0.5, R = 0.5, M = 2.0,$ and $Q = 1.0$

Figure 20. $N_s$ distribution profile for $Ec = 0.10,$ $Pr = 0.71, R = 0.5, M = 2.0,$ and $Q = 1.0$
Figure 21. $N_s$ distribution profile for $K = 0.5$, $Pr = 0.71$, $R = 0.5$, $M = 2.0$, and $Q = 1.0$.

Figure 22. $N_s$ distribution profile for $K = 0.5$, $Pr = 0.71$, $R = 0.5$, $M = 2.0$, $Q = 1.0$, and $Ec = 0.10$.

Figure 23. $N_s$ distribution profile for $K = 0.5$, $Pr = 0.71$, $R = 0.5$, $M = 2.0$, $Q = 1.0$, and $Ec = 0.10$. 
Bejan number profiles

In addition, the effect of the Bejan number is also illustrated from Figures 24 to 31. Figure 24 explains the effect of uniform magnetic with Bejan number, and it is seen that the improvement in the intensity of magnetic field gains the irreversibility ratio Bejan number in the vicinity of the moving plate, and shows the opposite effect at the stationary plate of the channel. The Bejan number profile declines with the improvement in the Prandtl number and radiation as depicted from Figure 25 and 26 for the value of $Gr > 0$, while the contrary effect is for $Gr < 0$.

In the continuation, it is also found from Figure 27 and 28 that escalation in the heat source and permeability props up the Bejan number, although an increase in the Eckert number shows the reverse effect as noticed from Figure 29. The Bejan number rises with the value of $Gr < 0$ and it reduces when $Gr > 0$ as observed from Figure 30 and 31. The result is relatively accurate when the Bejan number, $Be$ lies from 0 to 1. It is noticed that the irreversibility due to heat transfer amplifies when Bejan number $Be > 0.50$, whereas viscous dissipation influences the irreversibility when Bejan number $Be < 0.50$ and equal contribution of entropy distribution defines when $Be = 0.50$. The results of this analysis are in accordance with the results discussed by Butt and Ali [21].

![Figure 24](image1.png)

**Figure 24.** Be distribution profile for $K = 0.5, Pr = 1.0, R = 0.5, Q = 1.0$, and $Ec = 0.10$

![Figure 25](image2.png)

**Figure 25.** Be distribution profile for $K = 0.5, Pr = 1.0, M = 2.0, Q = 1.0$, and $Ec = 0.10
Figure 26. Be distribution profile for $K = 0.5$, $M = 2.0$, $R = 0.5$, $Q = 1.0$, and $Ec = 0.10$

Figure 27. Be distribution profile for $K = 0.5$, $M = 2.0$, $R = 0.5$, $Pr = 1.0$, and $Ec = 0.10$

Figure 28. Be distribution profile for $Q = 1.0$, $M = 2.0$, $R = 0.5$, $Pr = 1.0$, and $Ec = 0.10$
The coefficient of skin friction

The coefficient of skin friction is calculated at the wall of moving and fixed plates with the aid of MATLAB software, and their values are reported from Table 1. It is noticed that rise in the radiation,
buoyance force, heat source and magnetic field upsurges the skin friction at the wall of moving plate, whereas it declines with the rise in the viscous dissipation

Table 1. Coefficient of Skin friction at both plates with different physical parameter values when $\omega = 10$ and $\omega t = \frac{\pi}{2}$.

| $\varepsilon$ | $Gr$ | $M$ | $Ec$ | $K$ | $Pr$ | $Q$ | $R$ | $Re$ | $Cf_0$ | $Cf_1$ |
|--------------|-------|-----|------|-----|------|-----|-----|------|--------|--------|
| 0.00         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 0.8900 | -4.0075 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 0.8950 | -4.0135 |
| 0.01         | **10.0** | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 2.1214 | -10.2318 |
| 0.01         | 5.0   | 2.0 | 0.01 | **4.0** | 0.71 | 0.5 | 1.0 | 2.0  | 0.8915 | -5.9969 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | **0.04** | 0.71 | 0.5 | 1.0 | 2.0  | 0.5741 | -6.4844 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 0.8804 | -2.7945 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | **1.0** | 0.71 | 0.5 | 1.0 | 2.0  | 0.9298 | -4.4298 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 0.9260 | -4.0730 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | 1.0343 | -4.1179 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 2.0  | **4.0** | 0.4475 | -2.0068 |

The Rate of heat transfer/ Nusselt number
The rate of heat transfer at the wall of plates is calculated and displayed from Table 2. It is observed that magnitude of Nusselt number increases at the wall of the moving plate when the value of buoyance force, permeability, viscous dissipation and magnetic field rise, and the boost in the heat source and radiation decline the Nusselt number. In addition, the rise in the magnitude of the buoyance force, uniform magnetic field, viscous dissipation and permeability reduce the heat transfer at the wall of the fixed plate, whereas Nusselt number upsurges with the escalation in the radiation and heat source.

Table 2. Heat transfer / Nusselt number at both plates with different physical parameter values when $\omega = 10$ and $\omega t = \frac{\pi}{2}$.

| $\varepsilon$ | $Gr$ | $M$ | $Ec$ | $K$ | $Pr$ | $Q$ | $R$ | $Nu_0$ | $Nu_1$ |
|--------------|-------|-----|------|-----|------|-----|-----|--------|--------|
| 0.00         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 0.6381 | 1.1557 |
| **0.01**     | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 0.6436 | 1.1473 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 0.7146 | 0.9695 |
| 0.01         | 5.0   | 2.0 | 0.01 | **4.0** | 0.71 | 0.5 | 1.0 | 0.6407 | 1.1509 |
| 0.01         | **0.04** | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | 1.0 | 0.7074 | 1.0048 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | **0.5** | 0.71 | 0.5 | 1.0 | 0.6526 | 1.1362 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | **1.0** | 0.71 | 0.5 | 1.0 | 0.4762 | 1.2309 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | **1.0** | 1.0 | 0.5012 | 1.2371 |
| 0.01         | 5.0   | 2.0 | 0.01 | 0.2 | 0.71 | 0.5 | **3.0** | 0.0118 | 1.5474 |

8. Conclusions
In this paper, irreversibility distribution for MHD free convective oscillatory couette flow through a porous material occupied vertical channel in the existence of thermal radiation, heat source, and the strong magnetic field is examined with the suitable analytical scheme. It is observed that:
1. The fluid motion deaccelerates with increment in the magnetic field, and it is only possible due to the existence of the Lorentz forces.
2. Due to the increase in thermal radiation, heat releases within the system, which subsequently causes the development of fluid velocity and thermal boundary layer thickness.
The fluid temperature goes down as buoyancy force and intensity of the magnetic field are amplified; whereas it props up with the increase of heat source.

The total entropy generation decreases with the enhancement in the thermal radiation, magnetic strength, and heat source.

Magnetic field and thermal radiation play an important role to regulate the total irreversibility. It is concluded that the irreversibility distributions in terms of entropy generation can be reduced by a suitable change in these parameters. This result is useful for achieving the thermodynamic performance of the devices in the field of manufacturing and designing industries.

References

[1] Katagiri, M. (1962). Flow formation in couette motion in magnetohydrodynamics. *Journal Physical Society of Japan*, 17, 393-396.
[2] Drake, D.G., (1965). On the flow in channel due to periodic pressure gradient. *Quart. Journal Mech. Appl. Math*, 18, 1-10.
[3] Gupta, P.R. and Arora, K.L., (1974). Hydromagnetic flow between two parallel planes, one oscillating and other fixed. *Pure App. Geophys*, 112, 498-505.
[4] Singh, C.B. and Ram, P.C., (1978). Unsteady magnetohydrodynamics flow through a channel. *Journal of Scientific Research*, 27, 2.
[5] Sengupta, P.R. and Ray, T.K., (1990). Oscillatory couette flow of a viscoelastic electrically conducting fluid through a porous medium within a parallel plate channel in presence of a transverse magnetic field in a rotating system. *Archives of Mechanics*, 42, 717-721.
[6] Makinde, O.D. and Mhone, P.Y., (2005). Heat transfer to MHD oscillatory flow in a channel filled with porous medium. *Romanian Journal of Physics*, 50, 931-938.
[7] Singh, C.B. and Okwoya. Jamesh M., (2008). Couette flow between two parallel infinite plates in the presence of a transverse magnetic field. *Journal of Kenya Meteorol. Soc.*, 2, 90-94.
[8] Narahari, M. (2010). Effect of thermal radiation and free convection currents on the unsteady couette flow between two vertical parallel plates with constant heat flux at one boundary. *WSESA Transaction on Heat and Mass Transfer*, 5, 21-30.
[9] Raju, M.C. and Verma, S.V.K., (2011). Unsteady MHD free convection oscillatory couette flow through a porous medium with periodic wall temperature. *i-manager's Journal on Future Engineering and Technology*, 6, 7-12.
[10] Chand, K., Singh, K.D. and Kumar, S., (2012). Hall effect on radiating and chemically reacting MHD oscillatory flow in a rotating porous vertical channel in slip flow regime. *Advances in Applied Sciences Research*, 3, 2424-2437.
[11] Pal, Dulal and Talukdar, B., (2012). Influence of soret effect on MHD mixed convection oscillatory flow over a vertical surface in a porous medium with chemical reaction & thermal radiation. *International Journal of Nonlinear Science*, 14, 65-78.
[12] Devika, B., Narayana, P.V. Satya and Venkataramana, S., (2013). MHD oscillatory flow of a viscoelastic fluid in a porous channel with chemical reaction. *International Journal of Engineering Science Invention*, 2, 26-35.
[13] Gul, Taza., Rehman, Inayatur., Islam, S., Khan, Muhammad Altaf., Ullah, Wajid and Shah Zahir., (2015). Unsteady third order fluid flow with heat transfer between two vertical oscillating plates. *Journal of Applied Environmental and Biological Sciences*, 5, 72-79.
[14] Jha, Basant K., B.Y. Isah and Uwanta, I.J., (2015). Unsteady MHD free convective couette flow between vertical porous plate with thermal radiation. *Journal of King Saud University Science*, 27, 339-348.
[15] Sharma, P.R. and Choudhary S., (2015). Free convective oscillatory couette flow through porous medium in the presence of transverse magnetic field and heat source. *Journal of International Academy of Physical Science*, 19, 259-275.
[16] Narayana PV Satya., Venkateswarlu, B and Devika, B., (2016). Chemical reaction and heat source
effect on MHD oscillatory flow in irregular channel. *Ain Shams Engineering Journal*, 7, 1079-1088.

[17] Falade, J.A., Ukaegbu, Joel C., Egere, A.C. and Adesanya Samuel O., (2017). MHD oscillatory flow through a porous channel saturated with porous medium. *Alexandria Engineering Journal*, 56, 147-152.

[18] Cogley, A.C., Vincenti, W.G. and Gilles, S.E., (1968). Differential approximation for radiative transfer in a non grey gas near equilibrium. *AIAA Journal*, 6, 551-553.

[19] Wood, L.C., *Thermodynamics of fluid systems*. Oxford University Press, 30 (1975), 2115-2123.

[20] Bejan, A., (1979). A study of entropy generation in fundamental convective heat transfer. *ASME Journal of Heat Transfer*, 101, 718-725.

[21] Butt, Adnan Saeed and Ali A., (2014). Entropy analysis of flow and heat transfer caused by a moving plate with thermal radiation. *Journal of Mechanical Science & Technology*, 28.1, 343-348.