Propulsion and Power Research 2017;6(3):186–194

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Propulsion and Power Research

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ORIGINAL ARTICLE

Thermal boundary layer in stagnation-point flow past a permeable shrinking sheet with variable surface temperature

Md. Sharif Uddin[a], **Krishnendu Bhattacharyya**[b,c,*]

[a]*Mathematics Discipline, Khulna University, Khulna 9208, Bangladesh*
[b]*Department of Mathematics, Institute of Science, Banaras Hindu University, Varanasi 221005, Uttar Pradesh, India*
[c]*Department of Mathematics, The University of Burdwan, Burdwan 713104, West Bengal, India*[1]

Received 16 July 2015; accepted 23 May 2016
Available online 13 September 2017

KEYWORDS

Dual solutions;
Heat transfer;
Boundary layer;
Stagnation-point flow;
Non-isothermal permeable shrinking sheet;
Suction/injection;
Variable surface temperature

Abstract An investigation is made to study the heat transfer in boundary layer stagnation-point flow over a non-isothermal permeable shrinking sheet with suction/injection. In this study, power-law variation of sheet temperature is considered. By similarity transformation, the governing equations with the boundary conditions are transformed to self-similar nonlinear ordinary differential equations and then those are solved numerically by shooting method. In presence of variable sheet temperature, the variation of temperature is analysed. For larger shrinking rate compared to that of straining rate, dual solutions for velocity and temperature are obtained. It is found that for positive value of power-law exponent of variable sheet temperature heat transfer at the sheet as well as heat absorption at the sheet with temperature overshoot near the sheet occur and for negative value heat transfer from the sheet occurs though there is overshoot away from the sheet. With increasing positive power-law exponent heat transfer reduces for first solution and heat absorption enhances for second solution. Whereas, with increasing magnitude of negative power-law exponent heat transfer increases for second solution and for first solution the heat transfer increases for larger shrinking rate and it decreases for smaller shrinking rate. Due to suction heat transfer/absorption increases in all cases and for injection heat transfer/absorption increases for first solution and decreases for second solution.

*Corresponding author. Tel.: +91 9474634200.
E-mail addresses: krish.math@yahoo.com, krishnendu.math@gmail.com (Krishnendu Bhattacharyya).

Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

[1]Previous affiliation of K. Bhattacharyya.

http://dx.doi.org/10.1016/j.jppr.2017.07.007

Also, interesting effects of suction/injection and Prandtl number on temperature distribution are observed when the sheet temperature varies (directly/inversely) along the sheet.

1. Introduction

The fluid flow due to a stretching/shrinking sheet is a very important problem in fluid mechanics because of its applications in numerous engineering processes, such as, polymer processing, glass-fiber production, metal spinning, paper production, aerodynamic extrusion of plastic sheets and many more. The flow over a linearly stretching sheet was first investigated by Crane [1]. In the literature, the various extensions of Crane's [1] work can be found [2–17]. On the other hand, the concept of the flow pattern opposite to that of stretching sheet flow i.e. the flow due to a shrinking sheet is newly developed and needs attention of researchers. Shrinking sheet problem has various technological applications and shrinking film is one of the common applications in many industries. The flow development over a shrinking sheet was first described by Wang [18] when he investigating the liquid film on unsteady stretching sheet. Later, the detail of the existence, uniqueness for the steady flow over porous shrinking sheet with mass suction was considered by Miklavčič and Wang [19] and they found that it depends on externally applied mass suction imposed through the porous sheet. Hayat et al. [20] gave an analytic solution of magnetohydrodynamic (MHD) flow of a second grade fluid over a shrinking sheet using homotopy analysis method (HAM). Hayat et al. [21] also reported an analytic HAM solution for MHD rotating flow of a second grade fluid over a shrinking sheet. Muhaimin et al. [22] showed the effects of heat and mass transfer on MHD boundary layer flow over a shrinking sheet subject to suction. A series solution of three-dimensional MHD and rotating flow over a porous shrinking sheet was obtained by Hayat et al. [23] using HAM. Fang and Zhang [24] found a closed-form exact solution of steady MHD flow due to a porous shrinking sheet with wall mass transfer. Fang et al. [25] studied the unsteady flow over a shrinking surface with mass suction. Hayat et al. [26] discussed the mass transfer in the steady two-dimensional MHD boundary layer flow of an upper-convected Maxwell fluid past a porous shrinking sheet in the presence of chemical reaction. Muhaimin et al. [27] discussed the mass and heat transfer effects on the boundary layer past a porous shrinking sheet in the presence of suction and chemical reaction. Fang et al. [28] demonstrated the MHD flow over a shrinking sheet under slip boundary conditions. Bhattacharyya [29] investigated effects of radiation and heat source/sink on unsteady MHD boundary layer flow and heat transfer over a shrinking sheet with suction/injection. Bhattacharyya [30] studied the boundary layer flow over an exponentially shrinking sheet and the magnetic effect on the flow field was studied by Bhattacharyya and Pop [31]. Ishak et al. [32] described the flow of non-Newtonian power-law fluid over a shrinking sheet with suction. Recently, Bhattacharyya et al. [33] analysed the dual nature of solutions of the boundary layer flow of Maxwell fluid past a permeable shrinking sheet and Zaimi and Ishak [34] showed the flow and heat transfer of a viscous fluid over a permeable stretching/shrinking sheet with convective surface boundary condition.

The stagnation-point flow towards a shrinking sheet was investigated by Wang [35] for both two-dimensional and axisymmetric cases and he obtained dual solutions for certain conditions. Ishak et al. [36] discussed the steady boundary layer stagnation-point flow of a micropolar fluid over a shrinking sheet. Bhattacharyya and Layek [37] studied the effects of suction/blowing on the boundary layer stagnation-point flow and heat transfer towards a shrinking sheet in presence of thermal radiation. Bhattacharyya et al. [38] showed the slip effects on the stagnation-point flow and heat transfer over a shrinking sheet. Mahapatra et al. [39] discussed the momentum and heat transfer for MHD stagnation-point flow past a shrinking sheet. Yacob et al. [40] demonstrated the melting heat transfer in boundary layer stagnation-point flow of micropolar fluid towards a stretching/shrinking sheet. The unsteady boundary layer stagnation-point flow over a shrinking sheet was investigated by Bhattacharyya [41] and Nik Long et al. [42]. The mass transfer in boundary layer stagnation-point flow towards a shrinking sheet was showed by Bhattacharyya [43] and the stagnation-point flow and heat transfer over shrinking sheet in porous medium was investigated by Rosali et al. [44]. Mahapatra and Nandy [45] made the stability analysis of dual solutions for boundary layer stagnation-point flow and heat transfer due to a non-linearly shrinking surface. Bhattacharyya et al. [46] studied the MHD boundary layer stagnation-point flow over a permeable shrinking sheet with suction/blowing and chemical reaction. Some other important contributions in this area were made by Khan et al. [47], Bhattacharyya [48], Pal and Mandal [49], Sharma et al. [50], Nandy and Pop [51] and Mansur et al. [52].

Motivated by the fact that the shrinking sheet flow with heat transfer is a newly developed problem with several engineering and industrial applications, in the present paper, the heat transfer for boundary layer stagnation-point flow over non-isothermal porous shrinking sheet with suction/