Alexandria Engineering Journal (2016) 55, 37–49

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Alexandria Engineering Journal

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Magnetohydrodynamic unaxisymmetric stagnation-point flow and heat transfer of a viscous fluid on a stationary cylinder

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Received 30 November 2015; revised 2 January 2016; accepted 16 January 2016
Available online 6 February 2016

KEYWORDS

Unaxisymmetric stagnation-point flow;
Heat transfer;
Stationary cylinder;
Magnetohydrodynamic flow;
Numerical solution;
Non-uniform transpiration

Abstract The steady-state viscous flow and heat transfer in the vicinity of an unaxisymmetric stagnation-point of an infinite stationary cylinder with non-uniform normal transpiration $U_0(\varphi)$ and uniform transverse magnetic field and constant wall temperature are investigated. The impinging free-stream is steady and with a constant strain rate $\bar{k}$. A reduction of Navier–Stokes and energy equations is obtained by use of appropriate similarity transformations. The semi-similar solution of the Navier–Stokes equations and energy equation has been obtained numerically using an implicit finite-difference scheme. All the solutions aforesaid are presented for Reynolds numbers, $Re = \bar{k}a^2/2\upsilon$, ranging from 0.01 to 100 for different values of Prandtl number and magnetic parameter and for selected values of transpiration rate function, $S(\varphi) = U_0(\varphi)/\bar{k}a$, where a is cylinder radius and υ is kinematic viscosity of the fluid. Dimensionless shear-stresses corresponding to all the cases increase with the increase in Reynolds number and transpiration rate function while dimensionless shear-stresses decrease with the increase in magnetic parameter. The local coefficient of heat transfer (Nusselt number) increases with the increasing transpiration rate function and Prandtl number.
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1. Introduction

There are many solutions of the Navier–Stokes and energy equations regarding the problem of stagnation-point flow and heat transfer in the vicinity of a flat plate or a cylinder. These studies were started by Hiemenz [1], who obtained an exact solution of the Navier–Stokes equations governing the two-dimensional stagnation-point flow on a flat plate, and were continued by Homann [2] with an analogous axisymmetric study and by Howarth [3] and Davey [4], whose results for stagnation-point flow against a flat plate for asymmetric cases were presented. Wang [5,6] was the first to find an exact solution for the problem of axisymmetric stagnation-point flow on an infinite stationary circular cylinder; this was continued by Gorla's works [7–11], which are a series of steady and unsteady flows and heat transfer over a circular cylinder in the vicinity

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.01.016
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Nomenclature

a	cylinder radius
r	radial coordinate
z	axial coordinate
u, w	velocity components along (r, z)-axis
B_0	magnetic field
T	temperature
T_W	wall temperature
T_∞	freestream temperature
k	thermal conductivity
$\bar{k}$	freestream strain rate
$f(\eta, \varphi)$	function related to u-component of velocity
Nu	Nusselt number
$U_0(\varphi)$	transpiration
Re	Reynolds number
Pr	Prandtl number
M	magnetic parameter
$S(\varphi)$	transpiration rate function
P	non-dimensional fluid pressure
p	fluid pressure
h	heat transfer coefficient
q_w	heat flow at wall

Greek symbols

η	similarity variable
φ	angular coordinate
α	thermal diffusivity
ρ	fluid density
υ	kinematic viscosity
$\bar{\sigma}$	fluid electrical conductivity
μ	dynamic viscosity
$\theta(\eta, \varphi)$	non-dimensional temperature
σ	shear stress

of the stagnation-point for the cases of constant axial movement and the special case of axial harmonic motion of a non-rotating cylinder. Cunning et al. [12] have considered the stagnation-point flow problem on a rotating circular cylinder with constant angular velocity; Grosch and Salwen [13] as well as Takhar et al. [14] studied special cases of unsteady viscous flow on an infinite circular cylinder. The most recent works of the same types are the ones by Saleh and Rahimi [15] and Rahimi and Saleh [16,17], which are exact solution studies of a stagnation-point flow and heat transfer on a circular cylinder with time-dependent axial and rotational movements, as well as studies by Abbasi and Rahimi [18–21], which are exact solutions of stagnation-point flow and heat transfer but on a flat plate. Some existing compressible flow studies but in the stagnation region of bodies and by using boundary layer equations include the study by Subhashini and Nath [22] as well as Kumari and Nath [23,24], which are in the stagnation region of a body, and work of Katz [25] as well as Afzal and Ahmad [26], Libby [27], and Gersten et al. [28], which are all general studies in the stagnation region of a body. Recently, Alizadeh et al. [29] have considered the unaxisymmetric stagnation-point flow and heat transfer of a viscous fluid on a moving cylinder with time-dependent axial velocity.

Studies of magnetohydrodynamic flow and heat transfer due to a stretching cylinder were performed by Ishak et al. [30] who obtained numerical solutions using the Keller-box method, Joneidi et al. [31] who obtained solutions using the homotopy analysis method, and Butt and Ali [32] who included the effects of entropy generation. Butt and Ali [32] generalized the results of Joneidi et al. by considering the cylinder to be embedded in a porous medium along with a partial slip boundary condition. Chauhan et al. [33] examined unsteady flow and heat transfer due to a stretching cylinder in consideration of two general types of thermal boundary conditions. Also, magnetohydrodynamic stagnation flow and heat transfer toward a stretching permeable cylinder have been analyzed in the recent studies conducted by Munawar et al. [34]. Uddin et al. [35] have considered the Group Analysis of Free Convection Flow of a Magnetic Nanofluid with Chemical Reaction. Studies of MHD axisymmetric flow of third grade fluid by a stretching cylinder were performed by Hayat et al. [36] who obtained solutions using the homotopy analysis method, Magnetohydrodynamic mixed convective slip flow over an inclined porous plate with viscous dissipation and Joule heating has been analyzed in the recent studies conducted by Das et al. [37]. Uddin et al. [38] have presented the hydromagnetic transport phenomena from a stretching or shrinking nonlinear nanomaterial sheet with Navier slip and convective heating. Adesanya and Falade [39] have studied a thermodynamic analysis of hydromagnetic third grade fluid flow through a channel filled with porous medium. Uddin et al. [40] studied the Group analysis and numerical computation of magneto-convective non-Newtonian nanofluid slip flow from a permeable stretching sheet and solved the governing problem by using Runge–Kutta–Fehlberg fourth-fifth order numerical method provided in the symbolic computer software Maple 14. Hayat and Nawaz [41] computed exact solution for the unsteady stagnation point flow of viscous fluid caused by an impulsively rotating disk. He noticed the effects of Hartman, Schmidt and mass Grashof numbers on the dimensionless velocity, temperature and concentration.

All the studies mentioned above are regarding the axisymmetric flow and heat transfer and none has considered the effect of flow being unaxisymmetric and magnetohydrodynamic. In the present analysis, the problem of magnetohydrodynamic unaxisymmetric stagnation-point flow and heat transfer of a viscous fluid on a stationary cylinder with non-uniform transpiration and constant wall temperature are considered for the first time. A reduction of Navier–Stokes and energy equations is obtained by use of appropriate similarity transformations. The semi-similar solution of these equations is obtained numerically using an implicit finite-difference scheme. All the solutions aforesaid are presented for Reynolds numbers, $Re = \bar{k}a^2/2\upsilon$, ranging from 0.01 to 100 for different values of Prandtl number and magnetic parameter and for

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