UNSTEADY MAGNETOHYDRODYNAMICS FLOW OF A MICROPOLAR FLUID WITH HEAT AND MASS TRANSFER

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requirements for the award of the degree of
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To My Beloved Family

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ABSTRACT

The unsteady boundary layer flow has become of great interest in the field of fluid mechanics including the area of convective double diffusion. This is due to the complexity of the problem by including extra independent time variable, especially in the study of magnetohydrodynamic flow immersed in a micropolar fluid. In this thesis, the unsteady two-dimensional laminar boundary layer and mixed convection stagnation point flow towards a stretching or shrinking sheet immersed in magnetohydrodynamic micropolar fluid are considered. Specific problems are considered with different effects such as Soret and Dufour effects, thermophoresis effect and slip effect. Along with these effects, the micropolar parameter, the magnetic parameter and the suction or injection parameter are also considered. The governing non-linear equations are transformed into a system of differential equations by using appropriate non-dimensional variables which are then solved numerically using an implicit finite difference scheme. Numerical results for the skin friction, the Nusselt number and the Sherwood number as well as the velocity, microrotation, temperature and concentration profiles for different physical parameters are presented graphically and in tabular form. The results obtained show that there is a smooth transition from small time solution to large time solution. It is also found that with an increase of Soret and Dufour numbers, the momentum boundary layer thickness increases whereas the microrotation boundary layer thickness decreases for assisting flow while a reverse trend is observed for opposing flow. The thermal and concentration boundary layer thicknesses increase in both cases. By increasing the values of the slip parameter, all the boundary layer thicknesses decrease. In addition, by increasing the values of thermophoresis, the concentration boundary layer thickness decreases.

ABSTRAK

Aliran lapisan sempadan tak mantap telah menjadi suatu kajian yang amat menarik di dalam bidang mekanik bendalir termasuklah juga bidang resapan kembar berolak. Ini disebabkan oleh penambahan pembolehubah tak bersandar masa yang menjadikan masalah ini semakin rumit, terutamanya di dalam kajian aliran hidrodinamik magnet di dalam bendalir mikropolar. Di dalam tesis ini, aliran lapisan sempadan lamina dan olakan campuran titik genangan dua matra tak mantap ke arah kepingan meregang atau mengecut di dalam bendalir mikropolar hidrodinamik magnet dipertimbangkan. Masalah yang dipertimbangkan melibatkan pelbagai kesan, khusususnya kesan Soret dan Dufour, kesan termoforesis dan kesan gelincir. Bersama dengan kesan ini, parameter mikropolar, parameter magnetik dan parameter sedutan atau suntikan juga dipertimbangkan. Persamaan menakluk tak linear diubah ke sistem persamaan pembezaan dengan menggunakan pembolehubah tak bermatra yang bersesuaian yang kemudiannya diselesaikan secara berangka menggunakan skim beza terhingga tersirat. Keputusan berangka bagi geseran kulit, nombor Nusselt dan nombor Sherwood beserta profil halaju, mikroputaran, suhu dan kepekatan bagi pelbagai parameter fizikal yang berbeza dipersembahkan secara grafik dan berjadual. Keputusan yang diperoleh menunjukkan adanya peralihan yang lancar daripada penyelesaian pada masa kecil kepada penyelesaian pada masa besar. Keputusan juga menunjukkan bahawa dengan meningkatnya nombor Soret dan Dufour, ketebalan lapisan sempadan momentum meningkat sedangkan ketebalan lapisan sempadan mikroputaran berkurangan bagi aliran berbantu manakala keadaan sebaliknya berlaku bagi aliran bertentang. Ketebalan lapisan sempadan terma dan kepekatan diperhatikan meningkat untuk kedua-dua kes. Peningkatan nilai parameter gelincir menyebabkan ketebalan kesemua lapisan sempadan berkurangan. Di samping itu, peningkatan nilai termoforesis juga mengakibatkan ketebalan lapisan sempadan kepekatan berkurangan.

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LIST OF SYMBOLS

Roman Letters

a,b - positive constants

b^* - induced magnetic field

B - magnetic field vector

B_0 - externally imposed magnetic strength in the $y-$direction

c_s - concentration susceptibility

$\bar{C}$ - fluid concentration

C - nondimensional fluid concentration

C_∞ - external concentration

C_w - surface concentration

C_p - specific heat at constant pressure

C_{fx} - skin friction coefficient

ΔC - concentration difference

Da^{-1} - inverse Darcy number

D_f - Dufour number

D_m - mass diffusivity

E - electric field vector

f - non-dimensional velocity

f_0 - suction or injection parameter

$\bar{\mathbf{F}}$ - body force

$\bar{\mathrm{F}}_x$ - scalar force in $x-$component

g - magnitude of the acceleration due to gravity

Gc - concentration Grashof number

Gr - thermal Grashof number

h - non-dimensional microrotation

j - microinertia density

J - electric current density vector

$\tilde{k}$ - thermal conductivity

k_1 - permeability of porous medium

k_1^* - vortex viscosity

k_T - thermal diffusion ratio

K - micropolar material parameter

L - characteristic length

L_1 - slip length

m_w - non-dimensional mass flux from the surface of the wall

M - magnetic parameter

MD - effective Darcy number

n - ratio of the microrotation vector component to the fluid skin friction at the wall

$\bar{N}$ - component of the microrotation vector normal to $x-y$ plane

N - non-dimensional component of the microrotation vector normal to $x-y$ plane

Nu_x - Nusselt number

O - order of magnitude

$\bar{p}$ - pressure

p - non-dimensional pressure

$\bar{p}_d$ - dynamic pressure

$\bar{p}_h$ - hydrostatic pressure

Pr - Prandtl number

q_w - non-dimensional heat flux from the surface of the wall

Re - Reynolds number

Sc - Schmidt number

Sh_x - Sherwood number

S_r	-	Soret number
$\bar{t}$	-	time
t	-	non-dimensional time
$\bar{T}$	-	fluid temperature
T	-	non-dimensional fluid temperature
T_m	-	mean fluid temperature
T_r	-	reference temperature
T_w	-	surface temperature
T_∞	-	external temperature
ΔT	-	temperature difference
$\bar{u}_e(\bar{x})$	-	dimensional external velocity
$u_e(x)$	-	non-dimensional external velocity
$\bar{u}_w(\bar{x})$	-	dimensional velocity along the sheet
$u_w(x)$	-	non-dimensional velocity along the sheet
$\bar{u},\bar{v}$	-	velocity components along $\bar{x},\bar{y}$ axes
u,v	-	non-dimensional velocity components along x and y
U_∞	-	reference velocity
$\bar{V}$	-	dimensional velocity vector
$\bar{V}_T$	-	dimensional thermophoretic velocity
v_0	-	velocity suction or injection
$\bar{x},\bar{y}$	-	cartesian coordinates along the plate and normal to it, respectively
x,y	-	non-dimensional cartesian coordinates along the wall and normal to it, respectively
Δ	-	gradient

Greek Letters

α	-	thermal diffusivity
β	-	coefficient of thermal expansion

β^* - coefficient of concentration expansion

∂ - partial derivative

γ - spin gradient viscosity

ξ, η, ζ - transformed coordinate

δ - slip parameter

δ^* - boundary layer thickness

θ - non-dimensionl temperature

κ - thermal conductivity

κ^* - thermophoretic coefficient

μ - dynamic viscosity

μ_m - magnetic permeability

υ - kinematic viscosity

ρ - density

ρ_∞ - fluid density in the ambient medium

ε - shrinking parameter

ε^* - convergence tolerance

ϕ - non-dimensionl concentration

ψ - stream function

τ - thermophoretic parameter

τ_w - non-dimensional wall shear stress or skin friction

λ^* - concentration buoyancy parameter

λ - mixed convection parameter

σ - electrical conductivity

χ - velocity ratio parameter

Ω - buoyancy ratio

Subscripts

∞, e - far field or free stream condition

w - wall condition

d - dynamic pressure

p - constant pressure condition

Superscripts

k - number of iteration

$'$ - differentiation with respect to η

LIST OF APPENDICES

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The large volume of published studies on the boundary layer flow indicates the importance of the subject in engineering applications, such as hot rolling, skin friction drag reduction, grain storage, glass fiber and paper production. The importance of unsteady boundary layer flow is increasing in the field of fluid mechanics especially in the area of convective double diffusion. One of the main reason for such a importance is result of the complexity of the problem by including extra independent time variable. Generally, the ideal flow environment around the device is steady, although there are numerous situations for instances self-induced motions of the body, fluctuations, non-uniformities in the surrounding fluid, where undesirable unsteady effects arises. The study of unsteady boundary layer owes its importance to the fact that all the boundary layers, are, in sense, unsteady. Unsteady flows are generally observed in technological and environmental situations. Some of these observed in geophysical and biological flows, the processing of the materials, and in the spread of pollutants and fires. In the same vein, notable serious discussion on the unsteady boundary layer flow were previously carried out by researcher’s like Riley (1975) and Telionis (1981).

The study of fluids uses two lenses to explain the concept at length. The two categories are Newtonian and non-Newtonian. The Newtonian fluid indicates that when the fluids shear stress is directly and linearly proportional to the rate of angular deformation, whereas in the non-Newtonian fluid, shearing stress is not related to the rate of shearing strain. The equations which govern the flow of Newtonian fluid are the Navier-Stokes equations. There are few exceptions where Newtonian fluid fails to describe the properties of the fluid, these includes industrial colloids fluid, polymeric suspensions, liquid crystals and dust in air and blood flow in arteries and capillaries. Limitation in the explanation of these fluids led development of theories on non-Newtonian fluids. A classic example of the non-Newtonian fluids, that became centre of researcher's attention, is of micropolar fluid.

Eringen (1964) earlier developed the fluid mechanics of deformable microelements, which were termed as Simple Microfluids. Eringen defined the simple microfluid as: "A viscous medium whose behavior and properties are affected by the local motion of particles in its microvolume". These fluids are characterized by 22 viscosity and material constants and when applied to flow problems the result is a system of 19 partial differential equations with 19 unknown that may not be amenable to be solved. Eringen (1966) subsequently introduced a subclass of fluids which he named micropolar fluids that ignores the deformation of the microelements but still allows for the particle micromotion to take place. The theory of micropolar fluids, which consist of rigid, randomly oriented particles suspended in a viscous medium. These special features of micropolar fluids were discussed comprehensively by Ariman *et al.* (1973). In general, as part of the momentum is lost in rotating of particles, the flow of a micropolar fluid is less prone to instability than that of a classical fluid. The stability of micropolar fluids problems have been investigated by Lakshmana Rao (1970) as well as Sastry and Das (1985).

The study of micropolar fluid with heat and mass transfer has many engineering applications. These applications include refrigerator coils, power generators, metal and plastic extrusion, paper production, crystal growing, electric transformers and transmission lines. Eringen (2001) earlier demonstrated the adequacy of applying micropolar fluid theory in order to describe the liquid crystal behavior. Eringen in-addition indicated, other possible substances that may be modeled by micropolar fluid, these are magnetic fluids, clouds with dust, anisotropic fluids and biological fluids. It seems worth to mention importance of the study of non-Newtonian fluid as a result of the behavior that is not described by the Newtonian relationships.

Recent evidences highlight increasing interest of researchers in the stagnation point flow in micropolar fluid. A review of fluid dynamics history reveals stagnation point flows as one of the unique issue of the field. These problems can take any form, such as steady or unsteady, viscous or inviscid, two dimensional or three-dimensional, forward or reverse, and normal or oblique. The impetus for studying convective flows near the stagnation point region is due to the fact that the heat transfer is maximum at the stagnation point. Similarly, Sharidan (2005) further added that solutions at stagnation point may also serve as a starting solution for the solution over the entire body.

The study of dynamics of electrically conducting fluid is known as magnetohydrodynamics (MHD). The study of MHD flow of an electrically conducting fluid is of considerable interest in modern metallurgical and metal-working processes. There has been a great interest in the study of MHD flow with heat and mass transfer in any medium. This is largely, because of, the effect of magnetic field on the boundary layer flow control and on the performance of many systems using electrically conducting fluids. This type of flow has attracted the interest of numerous researchers. One of the most significiant reason of this importance is its applications in engineering problems such as MHD generators, plasma studies, nuclear reactors, geothermal energy extractions. However as a result of the application of magnetic field, hydromagnetic techniques are used for the extraction of pure molten metals from non-metallic inclusions. This is why; the type of problems that are dealing with is very useful for polymer technology and metallurgy.

Despite of the importance of MHD micropolar fluid flow near the stagnation point, recent efforts in this regard help identify new effects on the flow such as Soret and Dufour effects, slip effect and thermophoresis effect. Critical review of thermophoresis causes small particles to deposit on cold surfaces. Thermophoresis plays a central role in the fiber optical synthesis. Kishan and Maripala (2012) found that this importance is the result of its identification as the principal mechanism of mass transfer which used in the technique of modified chemical vapor deposition (MCVD). Similarly, the mathematical modeling of the deposition of silicon thin films, using MCVD methods, has been accelerated by the quality control measures enforced by the micro-electronics industry. These topics involve variety of complex fluid dynamical processes including thermophoretic transport of particles deposits, heterogeneous/homogenous chemical reactions, homogenous particulate nucleation and coupled heat and energy transfer. Other notable example relating to thermophoresis is the blackening of glass globe of kerosene lanterns, chimneys and industrial furnace walls by carbon particles, corrosion of heat exchanger, which reduces heat transfer coefficient, and fouling of gas turbine blades (Kandasamy *et al.* 2010).

In case of heat and mass transfer, Soret and Dufour effects are significant when the temperature and concentration gradients are highs. Thermal diffusion (thermo diffusion or Soret effect) corresponds to species differentiation developing in an initial homogeneous mixture submitted to a thermal gradient (Soret, 1980) while the energy flux caused by a composition gradient is called Dufour (diffusion-thermo) effect. These effects are considered as second order phenomena, on the basis that they are of smaller order of magnitude than the effects described by Fourier's and Fick's laws, but they may become significant in areas such as geosciences or hydrology (Benano-Melly *et al.* 2001).

Whilst discussing the field of fluid mechanics it is worth to mention important aspects like "partial slip condition". One of the important pillars on which the fluid mechanics is based is the no-slip condition. Although, there are situations where the conditions role is not significant or it is no more valid. These are the conditions where partial slip between the fluid and the moving surface may occur. Generally in case of no-slip condition it is noted that the molecule of the fluid flowing near the boundary stiks with the surface. In numerous practical situations it is important to replace the no-slip condition by the partial slip condition. This is because th no-slip condition at the solid fluid interface is no longer applicable when fluid flows in micro electro mechanical system (MEMS). The non-equilibrium region near the interface is more accurately described by the slip flow model. In order to deal with the problem, Navier recommended general boundary condition which shows the fluid slip at the surface. Navier similarly suggested that, the difference of the fluid velocity and the velocity of the boundary is proportional to the shear stress at that boundary.

1.2 Problem Statements

Interest in the magnetohydrodynamic flow of micropolar fluid has increased substantially over the past few decades due to the occurrence of these fluids in many applications. The behavior of this flow near the stagnation point towards a stretching or shrinking sheet has been studied theoretically by many researchers. The phenomenon of this fluid affected by some important effects such as thermophoresis effect, suction or injection effect, slip effect, Soret and Dufour effects are not yet explore but interesting to be investigated. Therefore, this research is conducted to explore the following questions. What is the behavior of this fluid in nature near the forward stagnation point with the effect of thermophoresis and suction or injection towards a horizontal sheet? In-addition efforts are also required to see how do the micropolar fluids models compared with the Newtonian fluids models on the stagnation point flow towards a shrinking sheet with thermophoresis and slip effects? Apart from these need also exists to view how are the reduced skin friction, the reduced Nusselt number and the reduced Sherwood number affected due to the presence of magnetic parameter, slip effect and mixed convection parameter on stagnation point flow towards a permeable shrinking sheet? How are the skin friction, the Nusselt number and the Sherwood number affected due to the presence of Soret and Dufour effects towards a stretching sheet in a porous medium?

1.3 Objectives and Scope

The purpose of this study is to investigate theoretically the unsteady boundary layer flow of a micropolar fluid near the stagnation point towards a stretching or shrinking sheet. This involves with developing the mathematical formulation and numerical simulation for computation, in order to calculate the flow characteristics as well as analyzing the numerical results of the following MHD heat and mass transfer problems:

1. The thermophoresis and suction or injection effects on the stagnation point flow towards a horizontal sheet;
2. The thermophoresis and slip effects on the stagnation point flow towards a horizontal shrinking sheet;
3. The slip effect on the mixed convection stagnation point flow towards a permeable shrinking sheet;
4. The Soret and Dufour effects on the mixed convection stagnation point flow towards a stretching sheet in a porous medium.

This investigation examines the laminar two-dimensional incompressible flow of a micropolar fluid. These problems are solved numerically by using an implicit finite difference scheme, namely Keller’s box. The Keller box method was earlier introduced by Keller (1970) and was used widely in solving the parabolic differential equations. The Newton’s method can be used if the differential equations that need to be solved are nonlinear. The implicit nature of the Keller’s Box method has generated a tridiagonal matrix, like other implicit method, however, the speciality of the Keller’s Box method is, the entries are expressed in blocks rather than scalars. The work of Cebeci and Bradshaw (1984), Cebeci (2002), Nazar (2003), Sharidan (2005) and Lok (2008) provide details about the method. No real experiments have been conducted to validate the numerical results.

1.4 Significance of Study

The Newtonian fluids have few limitations, one of such shortcomings is its incapability to describe some engineering and industrial processes which are made up of materials having an internal structure. The theory of micropolar fluid model introduced by Eringen (1966) exhibits the local effects arising from the microstructure and micro motion of the fluid elements. The presence of smoke or dust particularly in gas may also modeled using micropolar fluid dynamics. Vogel and Patterson (1964) and Hoyt and Fabula (1964) conducted experiments with fluids that containing the amounts of minute polymeric additives. It was observed that the skin friction reduced near a rigid body. Gray and Hilliard (1966) in his invention, introduce relatively small amounts of a non-Newtonian fluid, a long-chain polymer such as polyethylene oxide, into the water adjacent the bow of the ship. This alters the shear characteristics of the fluid in boundary layer of the ship which decreases the overall frictional drag of the vessel. This leads to the increasing ship speed and it decreases the required power to maintain a given vessel speed. There are some advantages in the fields of aeronautics and submarine navigation.

It is becoming extremely difficult to ignore importance of micropolar fluid with heat and mass transfer in areas like aeronautics and submarine. Similarly it have significiant importance in engineering applications, such as exothermic reaction in packed-bed reactors, heat transfer associated with storage of nuclear waste, cooling metallic plate in a bath and heat removal from nuclear fuel debris. Besides, the study of micropolar fluids, there are other applications in several industrial and technical processes such as nuclear reactors cooled during emergency shutdown, solar central receivers exposed to wind current, electronic devices cooled by fan and heat exchangers placed in a low-velocity environment.

Moreover, due to the use of the micropolar fluid in different manufacturing and processing industries, considerable attention has been given towards the understanding the important phenomena involving in heat exchange devices (Elbarbary and Elgazery, 2005). This importance require scientists and engineers to be familiar with the flow behavior and properties of such fluids or the way to use such kind of properties to predict flow behavior in the process equipment. In-addition it is also beneficial to know the nature of the flow, heat and mass transfer of micropolar fluid towards a stagnation point and the influence of the material properties to the stagnation point heat and mass transfer problems.

1.5 Thesis Outline

This thesis is comproised of eight chapters. The first chapter is introduction, which provides detail account of research background, problem statement, objectives, scope and significance of research. The study then moves to conduct critical review of the previous literature. Based on the efforts of chapter two in the Chapter 3 efforts was made for the mathematical formulation.

The fourth chapter is concerned with the thermophoresis and suction or injection effects on an unsteady MHD stagnation point flow in a micropolar fluid towards a horizontal sheet. The governing boundary layer equations are solved numerically by using Keller-box method. Graphical results presented includes velocity, microrotation, temperature and concentration profiles as well as the physical quantities, namely the skin friction, the Nusselt number and the Sherwood number, which significance in characterizing the heat and mass transfer. Apart from these different physical parameters such as MHD parameter, micropolar parameter, suction or injection parameter, thermophoresis parameter and time variable are also considered in this chapter. In-addition both weak concentration and strong concentration are considered in this chapter. The case $n = 0$ represents concentrated particle flow in which micro-element to wall surface are unable to rotate and denote strong concentration; $n = 0.5$ present the vanishing of the anti-symmetric part of the stress tensor and denote weak concentration while $n = 1$ indicates the turbulent boundary layer flows. A FORTRAN program for the effect of thermophoresis and suction or injection on the stagnation point flow towards a horizontal sheet is given in Appendix B.

In Chapter 5, the unsteady MHD boundary layer flow near the stagnation point on a shrinking sheet with thermophoresis and slip effects is considered. Based on the explanation provided in Chapter 4, both weak $(n = 0.5)$ concentration and strong $(n = 0)$concentration are considered. Graphs are plotted and discussed for various emerging parameters such as slip parameter, shrinking parameter, thermophoresis parameter, micropolar parameter and time variable.

The study, in Chapter 6, then looks at the numerical solution of the unsteady MHD mixed convection flow near the stagnation point on a shrinking sheet with slip effect. The effect of mixed convection parameter λ which is involved in the momentum equation is studied for both assisting $(\lambda > 0)$ and opposing flows $(\lambda < 0)$. The mixed convection parameter λ is a measure of the relative importance of free convection in relation to forced convection. When $\lambda \cong 1$, the free and forced convection are of the same order of magnitude. If $\lambda << 1$, flow is primary by forced convection while $\lambda >> 1$ free convection become dominant (Martynenko and Khramtsov, 2005).

In Chapter 7, the unsteady MHD mixed convection flow near the stagnation point in micropolar fluid on a stretching sheet in a porous medium with Soret and Dufour effects is considered. As in the Chapter 6, both cases of assisting $(\lambda > 0)$ and opposing $(\lambda < 0)$ flows are also considered. The novel aspect of this study is the focus on the porosity and Soret and Dufour effects. The numerical results have been plotted for the indispensable dimensionless parameters to show the influences on the velocity, microrotation, temperature as well as the three physical quantities.

Finally, the summary of this thesis and the suggestions for future research are given in Chapter 8. The list of the publication and current status are given in Appendix C.

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