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Original Research Article

Inherent irreversibility impacts on thermal boundary layer flow over a mobile plate with convective surface boundary conditions

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ABSTRACT

Background: The irreversibility impacts on flow and heat transfer processes can be quantified through entropy analysis. It is a significant tool which can be utilized to deduce about the energy losses. The current study investigates the inherent irreversibility impacts during a flow of boundary layer and heat transfer on a mobile plate.
Methods: The flow is examined under thermal radiation and convective heat conditions. The fundamental governing equations of flow and heat phenomenon are transmuted into ordinary differential equations by employing similarity transmutations and shooting technique is utilized in order to solve the resultant equations. The temperature and velocity profiles are acquired to reckon Bejan and entropy generation number. Pertinent results are elucidated graphically for the movement of plate and flow in same and opposite directions.
Results: A decline in temperature profile is noted with rise in values of Pr in both cases when the movement of surface and free stream is in similar and converse directions. A decrease in temperature is observed for both cases with increase in N_R while with the rise in Biot number a, the temperature profile also increases. Entropy generation rate near the surface is high in case when surface and free stream are moving in opposite directions as compared to case when they move in same directions.
Conclusions: It is observed that irreversibility impacts are more remarkable when the movement of fluid and plate is in opposite direction. Moreover, irreversibility impacts of heat transfer are prominent in free stream region.

Keywords: Boundary layer, Entropy generation, Heat transfer, Thermal radiation, Convective boundary condition

INTRODUCTION

Blasius initiated the investigation of boundary layer flow on a plane surface.[1] Sakiadis studied the flow of boundary layer on a mobile surface in a tranquil fluid.[2] The equations achieved in both studies were similar but the boundary conditions were different. Abdel Hafez examined the flow of boundary layer on a mobile flat plate in a parallel stream.[3] However, he only discussed the case when the movement of mean stream and surface was in similar direction.

Afzal et al introduced the composite velocity and devised a single set of equations.[4] Moreover, he also discussed the case when free stream and surface move in converse directions. Ashak et al examined the flow and heat transfer phenomenon over a mobile permeable surface in parallel stream.[5] Aziz reported the flow of boundary layer on a plane surface with convective surface boundary condition.[6] Bataller analyzed the impacts of thermal radiation and convective surface heat transfer in both Blasius and Sakiadias flow.[7] Makinde studied the effects of buoyancy force over a stationary plate and the internal heat generation effects on moving vertical plate under convective boundary condition.[8,9]

The irreversibility effects in flow and heat transfer processes can be quantified through entropy analysis. It is a significant tool which can be utilized to deduce about the energy losses. Bejan introduced the method to study the irreversibility impacts by using the entropy generation rate as a standard tool. He reported that various sources like magnetic field effects, fluid friction, heat transfer along with temperature gradient etc. are accountable for entropy production.[10,11] Later on, entropy generation in flow and heat transfer over still and kinetic surfaces attracted the attention of many researchers. Influence of magnetic field on local entropy generation as a result of laminar flow over a levelled plate was inspected by Al-Odat et al.[12] The entropy generation in laminar falling liquid film besides an inclined permeable heated plate was observed by Saouli.[13] Esfahani and Jafarian analyzed entropy of boundary layer flow over a plane plate by using different techniques.[14] Makinde and Osalus studied the influence of entropy generation in a liquid film falling besides a leaned porous hot plate.[15] Makinde studied entropy of non-Newtonian liquid film along a leaned plate with constant temperature under gravity.[16]

Reveillere and Baytas examined the reduction of entropy generation in flow of boundary past a porous plate.[17] The effect of entropy over magneto-hydrodynamic and heat flows were studied under convective boundary condition by Makinde.[18] Also, he investigated the entropy effects on a plane plate with fluctuating viscosity, in the existence of thermal radiation.[19] Butt et al. explored the impact of entropy generation in Blasius flow under thermal radiations.[20] Bejan devised a strategy to enhance and upgrade the disarray produced during a phenomenon. Features of heat, entropy generation and MHD can be seen in renowned studies given in Refs.[21-33]

The goal of current study is to explore the irreversibility effects within flow and heat transfer across a mobile plate. Thermal radiation and convective boundary conditions were applied during this research venture. Results of numerically obtained solutions are analyzed via graphs and discussed for both cases, when the movement of plate and free stream is in the same and opposite directions.

METHODS

Mathematical formulation

Let us take an account of a steady, two dimensional laminar flow of incompressible viscous fluid past over a plane plate moving with fixed velocity U_w in similar or converse direction to the free stream with velocity U_∞. The x-axis is taken along the plate and the y-axis is normal to the plate. The stream temperature of cold fluid is denoted by T_∞ and the base of the plate is warmed by a hot fluid at temperature T_f, which gives a heat transfer coefficient h_f.

Then the equations governing the flow and heat transfer are as follow

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}, \tag{3}$$

The boundary conditions for the velocity field are:

$$u=U_w,\quad v=0 \quad \text{at } y=0, \qquad u\to U_\infty \quad \text{as} \quad y\to\infty. \tag{4}$$

The boundary conditions for temperature at the surface and far into the cold fluid are:

$$-k\frac{\partial T}{\partial y}=h_f\left(T_f-T_w\right) \quad \text{at} \quad y=0, \qquad T\to T_\infty \quad \text{as} \quad y\to\infty. \tag{5}$$

Here u and v denotes the x and y components of the velocities respectively, ρ is fluid density, C_p represents the specific heat at constant pressure, v is the kinematic viscosity of the fluid, k is the thermal conductivity of the fluid, q_r is the radiative heat flux, T is the fluid temperature in the boundary layer, T_w is the uniform temperature on the top surface, T_∞ is the temperature of the ambient cold fluid. Then obviously $T_f > T_w > T_\infty$.$(x+a)^n=\sum_{k=0}^{n}\binom{n}{k}x^k a^{n-k}$

Using the Rossel and approximation for radiation, the radiative heat flux can be simplified as

$$q_r=-\frac{4\sigma_1}{3k_1}\frac{\partial T^4}{\partial y}, \tag{6}$$

Where k_1 and σ_1 are the mean absorption coefficient and Stefen-Boltzmann constant respectively. In order to express T^4 as a linear function of temperature, the temperature differences within the flow are assumed sufficiently small.

This is carried out by expanding T^4 in a Taylor series about the temperature T_∞ while higher order terms are neglected. As a result following approximation are achieved.

$$T^4 = 4T_\infty^3 T - 3T_\infty^4. \quad (7)$$

By using (6) and (7) in Equation (3), we get

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma_1 T_\infty^3}{3k_1}\frac{\partial^2 T}{\partial y^2}. \quad (8)$$

The energy equation obtained by introducing (8) in (3) is

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \left(\alpha + \frac{16\sigma_1 T_\infty^3}{3\rho c_p k_1}\right)\frac{\partial^2 T}{\partial y^2}, \quad (9)$$

where $\alpha=\frac{k}{\rho c_p}$ is the thermal diffusivity. If $N_R=\frac{kk_1}{4\sigma_1 T_\infty^3}$ is considered as the radiation parameter, Eq. (9) becomes

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\alpha}{k_0}\frac{\partial^2 T}{\partial y^2}, \quad (10)$$

with $k_0=\frac{3N_R}{3N_R+4}$ When $k_0=1$, the thermal radiation effects are not taken into account.

Similarity transformations for velocity and temperature fields are introduced as

$$\eta = y\sqrt{\frac{U}{\nu x}}, \quad u = Uf'(\eta), \quad v = \frac{1}{2}\sqrt{\frac{U\nu}{x}}(\eta f' - f), \quad \theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty}. \quad (11)$$

where prime represents derivatives with respect to η and $U= U_w+U_\infty$. Using Eq. (11), Eqs. (2) and (10) take the form

$$f''' + \frac{1}{2}ff'' = 0, \quad (12)$$

$$\theta'' + \frac{1}{2}\Pr k_0 f\theta' = 0, \quad (13)$$

where $\Pr=\frac{a}{\nu}$. In order to attain the similarity solution of (1-5), we assume that

$$h_f = cx^{-1/2}.$$

The non-dimensional boundary conditions are

$$f(0) = 0, \quad f'(0) = r, \\ f'(\eta) \to 1 - r \text{ as } \eta \to \infty. \quad (14)$$

$$\theta'(0) = -a[1 - \theta(0)], \\ \theta(\eta) \to 0 \text{ as } \eta \to \infty. \quad (15)$$

where $r=\frac{U_w}{U}$ is the velocity ratio parameter and $a=\frac{c}{k}\sqrt{\frac{\nu}{U}}$ is the convective parameter.

It is noticed that if we take $r=0$ and $k_0=1$ the current problem reduces to that of Aziz.[6]

The case $0<r<1$, represents the movement of plate and fluid in the same direction whereas

$1<r<0$ corresponds to their movement in opposite direction. Free stream moves along positive x-axis while the movement of plate is directed towards negative x-axis when $r<0$ however the movement of plate and free stream is reverse for the case when $r>1$.

Entropy generation

The volumetric entropy generation rate for viscous fluid under thermal radiation is denoted and defined as follow

$$S_G = \frac{k}{T_f^2}\left[\left(\frac{\partial T}{\partial y}\right)^2 + \frac{16\sigma_1 T_\infty^3}{3kk_1}\left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{\mu}{T_f}\left(\frac{\partial u}{\partial y}\right)^2. \quad (16)$$

Eq. (16) clearly shows that there is participation of three sources of entropy generation.

The first, second and third terms on right side represent the entropy generation rate due to heat transfer, thermal radiation and fluid friction respectively.

The dimensionless numbers for *Ns* are be defined as

$$Ns = \frac{S_G}{S_{G_0}} = \frac{1}{\mathrm{Re}_x}\left[\frac{1}{k_0}\theta'^2 + \frac{Br}{\Omega}f''^2\right]. \quad (17)$$

where

$$S_{G_0} = \frac{k(T_f - T_\infty)U^2}{T_f^2\nu^2}, \quad \Omega = \frac{T_f}{T_f - T_\infty}, \quad Br = \frac{\mu U^2}{k(T_f - T_\infty)}, \quad \mathrm{Re}_x = \frac{Ux}{\nu},$$

Irreversibility parameter Bejan number can be defined as

$$Be = \frac{\textit{Entropy generation due to heat transfer}}{\textit{Total entropy generation}} \quad (18)$$

Eq. (18) shows that the Bejan number ranges from 0 to 1. The fluid friction causes the dominance of irreversibility for zero value of Bejan number while irreversibility dominates the flow system for $Be=1$. Both factors contribute equally to entropy generation in the case when Be is equal to half.

RESULTS

Shooting technique is used to attain the numerical solution of differential equations (12) and (13) under the boundary conditions (14), (15) and symbolic software MATHEMATICA is utilized to carry out the calculations. The results for $\Theta(0)$ and $\Theta'(0)$ are compared with those given by Aziz in Table 1 in absence of thermal radiation and r=0 in order to check the validity of our work.[6] The results obtained were concordant with previous studies which further authenticate our results.

The impacts of physical parameters appeared in governing equations on velocity and temperature profiles when plate and free stream are moving in same and opposite directions are elucidated through graphs. Furthermore, Bejan number *Be* and entropy generation number *Ns* are plotted to observe that which parameter is responsible for more entropy production.

In Figure 1, the velocity profile is presented against η for various values of velocity ratio parameter r. It is observed that for $r<0.5$, $f'(\eta)$ increases with η. However for $r<0.5$, a decrease in velocity profile is observed. For $r=0.5$, the surface velocity and free stream velocity are equal.

Table 1: Comparison of our results of θ (0) and θ' (0) with those reported by Aziz when k_0= 1 and r=0.[6]

	Pr=0.72				*Pr=10*			
a	θ(0) Aziz[6]	θ(0) Present	θ'(0) Aziz[6]	θ'(0) Present	θ(0) Aziz[6]	θ(0) Present	θ'(0) Aziz[6]	θ(0) Aziz[6]
0.05	0.1447	0.1447	0.0428	0.0428	0.0643	0.0643	0.0468	0.0468
0.10	0.2528	0.2528	0.0747	0.0747	0.1208	0.1208	0.0879	0.0879
0.20	0.4035	0.4035	0.1193	0.1193	0.2155	0.2155	0.1569	0.1569
0.40	0.5750	0.5750	0.1700	0.1700	0.3546	0.3546	0.2582	0.2582
0.60	0.6699	0.6699	0.1981	0.1981	0.4518	0.4518	0.3289	0.3289
0.80	0.7301	0.7301	0.2159	0.2159	0.5235	0.5235	0.3812	0.3812
1.0	0.7718	0.7718	0.2282	0.2282	0.5787	0.5787	0.4213	0.4213
5.0	0.9441	0.9441	0.2791	0.2791	0.8729	0.8729	0.6356	0.6356
10.0	0.9713	0.9713	0.2871	0.2871	0.9321	0.9321	0.6787	0.6787
20.0	0.9854	0.9854	0.2913	0.2913	0.9649	0.9649	0.7026	0.7026

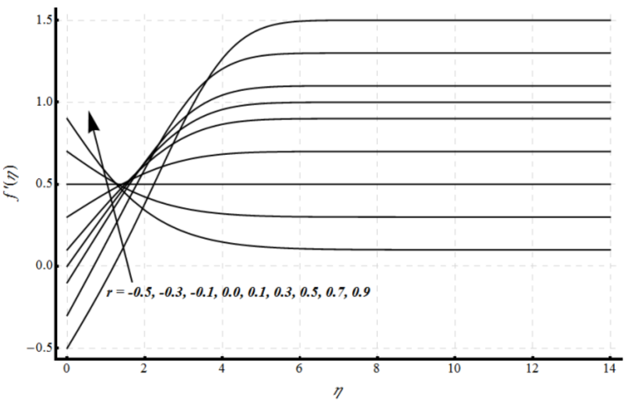

Figure1: Effects of velocity ration parameter r on $f'(\eta)$.

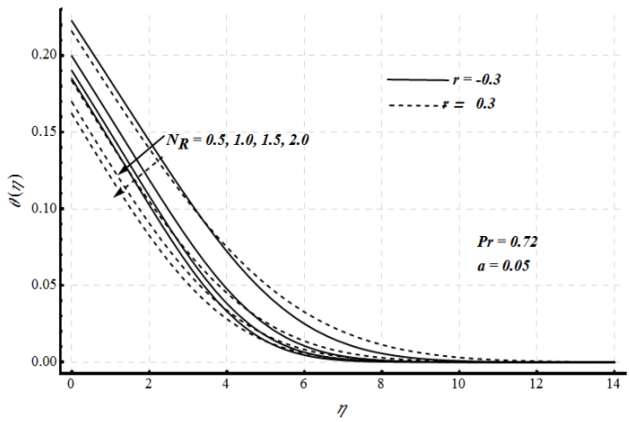

Figure 3: Effects of radiation parameter N_R on $\theta(\eta)$.

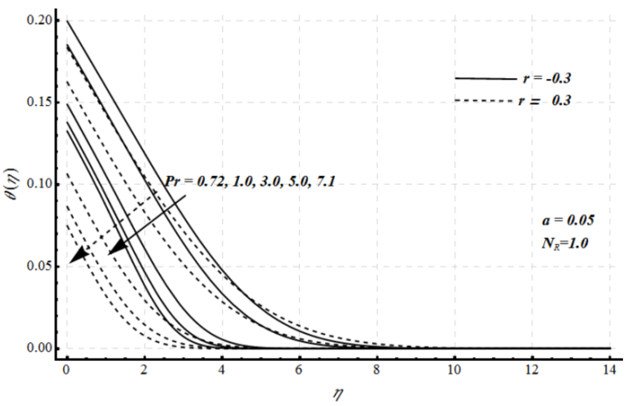

Figure 2: Effects of Prandtl number Pr on Θ (η).

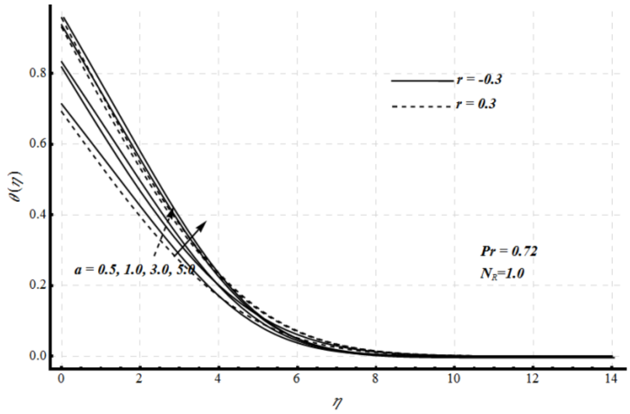

Figure 4: Effects of Biot number a on $\theta(\eta)$.

The impacts of different parameters on temperature are shown in Figures 2-4 for both cases when the movement of plate and free stream are in alike and converse directions. The solid and broken lines represent the cases when the movement of free stream and plate is in converse and alike directions. The impacts of *Pr* against temperature profile are shown in Figure 2 which indicates the decline in temperature with the rise of *Pr* in both cases but this decline is more rapid when the direction of movement of free stream and plate is similar. Figure 3 illustrates the impact of N_R on temperature which shows the reduction in temperature for both cases. On the other hand, in Figure 4, a rise in temperature is observed with the rise in Biot number "a".

The imperative parameter known as Bejan number *Be* gives a view about the dominance of irreversibility of fluid friction over the transfer of heat and vice versa.

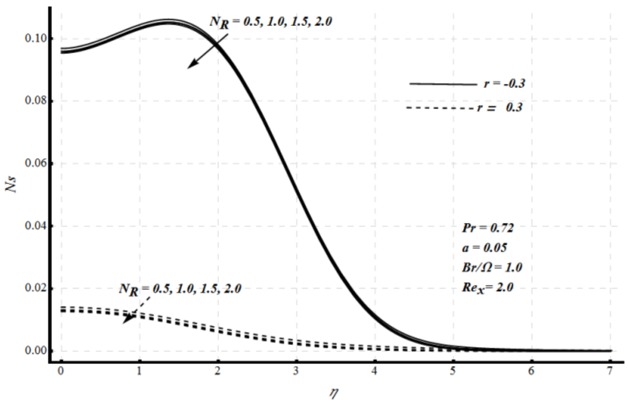

Figure 5: Effects of radiation parameter N_R on *Ns*.

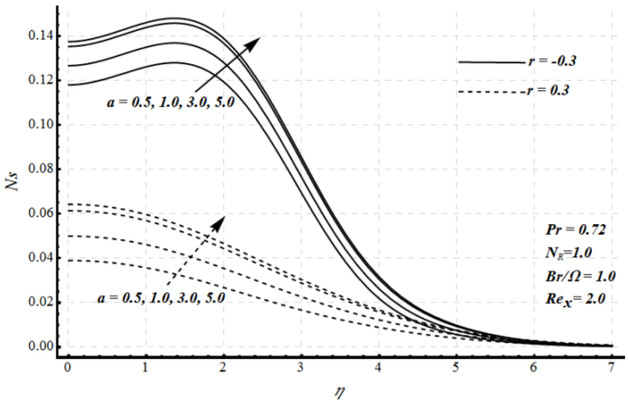

Figure6: Effects of Biot number *a* on *Ns*.

Figures 5-7 represent the impacts of different parameters on *Ns* against *η*. Figure 5 depicts the effect of N_R on *Ns*. It is observed that *Ns* rate near the surface is much higher when the movement of free stream and surface is opposite. Moreover, it can be deduced that *Ns* falls with the rise in N_R. However these impacts are negligible. Figure 6 represents that *Ns* increases with Biot number *a* for both the scenarios. Figure 7 elucidates the influence of Br / Ω on *Ns*. However, irreversibility effects are much higher when the movement of free stream and surface is opposite because viscous effects are significant in this scenario.

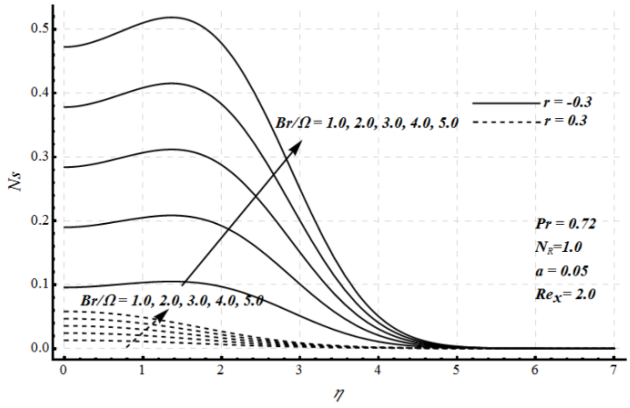

Figure 7: Effects of group parameter Br / Ω on *Ns*.

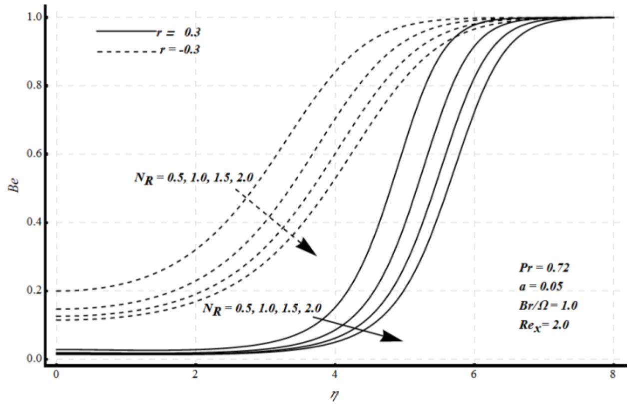

Figure 8: Effects of radiation parameter N_R on *Be*.

Figure 8 represents the influence of Bejan number against different values of N_R. When surface and free stream are moving in opposite directions, the surface and nearby region is fully dominated by the irreversibility of fluid friction with the rise in value of N_R. These impacts are dominant in the region of free stream. For the case when surface and free stream are moving in same direction, an increase in value of N_R causes fluid friction irreversibility to increase near the surface. However, these effects are less as compared to first case.

Figure 9 depicts that irreversibility effects fall with the rise in Biot number *a* near the plate in both cases. Moreover, it is noticed that dominance of irreversibility effects is more prominent in the scenario when movement of surface and free stream is opposite. These effects are more prominent in boundary layer and free stream regions.

Figure 10 elucidates the influence of Br / Ω on *Be*. A rise in value of Br / Ω results an increase in fluid friction irreversibility at the surface of plate and in the neighboring region. However, these effects are more significant in the case when the movement of plate and free stream is opposite. In free stream region, heat transfer irreversibility effects are prominent.

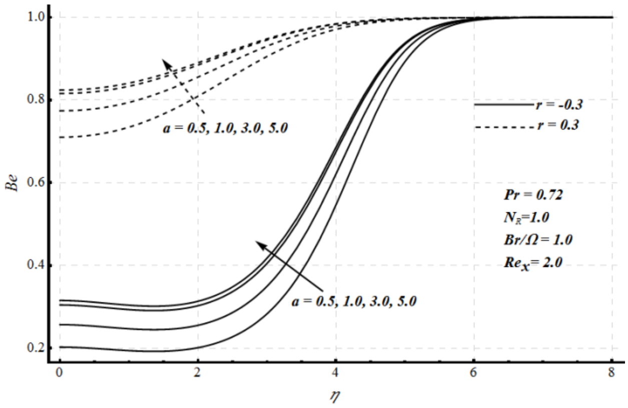

Figure 9: Effects of Biot number *a* on *Be*.

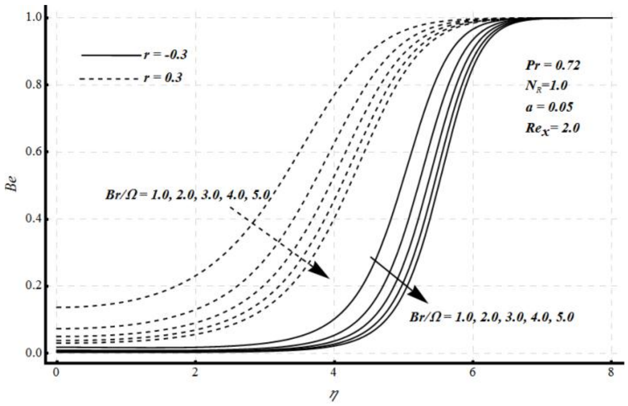

Figure 10: Effects of group parameter *Br / Ω* on *Be*.

DISCUSSION

The irreversibility impacts on flow and heat transfer processes can be quantified through entropy analysis. It is a significant tool which can be utilized to deduce about the energy losses. The current study investigates the inherent irreversibility impacts during a flow of boundary layer and heat transfer on a mobile plate. Thermal radiation and convective boundary conditions were applied during this research venture. It is observed that irreversibility impacts are more remarkable when the movement of fluid and plate is in opposite direction. Moreover, irreversibility impacts of heat transfer are prominent in free stream region.

CONCLUSION

The focal findings of our study are mentioned below.

For *r<0.5*, a rise in velocity is noted with the rise in distance *Ŋ* from the surface. However for *r<0.5*, a decline in velocity profile is noted. For *r=0.5*, the velocity of surface and free stream are same. A decline in temperature profile is noted with rise in values of *Pr* in both cases when the movement of surface and free stream is in similar and converse directions. A decrease in temperature is observed for both cases with increase in N_R. With the rise in Biot number *a*, the temperature profile also increases. Entropy production rate near the surface is high in case when surface and free stream are moving in opposite directions as compared to case when surface and free stream are in same directions. Entropy generation number *Ns* decreases slightly with radiation parameter N_R and increases with Biot number *a* and group parameter *Br* / Ω. Irreversibility effects and fluid friction become stronger at the surface of plate and in neighboring region with increase in values of N_R and *Br* / Ω while it decreases with Biot number *a*.

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