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Entropy generation in MHD mixed convection stagnation-point flow in the presence of joule and frictional heating

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A R T I C L E I N F O

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A B S T R A C T

This article looks at the second law analysis of MHD boundary layer stagnation-point flow past over linearly stretched sheet. The thermal boundary condition is supposed to be non-isothermal and the effects of friction and Joule heating have been analysed. By using similarity transformations, the model nonlinear partial differential equations in two independent variables are reduced to ordinary differential equations. The numerical techniques, namely shooting and fourth order Runge-Kutta are used to give a numerical solution. An expression for dimensionless entropy generation and Bejan number are obtained and computed using velocity and temperature profiles. The main objective of this article is to analyse the effects of a magnetic parameter, Prandtl number, Eckert number, stretching parameter, mixed convection parameter and dimensionless temperature parameter on the volumetric rate of entropy production and Bejan number. It is found that entropy generation increases with enhancing values stretching parameter and decrease with the increasing values of dimensionless temperature parameter.

1. Introduction

First law of thermodynamics deals about the quantity of energy and conversion of energy from one form to another with no regard to quality. The major concern of engineers is to preserve the quality as well as the degree of degradation of energy during a real process. The quantity of energy is conserved (first law of thermodynamics) during a real process but the quality of energy is bound to decrease (second law of thermodynamics) and this decrease in quality of energy is measured by entropy i.e entropy generation reduces the quality of energy [1]. In order to minimize this reduction in quality of energy (the exergy) in a fluid flow problem it is very important to examine the distribution of entropy generation within flow field.

In the past, many researchers have studied the problem of entropy generation minimization in fluid flow with heat transfer. Second law analysis [2,3] focusing on entropy generation rate and its minimization in order to understand the irreversibilities in applied engineering and transport processes. Since the entropy generation in the thermodynamic system is the measure of the destruction of available work of the system and thus reduce the efficiency, therefore determination of distribution of entropy generation within the fluid flow region can help in increasing the system efficiency and achieving the optimal thermal or mechanical design. So, minimization of entropy generation is important in upgrading the performance of the system. For the first time Bejan [4,5] calculate the volumetric entropy generation rate in fluid flow process and followed by many other researchers [6–11].

Boundary layer flow over a stretching sheet has fascinated the attention of recent investigators in the field. This is because of the

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Table 1
Comparison of present study with the literature [25] for skin friction coefficient and Nusselt number.

Pr	Assisting flow				Opposing flow			
	$Re_x^{1/2}C_f$		$Re_x^{-1/2}Nu_x$		$Re_x^{1/2}C_f$		$Re_x^{-1/2}Nu_x$	
	[25]	Present	[25]	Present	[25]	Present	[25]	Present
0.72	0.3645	0.3645	1.0931	1.0931	−0.3852	−0.3852	1.0293	1.0293
6.8	0.1804	0.1804	3.2902	3.2896	−0.1832	−0.1832	3.2466	3.2461
20	0.1175	0.1175	5.6230	5.6201	−0.1183	−0.1183	5.5923	5.5896
40	0.0873	0.0872	7.9463	7.9383	−0.0876	−0.0876	7.9227	7.9149
60	0.0729	0.0728	9.7327	9.7180	−0.0731	−0.0730	9.7126	9.6982
80	0.0640	0.0639	11.2413	11.2187	−0.0642	−0.0641	11.2235	11.2012
100	0.0578	0.0577	12.7526	12.5411	−0.0579	−0.0578	12.5564	12.5252

fact that such flows appear in several engineering and industrial processes. Crane [12] reported the analytical solution of boundary layer flow driven by a linearly stretching sheet. After the seminal work of Crane [12], several investigations have been made to study the flow over linear, exponential, non-linear and oscillatory stretching sheets under different features of heat transfer, magnetohydrodynamics (MHD), suction/injection, porous medium, mass transfer, chemical reaction, Soret and Dufour effects, heat source/sink, Newtonian heating and convection boundary conditions [13–22]. Chiam studied the stagnation point flow of a viscous fluid in the presence of suction/injection. [23]. Mahapatra and Gupta [24] discussed the stagnation point flow and heat transfer due to a linear stretching sheet. Ishak et al. [25,26] analysed the mixed convection stagnation point flow towards a vertically impermeable and permeable stretching sheet. Stagnation point flow towards a stretching surface in the presence of homogeneous-heterogeneous chemical reaction has been analysed by Bachok et al. [27]. Butt et al. [28] analysed numerically the magnetic field effects on entropy generation in viscous flow over a stretching cylinder embedded in a porous medium.

The purpose of the present contribution is to perform second law analysis of MHD mixed convection stagnation point flow over a vertically stretching sheet in the presence of energy dissipation and Joule heating. Numerical solutions are obtained using shooting technique along with fourth order Runge-Kutta method. To analyse the effects of dimensionless parameters numerical results are plotted and discussed.

2. Formulation of the problem

Consider the steady two dimensional magnetohydrodynamic mixed convection flow of viscous fluid caused by a linearly stretching sheet. The stretching sheet is assumed to be remain in the xy plane while x-axis is taken along a sheet and $y-axis$ normal to it. The flow being confined to $y > 0$. Further, it is assumed that the stretching velocity, free stream velocity and temperature of the stretching surface are $u_w(x) = cx$, $u_e(x) = ax$ and $T_w = T_\infty + bx^2$ respectively. Under the above assumptions and Prandtl boundary layer approximations the governing equations reduce to

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + \frac{\sigma B^2}{\rho}(u_e - u) + u_e\frac{du_e}{dx} \pm g\beta_T(T - T_\infty), \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B_o^2}{\rho c_p}(u_e - u)^2. \tag{3}$$

Where (u, v) are velocity components along x and y axes respectively, ρ, ν, σ, g, cp, T and k represent density, kinematic viscosity, electric conductivity, gravitational acceleration, specific heat at constant pressure, temperature of fluid inside the boundary layer and thermal conductivity respectively. For the existence of similarity equations, it is assumed that the thermal expansion coefficient $\beta_T \sim x^{-1}$ [29].

The assumed boundary conditions are

$$\left.\begin{array}{l} u = u_w(x) = cx, \quad v = 0, \;\; T = T_w = T_\infty + bx^2, \quad \text{at} \quad y = 0, \\ u \to u_e(x) = ax, \;\; T \to T_\infty, \quad \text{as} \quad y \to \infty, \end{array}\right\}. \tag{4}$$

Introducing the following similarity variables

$$\eta = \sqrt{\frac{u_w}{\nu x}}y, \;\; \psi = \sqrt{c\nu}xf(\eta), \;\; \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}. \tag{5}$$

Making use of Eq. (5), continuity Eq. (1) is identically satisfied while Eqs. (2) and (3) take the following form:

$$f''' + ff'' - f'^2 + M^2(A - f') + A^2 \pm \lambda\theta = 0, \tag{6}$$