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Entropy generation and heat transfer in boundary layer flow over a thin needle moving in a parallel stream in the presence of nonlinear Rosseland radiation

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ABSTRACT

Analysis of entropy generation and heat transfer in the boundary layer flow over a thin needle moving in a parallel stream is performed in this work. Energy dissipation and nonlinear radiation terms are incorporated in the energy equation. It is assumed that the free stream velocity u_∞ is in the direction of positive $x-axis$ (axial direction) and the thin needle moves in the direction of free stream velocity. The problem is self-similar in the presence of viscous dissipation and non-linear Rosseland thermal radiation. The reduced self-similar governing equations are solved numerically using shooting and fourth order Runge-Kutta method. The expressions for dimensionless volumetric entropy generation rate and Bejan number are also obtained by selecting suitable similarity variables. The effects of the Eckert number, heating parameter, radiation parameter, Prandtl number, velocity ratio parameter and dimensionless size of a thin needle are described graphically in detail. The analysis reveals that the entropy generation decreases by decreasing the size of the thin needle. Entropy generation number increases with the increasing values of the Eckert number, Prandtl number and the temperature parameter. Moreover, it is observed that the Bejan number decreases by increasing the thermal radiation parameter. Validation of present analysis is performed by comparing the obtained results with those available in the existing literature and found a very good agreement.

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1. Introduction

All bodies having a temperature above absolute zero emit energy in the form of electromagnetic waves. This type of energy exchange due to temperature is termed as thermal radiation. Thermal radiation greatly influences the effects of heat transfer mainly in the high temperature regime such as cooling system, solar power technology, hypersonic flights, space vehicle re-entry and rocket combustion chambers. Smith [1] firstly, investigated the effects of thermal radiation on boundary layer flow. In the presence of convection and thermal radiation the energy conservation equation becomes a complicated nonlinear integro-differential equation, therefore, Rosseland approximation [2] is used to avoid the mathematical complexity. Perdikis and Raptis [3] applied the linear Rosseland approximation to study the heat transfer analysis in the boundary layer flux on a stationary flat plate. After this, many researchers studied the effects of thermal radiation in the boundary layer using the linearized form of the Rosseland approximation [4–8]. The linearized form of the Rosseland approximation is valid only when the temperature difference between the solid boundary and the ambient fluid is low. Magyari and Pantokratoras [9] re-examined the linear Rosseland approximation problem and showed that the problem is governed by a single-parameter approach instead of two parametric approach. The influence of nonlinear Rosseland thermal radiation on classical Blasius and Sakiadis flow has been studied by Pantokratoras and Fang [10,11]. They concluded that nonlinear Rosseland radiation approximation is valid for low and high temperature difference between the wall and the bulk fluid. Furthermore, the temperature profile is S-shaped in a case of nonlinear Rosseland approximation as compared to a linear approximation.

The boundary layer flow of viscous fluid over a thin needle was studied by Lee [12]. Cebeci and Na [13] examined the free convection heat transfer from a thin needle. They found a similarity between the heat transfer from a thin needle and flat plate, in the sense that both are increasing function of Prandtl number. The

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laminar free convection flow over an isothermal vertical needle was reported by Narian and Uberoi [14]. Narain and Uberoi [15] also investigated the mixed convective flow over the thin needle, taking separately the isothermal and isoflux boundary conditions. Trimbitas et al. [16] numerically discussed the mixed convection boundary layer flow of nanofluid over a vertically stationary thin needle. Ishak et al. [17] studied the boundary layer flow over a thin needle in a parallel free stream using Keller box method. They found that dual solution exists when the needle and free stream move in opposite directions. Ahmed et al. [18] modelled the boundary layer flow over a thin needle considering the variable heat flux boundary condition.

The study of MHD (magnetohydrodynamic) flow for electrically conducting fluid is of great interest in many engineering problems such as metal-working processes, plasma studies, cooling of nuclear reactors, petroleum industries, crystal growth and the boundary layer control in aerodynamics. Pavlov [19] studied the effects of magnetic field on boundary layer flow induced by a stretching sheet. Further analysis of MHD flow has been made by Ali et al. [20,21], Hsiao [22,23], Sheikh et al. [24], Khan [25], Vajravelu and Hadjinicolaou [26] and Chamkha [27].

In the design and development of engineering products both quality and quantity of energy are very important parameters. The second law of thermodynamics provides us with the necessary tools to determine the quality and degree of degradation of energy during a process. Irreversibility or entropy is that important tool which measures the quality of energy. According to the second law of thermodynamics, during the conversion of energy to some useful work there is a loss of energy which reduces the performance of energy conversion devices. This degrading of energy (destruction of energy) is proportional to entropy generation. Consequently, the production of entropy in a system results in a decrease in the amount of available energy (exergy). Thus, the performance of a thermal system can be improved by reducing the generation of entropy. Therefore, it is very important to know the distribution of entropy generation during the thermodynamic process in order to reduce the entropy production.

For the first time, Bejan [28,29] studied the causes of entropy generation in the convective heat transfer problem. Bejan [28] found that the temperature gradient due to the finite difference in temperature and the velocity gradient (fluid friction) is responsible for the entropy production in the fluid flow process. Reveillere and Baytas [30] studied the effects of suction/injection on entropy generation in boundary layer flow over a flat plate. Abbassi et al. [31] investigated the entropy generation in the Poiseuille-Benard channel by using the finite element method. Mahmud and Fraser [32] performed the entropy analysis of forced convection flow inside a channel with circular cross section and the channel made by two parallel plates. Weigand and Birkefeld [33] provided the similarity solutions of energy transport equation. Aksoy [34] analytically investigated the effects of couple stresses on entropy generation in a fluid flow between two parallel plates. Further, many researchers carried out second law analysis for the fluid flow and heat transfer problem in order to minimize the generation of entropy [35–44]. However, the heat transfer analysis and entropy generation in boundary layer flow over a thin needle moving in a flowing fluid in the presence of viscous dissipation and nonlinear radiation has not been reported in the literature. Therefore, such problems for thin needle still need to be explored.

The aim of the present article is to investigate the heat transfer analysis and entropy generation in boundary layer flow over a thin needle moving in a parallel free stream of viscous fluid. The effects of viscous dissipation and nonlinear radiation are also taken into account. The entropy generation number is computed by substituting the velocity and temperature profile obtained from the momentum and energy equation. To validate the obtained numerical results, the comparison has been made with the existing results in the literature. The variations of velocity profile, temperature profile and entropy generation number with physical flow parameters are plotted graphically and discussed in detail.

2. Mathematical modeling

Consider the steady flow of an incompressible fluid over a thin needle moving with a constant velocity u_w in a parallel free stream. It is assumed that the thickness of the needle is comparable to or smaller than that of the momentum and thermal boundary layer over the, but the influence of the curvature in the transverse direction is significant. Pressure gradient along the needle is negligible i.e. $\frac{\partial p}{\partial x} = 0$ and $\bar{r} = R(x)$ describes the radius of the needle, where $\bar{r}$ and $\bar{x}$ represent the radial and axial coordinates. The flow configuration and coordinate system are shown in Fig. 1. Under these assumptions the boundary layer equations in cylindrical coordinates are

$$\frac{\partial}{\partial x}(ru) + \frac{\partial}{\partial r}(rv) = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r} = \frac{\nu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right). \tag{2}$$

Here, u and v respectively represent the velocity components in the axial and radial directions, ρ and ν shows density and kinematic viscosity of the fluid respectively. The following boundary conditions are assumed for the present study

$$\left.\begin{array}{ll} u = u_W, v = 0, & \text{at } r = R(x) \\ u \rightarrow u_\infty & \text{as } \quad r \rightarrow \infty \end{array}\right\}. \tag{3}$$

The following similarity variables are used in order the reduce Eq. (2) into ordinary differential equation (see Ref. [17])

$$\psi = \nu\, x\, f(\xi),\ \xi = \frac{Ur^2}{\nu x}, \tag{4}$$

where ψ is stream function satisfied Eq. (1) identically and defined as $u = \frac{1}{r}\frac{\partial \psi}{\partial r}$ and $v = -\frac{1}{r}\frac{\partial \psi}{\partial x}$, $U = u_W + u_\infty \neq 0$ is composite velocity and $f(\xi)$ represents dimensionless stream function. By setting $\xi = a$ (refers to the wall of the needle) in Eq. (4), we get $R(x) = \left(\frac{a\nu x}{U}\right)^{1/2}$ (prescribe the shape and size of the surface of revolution).

Using Eq. (4), Eq. (2) becomes

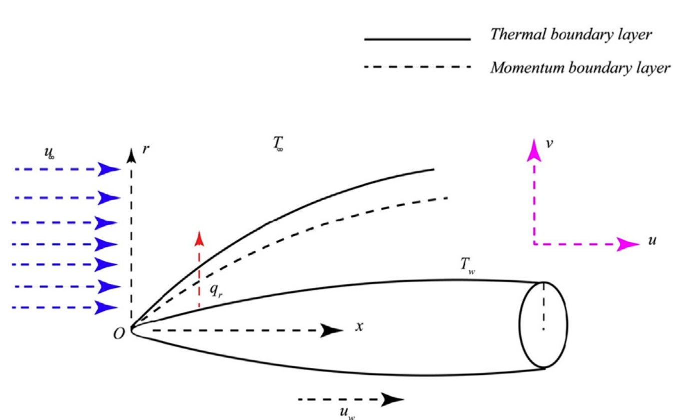

Fig. 1. Physical flow model and coordinate system.

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