STEADY FLOW OF SOME NON-NEWTONIAN FLUIDS THROUGH A POROUS MEDIUM BY USING ADOMIAN DECOMPOSITION METHOD

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mathematics)

Faculty of Science
Universiti Teknologi Malaysia

APRIL 2022

DEDICATION

This thesis is dedicated to my father, who could not see the end of this thesis. I am thankful to Allah that you have been my father, I have been so blessed with your love, and I have overcome the pains, and I wish if you are here because the journey is coming to an end. I will always remember you, and I will forever learn from your wisdom. My Duaa is going to you forever; my thesis is also dedicated to my family, husband, beloved children, and dearest friend, Shaymaa, who gave me unconditional support.

ACKNOWLEDGEMENT

First of all, I thank Allah SWT for blessing me with the opportunity, protection, and ability to complete my Ph.D thesis. My thanks to those who have assisted me and contribute to my ideas and broaden my knowledge. I would particularly like to express my sincere appreciation and gratitude to my thesis supervisors, Professor Dr. Zainal Abdul Aziz and Associate Professor Dr. Arifah Bahar, for their encouragement, guidance, critical review and kind supervision. Without their continued support and interest, this research would not have been completed or presented here.

My gratitude also goes to all my colleagues and friends who have helped make this research possible. I am thankful to all my family members, and I extend the utmost appreciation to my mother, brothers, and sisters. My thesis would never have been completed without those who have continued to provide essential knowledge, information, support, and encouragement to achieve my goals. My profound thanks to them all.

ABSTRACT

Non-Newtonian fluids are employed in a wide range of industrial applications. Non-Newtonian fluids that shows characteristics of both elastic and viscous fluids as a result of shear stress, are referred to as viscoelastic fluids. Constitutive equations of the viscoelastic fluids, flow patterns and viscous response are important challenges that need to be considered when modelling the flow in a porous medium. The predominant idea of this thesis is to find the analytical solutions of viscoelastic fluid in a porous medium. The primary goal of this research is to create a one-dimensional simulation for three different kinds of viscoelastic fluids, namely, Johnson-Segalman, Powell-Eyring, and Sisko fluids, in a porous medium. Further, Darcy's law is selected for simulating permeable media saturated by viscoelastic fluid. The effect of external magnetic field is an additional feature to the innovation of the constructed mathematical models. The system of nonlinear coupled partial differential equations supported by related boundary conditions are solved analytically by using the Adomian decomposition method (ADM). In the analysis, the impact of various physical parameters on velocity and temperature are scrutinized and the results are exhibited graphically. The wall shear stress versus governing constraints are also evaluated, and their results are summarised in the form of tables and graphs. The results demonstrated that for both isothermal and non-isothermal circumstances, the inclination angle causes a variation in shear stress. It is also observed that the viscosity and shear stress have a direct connection in the absence of a heating effect. Moreover, the viscosity of the non-isothermal state is sensitive to temperature variations for both lift and drainage problems. The findings validated the efficacy of the suggested technique, and the solutions are successfully approximated to the exact solutions.

ABSTRAK

Bendalir bukan Newton digunakan dalam pelbagai aplikasi perindustrian. Bendalir bukan Newton yang menunjukkan ciri-ciri bendalir elastik dan likat akibat tegasan ricih dirujuk sebagai bendalir viskoelastik. Persamaan konstitutif bagi bendalir viskoelastik, corak aliran dan gerak balas likat merupakan cabaran penting yang perlu dipertimbangkan semasa memodelkan aliran dalam medium berliang. Idea utama tesis ini ialah untuk mencari penyelesaian analisis bendalir viskoelastik dalam medium berliang. Matlamat utama penyelidikan ini ialah untuk mencipta simulasi satu dimensi untuk tiga jenis bendalir viskoelastik yang berbeza, iaitu bendalir Johnson-Segalman, Powell-Eyring, dan Sisko dalam medium berliang. Selanjutnya, hukum Darcy dipilih untuk mensimulasikan media berliang yang tepu oleh bendalir viskoelastik. Kesan medan magnet luaran merupakan ciri tambahan kepada inovasi model matematik yang dibina. Sistem tak linear yang digandingkan dengan persamaan pembezaan separa disokong oleh syarat sempadan yang berkaitan diselesaikan secara analitik dengan menggunakan kaedah penguraian Adomian (ADM). Dalam analisis ini, kesan pelbagai parameter fizikal terhadap halaju dan suhu diteliti dan hasilnya ditunjukkan secara grafik. Kuantiti fizikal tegasan ricih dinding dan pekali pemindahan haba berbanding kekangan yang mengawal juga dinilai, dan keputusannya diringkaskan dalam bentuk jadual dan graf. Keputusan menunjukkan bagi kedua-dua keadaan isoterma dan bukan isoterma, sudut kecondongan magnet menyebabkan kepelbagaian dalam tegasan ricih. Diperhatikan juga bahawa kelikatan dan tegasan ricih mempunyai sambungan langsung ketika tiada kesan pemanasan. Selain itu, kelikatan keadaan bukan isoterma adalah sensitif kepada suhu yang berubah-ubah untuk kedua-dua masalah angkat dan saliran. Dapatan mengesahkan keberkesanan teknik yang dicadangkan, dan penyelesaian berjaya dilakukan dengan anggaran yang lebih hampir dengan penyelesaian yang tepat.

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LIST OF ABBREVIATIONS

1D	-	One Dimensional
2D	-	Two Dimensional
ADM	-	Adomian Decomposition Method
BC	-	Boundary Conditions
HAM	-	Homotopy Analysis Method
HPM	-	Homotopy Perturbation Method
IC	-	Initial Conditions
MADM	-	Modified Adomian Decomposition Method
MHD	-	Magnetohydrodynamics
NDM	-	Natural Decomposition Method
OHAM	-	Optimal Homotopy Asymptotic Method
PDE	-	Partial Differential Equation
VIM	-	Variation Iteration Method

LIST OF SYMBOLS

a - Slip parameter
$\mathbf{b}$ - Induced magnetic field
$\mathbf{B}_0$ - Magnetic field strength
D/Dt - Material time derivative
$\mathbf{E}$ - Electric field
$\mathbf{D}, \mathbf{W}$ - Symmetric and antisymmetric part of the velocity
F - Total body force
$\mathbf{g}$ - Gravity
$\mathbf{I}$ - Identity tensor
$\mathbf{J}$ - Electric current density
K - Permeability
p - Pressure
$\mathbf{q}$ - Flux
$\mathbf{R}$ - Flow resistance given by the rigid matrix
$\mathbf{S}$ - Extra stress tensor
S_t - Stokes number
$\mathbf{T}$ - Cauchy shear stress
U_0 - Initial fluid velocity
u - Model velocity
$\mathbf{u}$ - Velocity vector
w_e - Weissenberg number
t - Time

Greek symbols

δ - The fluid layer thickness
ρ - Density
μ, η - Dynamic viscosity

λ_p - Relaxation time

λ_r - Retardation time

μ_{eff} - Effective viscosity

$\boldsymbol{\tau}$ - Shear stress tensor

ν - Kinematic viscosity

ϕ_i - Porosity

ϕ - Ratio of viscosities

θ - Angle of inclination

$\Theta_{w}.$ - Wall heat temperature

Θ_1 - Ambient temperature

Subscripts

xy - Dimensionless properties

Superscripts

T - Transpose properties

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CHAPTER 1

INTRODUCTION

1.1 Overview

Fluid mechanics is a significant branch of physics and engineering. It deals with the mechanics of fluids at rest or in motion and the forces acting on them. Fluid dynamics is a part of fluid mechanics that deals with the movement of the fluids, and their interaction with solids or other liquids at the boundaries, which describes their behaviour and related phenomena (Yunus and Cimbala, 2006). In recent years, there has been significant growth in fluid dynamics research. Generally, fluids can be categorised as Newtonian or non-Newtonian based on the relationship between shear stress and shear rate in the fluid. The relationship between shear stress and shear rate in the Newtonian fluid is linear. But, it is nonlinear for the non-Newtonian. (Chhabra and Richardson, 1999).

The study of flow of non-Newtonian fluids has considerably increased over the years due to their relevance in many practical applications such as food processing, oil drilling, automotive, and aircraft design. Boundary layer approximations can be a beneficial approach for modelling problems of non-Newtonian fluids. Research into boundary layer flow problems of non-Newtonian fluids in manufacturing processes such as aerodynamic extrusions of plastic sheets has provided a better understanding of the distribution of shear stress in the sheets under various operating conditions. It has also provided insight into current advances in fluid mechanics. This chapter provides a background of the researches related to the non-Newtonian fluid flow in a porous medium under some physical effects including magnetic field, angle of inclination and viscous dissipation. In the following section the problem statement is presented, and the research questions are highlighted. The objectives and scope of this study are defined based on the research questions. The significance of this study applicable to sciences and engineering are also highlighted in this chapter.

1.2 Research Background

Non-Newtonian fluids can be used in several industrial processes and applications including wastewater treatment, food industries, and polymers manufacturing. Most physical phenomena that occur during processing of non-Newtonian fluids such as the flow of plasma and the circulation of shallow-water waves can be described using differential equations (Debnath, 2011). Non-Newtonian fluids do not adhere to the Newton's law of viscosity (Nguyen and Nguyen, 2012). Fluids that exhibit both viscous and elastic characteristics during deformation are known as non-Newtonian viscoelastic fluids.

Non-Newtonian fluids varies in nature therefore many constitutive equations have been proposed to examine the physical properties of these fluids. It is difficult to describe the behaviour of these fluids using a single constitutive equation. Furthermore, the nonlinear properties of viscoelastic fluid make it difficult to obtain precise solutions to the equations of motion of these fluids. No universal method can be used to obtain the solution for the equation of motion. Therefore, many methods have been suggested to solve these equations (Duan et al., 2013; F.A Hendi, 2012).

The non-Newtonian fluid models are usually categorised into three types: differential type, rate type, and integral type. The rate type models describe the response of fluids with slight memory, which means that the state of stress in the fluid depends on the relative history of the fluid deformation. Example of this behaviour can be observed in diluted polymeric solutions. Among the different types of non-Newtonian fluids, the viscoelastic fluids are the most investigated because the fluids exhibit both viscous and elastic behaviour (Christensen, 2012; Malkus et al., 1990). Furthermore, viscoelastic materials exhibit specific flow and relaxation behaviour which makes them complex and challenging to study (Bird, 1976). The importance of viscoelastic fluids in commercial and industrial fields have motivated the scientific community to explore the complex dynamics of these fluids in a porous medium (Denn, 1990). The study of the behaviour of viscoelastic fluid in a porous medium is very important for scientific and engineering industries. Knowledge of the various dynamic phenomena exhibit by viscoelastic fluid in a porous medium can be used to make predictions of the stability of the fluid. Furthermore, understanding the flow of non-Newtonian fluids in a porous medium has many practical applications in engineering fields, such as the oil displacement in a porous pipe.

The flow of non-Newtonian fluid in porous media can be studied from a microscopic or macroscopic point of view. The microscopic study gives information about the bores inside the medium. This information can be used to predict the macroscopic behaviour of the system. The macroscopic approaches consider the global behaviour of the fluid flow, such as viscoelastic fluid properties. Moreover, no constitutive relation can forecast all non-Newtonian fluids (Fetecau and Fetecau, 2003; Hayat et al., 2019b). Under certain circumstances, the flow of non-Newtonian fluid in the porous medium becomes more complicated such as the flow under the Magnetohydrodynamic (MHD), which explains the dynamics of electrically conducting fluid. The critical fact behind the MHD is that the applied magnetic field induces electric current. The consequence of this process produces a Lorentz force which can significantly affect the motion of the fluid. This complexity makes it difficult to find the exact solutions for the fluid motion, compared to the numerical solutions. However, an approximate analytical solution can be found using the Adomian Decomposition Method (ADM). The ADM is very useful for solving linear equations, nonlinear ordinary equations, partial differential equations, algebraic equations, functional equations, and integral differential equations (Wazwaz, 2010).

The current study aims to develop a theoretical framework for understanding the flow of non-Newtonian fluids in porous medium. This study focuses on the processes involved in the lifting and draining of viscoelastic fluid in porous medium. Three non-Newtonian fluid models under steady state, homogeneous and shear flow conditions are investigated. The constitutive models are namely: Johnson-Segalman fluid, Powell-Eyring fluid, and Sisko fluid. The MHD is mathematically formulated for Powell-Eyring fluid and Sisko fluid only. It is not considered for Johnson-Segalman fluid due to the complexity of the fluid equation. The effects of the temperature on the viscosity of Sisko fluid are studied. The current study analyses the impact of effective parameters in porous medium. The ADM method is implemented to solve the governing equations of the three fluid models.

1.3 Problem Statement

Non-Newtonian fluids have nonlinear constitutive equations and complex properties, whereas Newtonian fluids have a linear constitutive relationship. Instabilities such as melt fracture and extrusion die flows were caused by this nonlinearity. These instabilities are caused by the normal fluid stresses (elasticity) or the existence and the nature of the boundary conditions (Phan-Thien and Mai-Duy, 2017). The constitutive equations for viscoelastic fluids determine the fluid viscosity consistency. Some of these constitutive equations are derived from empirical relationships, while others are complex and are derived from advanced molecular theories. Due to the complexity of these nonlinear constitutive equations, obtaining analytical solutions is a difficult task, as described below.

First, constitutive equations, which are the relationship between stress and the rate of strain tensors, predict how much pressure or stress is required to deform a material. For certain non-Newtonian fluids, the shear stress tensor is complicated, such as the Johnson-Segalman fluid because it is derived from molecular theory (Bird, 1976; Johnson Jr and Segalman, 1981). Second, stress control is more important than motion control because stress affects the fluidity and solidification of some substances, such as polymers (Renardy, 2005a). Some non-Newtonian fluids equations, such as Powell-Eyring fluid equation, becomes very complicated when subjected to external circumstances such as shear stress, MHD, body force, porous medium, and inclination (Chhabra and Richardson, 1999). Finally, in temperature-dependent viscosity, the fluid equation's momentum equation is combined with the energy equation, making the governing equation highly nonlinear, such as the heat transfer flow of the Sisko fluid in a porous medium. (Nield et al., 2006).

Understanding viscoelastic fluid flow in a porous medium where the flow becomes more complex is beneficial in many applications such as thermal insulation engineering, water movements in geothermal reservoirs, heat pipes, and nuclear waste. Theoretical research on this type of fluid which moves along various geometries, such as a wide flat plate and two belts with some significant effects: heat dissipation and MHD effects, are rarely studied. Therefore, these will be investigated in the current study. As a result, the advancement of non-Newtonian fluid modelling appears to be required, in order to investigate these fluid flow types in a porous medium thoroughly. Therefore, this research is conducted to study the lifting and drainage of the thin film of viscoelastic fluid that moves along a flat plate or between two belts. This research also looks at the factors which influence the fluid flow. These factors are inclination, magnetic field, viscosity, and heat effect. One way to solve these problems is to implement an approximate analytical approach using the ADM to explore the following issues:

1. Viscoelastic fluid control is a crucial factor in the design of industrial materials. However, in certain circumstances, the viscoelastic responses of Johnson-Segalman fluid remain difficult.
2. Most of the solutions available for the Powell-Eyring fluid equation are numerical solutions, mainly if the fluid flows in a porous medium (Jalil et al., 2013; Ogunseye et al., 2019; Oyelami and Dada, 2016 ; Zaman et al., 2013). However, the new characteristics of the shear stress of the fluid during its flow in a porous medium encourage the discovery of an approximate analytical solution.
3. The temperature-dependent viscosity of Sisko fluid requires that the energy equation to be coupled to the momentum equations. Moreover, if the induced effect of the no-slip condition, MHD, and a porous medium is considered, an approximate analytical solution is required.

1.4 Research Questions

The following questions are raised based on the problem statement.

1. Is there any influence of shear stress, inclination, and porous medium on the steady flow of Johnson-Segalman fluid?

2. What is the Powell-Eyring fluid behaviour under the MHD effect for the steady flow in a porous medium?

3. To what extent does the temperature-dependent viscosity affect the flow of MHD Sisko fluid between two vertical belts?

1.5 Research Objectives

Based on the above problems, this study focuses on developing mathematical models that describe the incompressible, steady, and one-directional flow of the non-Newtonian fluid in a porous medium. It investigates the related parameters that influence the flow behaviour for the lifting and drainage flow with vertical or inclined geometry. Isotropic porous media is assumed for all the study's objectives to avoid the porous medium's complex nature. The study also aims to implement ADM to obtain the selected models' approximate analytical solution for lifting and drainage flow. The research objectives are as follows:

1. To study the steady flow of Johnson-Segalman fluid over an inclined plate in a porous medium using ADM.

2. To analyse the physical behaviour of the steady flow of MHD Powell-Eyring fluid over an inclined plate in a porous medium using ADM.

3. To investigate the influence of temperature-dependent viscosity on the flow of MHD Sisko fluid between two vertical belts in a porous medium using ADM.

1.6 Research Scope

This research is focused on the steady flow of the incompressible viscoelastic fluids in porous medium. The fluid models employed in this study are the Johson-Segalman fluid, Powell-Eyring fluid, and Sisko fluid. The lifting and drainage flow under the gravitational force and the effects of angle of inclination are also considered. For simplicity, the homogeneous model is considered for one-dimensional flow situation. The complexity of the models mentioned in section 1.2 can vary depending on the constitutive equation of the fluid and how the porous term is defined. Darcy's law is implemented for the flow of Johnson-Segalman fluid over an inclined plate. Due to the complexity of the constitutive equation of the Johnson-Segalman fluid, a simple flat plate geometry is selected. The plate is inclined in a porous medium without considering the effects of the magnetic fields. Furthermore, nonlinear differential equation, which relates the stress to the strain rate for Powel-Eyring fluid, is derived based on the interaction between the fluid, the magnetic field and angle of inclination. Finally, Sisko fluid is catalysed by heat flow and viscous dissipation of the magnetic field in the porous medium. MAPLE 2015 software is utilised to find the approximate analytical solution of the proposed problem via ADM. The results obtained are plotted and compared to the related published work.

1.7 Significance of the Study

The flow of viscoelastic fluids in porous medium presents many unique challenges for non-Newtonian fluids. The ability to use a simplified analytical tool to find a solution to the problem of non-Newtonian flow is potentially an important planning and management tool for industries where application of flow of non-Newtonian fluids are important. This research will provide a theoretical insight into the flow behaviour in an inclined system. Hence, the significances of this study can be summarised as follows:

1. A simple and realistic mathematical model is developed to better understand the viscoelastic fluid behaviour in a porous medium, particularly the Johnson-Segalman fluid.
2. This research will shed light on how the magnetic field and other physical conditions which affect the lifting and drainage flow of the Powell-Eyring and Sisko fluid models can help to gain a better understanding of the physical

behaviour and flow characteristics for the non-Newtonian fluid flows in a porous medium.

3. The basic knowledge gains in the areas of magnetic field, shear stress, temperature-dependent viscosity, and non-Newtonian fluid, can be useful information for many applications in science and engineering.

4. The analytical solutions obtained in this study can be used as the basis for future research to verify the solutions of more complex mathematical models obtained utilizing numerical solutions.

1.8 Thesis Outline

This thesis consists of seven chapters. The introduction, research background, statement of the problem, research questions, research objectives, research scope, significance of the research, and the layout are covered in this chapter.

Chapter 2 reviews and analyses the previous work related to the research objectives and covers an extensive review of earlier studies carried out using ADM.

Chapter 3 is divided into two parts. The first part covers the formulation of the problems using the general principles of mechanics, the derivation of governing equations for steady incompressible non-Newtonian fluids related to each objective are taken into consideration. The second part provides a detailed description of ADM and the other alternative formulas of the method.

Chapter 4 presents an approximate analytical solution for steady flow of Johnson-Segalman fluid over an inclined plate in a porous medium. Comparison of the fluid flow behaviour for porous and non-porous medium is conducted. The model is validated by comparing the present solution with the solution obtained by Alam et al. (2012) in the case of non-porous medium.

Chapter 5 considers the steady flow of Powell-Eyring fluid induced by a magnetic field over an inclined plate in the porous medium. As in Johnson-Segalman fluid model, the viscosity is assumed to be constant, and the flow driven by the shear and gravity. Thermal effects are not considered in this chapter.

Chapter 6 investigates the steady flow of the Sisko fluid over a wide belt in porous medium, using temperature dependent viscosity. The effect of the magnetic field and viscous dissipation is also considered.

In Chapters 4, 5, and 6, the solutions of the problems are obtained using the ADM which produced approximate analytical solutions. These solutions satisfy all initial and boundary conditions. Moreover, the graphical representations of the velocity profile are presented to show the impact of essential flow parameters on velocity and temperature. Finally, Chapter 7 presents the overall conclusions and the proposed future work. References and appendixes are listed at the end of the thesis.

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LIST OF PUBLICATIONS

Journal papers

1. Fawzia, M.E., Bahar, A., Mustafa, S.D., Aziz, Z.A., Salah, F. (2021). Effects of Shear Stress on Magnetohydrodynamic (MHD) Powell Eyring Fluid over A Porous Plate: A Lift and Drainage Problem. *IAENG International Journal of Applied Mathematics,* (Q3, Correction submitted - **IJAM_2020_11_18b**).

2. Fawzia, M.E., Bahar, A., Mustafa, S.D., Aziz, Z.A. (2021). Magnetic Resistive Flow of Sisko Fluid in A Porous Channel with Variable Viscosity. *Numerical Methods for Partial Differential Equations*, (Q1, Correction submitted - **NMPDE-2020-4151**).

3. Fawzia, M.E., Mustafa, S.D., Bahar, A., Aziz, Z.A. (2019). Steady Flow of Johnson-Segalman Fluid through Porous Medium over an Inclined Plate. *Journal of Porous Media*. 22(5), 583- 598.

4. Fawzia, M.E., A., Aziz, Z.A. Salah, F., Mustafa, S.D., (2017). Approximate analytical solution of the MHD Powell-Eyring fluid flow near accelerated plate. Malaysian Journal of Fundamental and Applied Sciences. 416-420