MAGNETOHYDRODYNAMICS SQUEEZING NON-NEWTONIAN FLOWS WITH AND WITHOUT NANOFLUID BETWEEN TWO PARALLEL PLATES IN POROUS MEDIUM

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DEDICATION

This thesis is dedicated to my late father, Mat Noor Jusoh, who has been my all time supporter. You are the greatest gift I have ever receive from Allah SWT in my life. Thank you very much for all your prayers for me.

To my beloved mother, Ramlah Adam, who has been a source of encouragement and inspiration throughout my life. She is the greatest influencer in my life, who taught me to always trust in Allah SWT plans and believe in hard work. Thank you very much for loving me unconditionally, raising me, giving me strength and moral support that made the completion of this thesis possible.

To my brothers and sisters, who encourage and help me to get through all the hardship during my study.

My love for all of you can never be quantified.
May Allah SWT return all your kindness.

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ABSTRACT

The wide applications of ultrahigh cooling devices in the current industries are necessary to improve the effectiveness of thermal devices. The development of an advanced heat transfer fluid known as nanofluid is very important to satisfy the high cooling rate standard. Conventional fluid such as water, ethylene glycol, or engine oil has limited heat transfer capability owing to the low thermal conductivity. Therefore, the dispersion of metallic nanoparticles in the fluid is implemented to boost the thermal conductivity of the conventional fluid. The utilization of nanofluid in cooling devices has shown good results in energy saving and emission reduction. Furthermore, the flow of non-Newtonian fluid, especially Casson and Jeffrey fluid, has been acknowledged due to its flow behaviour depending on the shear stress applied. The fluid acts as a solid if the applied stress exerted is lower than yield stress, whereas the fluid begins to flow if the applied stress exerted is more than yield stress. Motivated by the significant features of non-Newtonian fluid and nanofluid, the aim of this study is to investigate the unsteady magnetohydrodynamic flow of Casson and Jeffrey fluids with and without nanoparticles embedded in a porous medium with slip boundary condition. The motion of fluid flow is generated by squeezing between two parallel plates with external stress. The effects of viscous dissipation and chemical reaction on fluid flow are also investigated. The nonlinear governing equations are transformed into ordinary differential equations using a similarity transformation and solved numerically via Keller-box method. The numerical and graphical results are obtained through MATLAB software. Meanwhile, the present results are validated by comparing them with the published results. Hence, a good agreement is obtained. The graphical results of velocity, temperature, and concentration profiles are analysed with various physical parameters. The results show that the increment of the fluid velocity and the wall shear stress in Casson and Jeffrey fluids with and without nanoparticles is caused by squeezing of plates. Meanwhile, the velocity, temperature, and concentration profiles decrease with the presence of magnetic field and also Casson and Jeffrey fluid parameters. It is discovered that the rate of heat transfer and temperature profile increase with the impacts of viscous dissipation and thermophoresis. In nanofluid, the rate of mass transfer decelerates for increasing Brownian motion, while it elevates when chemical reaction and thermophoresis increase.

ABSTRAK

Penggunaan yang meluas terhadap peranti penyejuk berkuasa tinggi dalam industri semasa adalah diperlukan bagi meningkatkan keberkesanan perisian terma. Pembangunan bendalir pemindahan haba termaju yang dikenali sebagai nanobendalir adalah sangat penting bagi memenuhi taraf kadar penyejukan yang tinggi. Bendalir konvensional seperti air, etilena glikol, atau minyak enjin mempunyai keupayaan pemindahan haba yang terhad kerana kekonduksian terma yang rendah. Oleh itu, penyerakan nanozarah logam dalam bendalir dilaksanakan bagi meningkatkan kekonduksian terma bendalir konvensional. Penggunaan nanobendalir dalam peranti-peranti penyejuk telah menunjukkan hasil yang baik dalam penjimatan tenaga dan mengurangkan pemancaran. Tambahan pula, aliran bendalir bukan Newtonan terutamanya bendalir Casson dan Jeffrey telah diiktiraf disebabkan pergerakan alirannya bergantung pada tegasan ricih yang dikenakan. Bendalir bertindak sebagai pepejal sekiranya tekanan yang dikenakan lebih rendah daripada tegasan alah, manakala bendalir mula mengalir sekiranya tekanan yang dikenakan lebih tinggi daripada tegasan alah. Didorong oleh ciri-ciri penting bendalir dan nanobendalir bukan Newtonan, tujuan kajian ini adalah untuk mengkaji aliran tak mantap magnetohidrodinamik bagi bendalir Casson dan Jeffrey dengan dan tanpa nanozarah di dalam medium berliang beserta syarat sempadan gelincir. Pergerakan aliran bendalir terjana oleh penghimpitan dua plat selari beserta tekanan luar. Kesan pelesapan likat dan tindak balas kimia ke atas aliran bendalir juga dikaji. Persamaan pembezaan separa tak linear diubah menjadi persamaan pembezaan biasa menggunakan transformasi keserupaan dan diselesaikan secara berangka melalui kaedah kotak-Keller. Keputusan berangka dan grafik diperoleh melalui perisian MATLAB. Sementara itu, pengesahan keputusan semasa dilakukan dengan membandingkan dengan keputusan yang telah diterbitkan. Oleh itu, persetujuan yang baik diperoleh. Keputusan secara grafik bagi profil halaju, suhu, dan kepekatan dianalisis dengan pelbagai parameter fizikal. Hasil kajian menunjukkan bahawa peningkatan halaju dan tegasan ricih dinding bagi bendalir Casson dan Jeffrey dengan dan tanpa nanozarah adalah disebabkan oleh penghimpitan plat. Manakala profil halaju, suhu, dan kepekatan menurun dengan kehadiran medan magnet dan juga parameter bendalir Casson dan Jeffrey. Didapati bahawa kadar pemindahan haba dan profil suhu meningkat dengan kesan lesapan likat dan termoforesis. Dalam nanobendalir, kadar pemindahan jisim adalah perlahan dengan peningkatan pergerakan Brownian, manakala ia meningkat dengan tindak balas kimia dan termoforesis.

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ADM	-	Adomian decomposition method
ANN	-	Artificial neural network
CM	-	Collocation method
DRA	-	Duan-Rach approach
DTM	-	Differential transform method
GM	-	Galerkin method
GOHAM	-	Galerkin optimal homotopy asymptotic method
HAM	-	Homotopy analysis method
HPM	-	Homotopy perturbation method
LSM	-	Least square method
MHD	-	Magnetohydrodynamic
MG	-	Maxwell-Garnetts
RVIM	-	Reconstruction of variational iteration method
VPM	-	Variation of parameters method

LIST OF SYMBOLS

Roman Letters

$\mathbf{A}_1$	-	Rivlin-Ericksen tensor
a	-	Reference length along the flow
B*	-	Total magnetic field
$\mathbf{B}_1$	-	Transverse magnetic field
$\mathbf{b}$	-	Induced magnetic field
B_0	-	Magnitude of applied magnetic field
Bi_1,Bi_2	-	Biot numbers
C	-	Concentration
C_w	-	Concentration at upper plate
Cf_x	-	Skin friction coefficient
c_f	-	Specific heat of fluid
c_p	-	Specific heat of nanoparticles
Da	-	Darcy number
De	-	Deborah number
D_m	-	Coefficient of mass diffusivity
D_B	-	Brownian diffusion coefficient
D_T	-	Thermophoresis coefficient
$\mathbf{E}$	-	Total electric field
Ec	-	Eckert number
$\mathbf{F}_x$	-	Body force along x-direction
$\mathbf{F}_y$	-	Body force along y-direction
f	-	Dimensionless velocity
g	-	Gravitational acceleration
Ha	-	Hartmann parameter
h	-	Distance of two plates

h_p	-	Specific enthalpy of nanoparticles
$\mathbf{I}$	-	Identity tensor
$\mathbf{J}$	-	Current density
$\mathbf{j}_A$	-	Mass flux
$\mathbf{j}_p$	-	Diffusion mass flux for nanoparticles
$\mathbf{j}_{p,B}$	-	Nanoparticles mass flux due to Brownian diffusion
$\mathbf{j}_{p,T}$	-	Nanoparticles mass flux due to thermophoretic effect
K	-	Porosity parameter
k_1	-	Permeability of porous medium
k_0	-	Permeability constant
k_B	-	Boltzmann constant
k_f	-	Thermal conductivity of fluid
k_c	-	Rate of chemical reaction
k_2	-	Constant of reaction rate
Le	-	Lewis number
l	-	Initial distance of two plates
M	-	Magnetic parameter
m	-	Mass of element
N_A	-	Molar flux induced by external forces
N_b	-	Brownian motion parameter
N_t	-	Thermophoresis parameter
Nu_x	-	Nusselt number
Pr	-	Prandtl number
p	-	Pressure
p_y	-	Yield stress of the fluid
q_s	-	Mass flux at the wall
$\dot{q}_x$	-	Heat flux in the x direction
$\dot{q}_y$	-	Heat flux in the y direction
q_w	-	Heat flux at the wall
$\mathbf{R^*}$	-	Darcy resistance
R	-	Chemical reaction parameter
Re_x	-	Reynold’s number

S	-	Squeeze number
Sh_x	-	Sherwood number
Sc	-	Schmidt number
t	-	Time
$\mathbf{T}$	-	Cauchy stress tensor
T	-	Temperature
T_H	-	Temperature at upper plate
T_∞	-	Temperature at free stream
T_w	-	Temperature at upper plate
u	-	Velocity in x-direction
u_w	-	Velocity at upper plate
v	-	Velocity in y-direction
v_w	-	Velocity at upper plate
$\mathbf{V}$	-	Velocity vector field
$\mathbf{V}_T$	-	Thermophoretic velocity
x	-	Dimensionless coordinate horizontal axis along the flow
y	-	Dimensionless coordinate vertical axis along the flow

Greek Letters

α_f	-	Thermal diffusivity of Casson fluid / Jeffrey fluid
β	-	Casson fluid parameter
δ	-	Boundary layer thickness
δ_m	-	Mass boundary layer thickness
δ_t	-	Thermal boundary layer thickness
η	-	Similarity variable
γ	-	Slip parameter
λ_1	-	Ratio of relaxation to retardation times
λ_2	-	Retardation time
μ	-	Dynamic viscosity
μ_B	-	Plastic dynamic viscosity
ν_f	-	Kinematic viscosity

ϕ	-	Dimensionless concentration
π_1	-	Product of deformation rate with itself
π_c	-	Critical value of the product
φ	-	Porosity of porous medium
ρ_f	-	Density of fluid
ρ_p	-	Density of nanoparticles
σ	-	Electrical conductivity
τ	-	Ratio of heat capacities
τ_{ij}	-	Shear force tensor for Casson fluid
τ_w	-	Wall shear stress
θ	-	Dimensionless temperature

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter consists of seven sections. Section 1.2 addresses the research background of non-Newtonian fluids, nanofluid, squeezing flow and several important physical effects considered in this study. The statement of problem and objectives of study are stated in Sections 1.3 and 1.4, respectively. Section 1.5 presents the scope of study and followed by the significance of study in Section 1.6. Lastly, thesis organization is described in Section 1.7.

1.2 Research Background

There are two types of fluids known as Newtonian and non-Newtonian fluids. The fluids are classified according to Newton's law of viscosity. The law states that the shear stress exerted on the fluid is directly proportional to the shear rate between the two layers. Mathematically, this law is written as

$$\tau \propto \mu \frac{\partial u}{\partial y}, \tag{1.1}$$

where τ denotes the shear stress, μ is the dynamic viscosity of the fluid and $\frac{\partial u}{\partial y}$ is the shear rate or velocity gradient [1]. The illustration of the shear rate between two layers is shown in Figure 1.1. Newtonian fluids are the fluid that obey Newton's law of viscosity. These fluids have constant viscosity which means the viscosity is independent of the shear stress. Meanwhile, non-Newtonian fluids do not obey Newton's law of viscosity. The viscosity of these fluids depends on the shear stress. Examples of non-Newtonian fluids are starch suspensions, custard, ketchup, blood, toothpaste and paint [2].

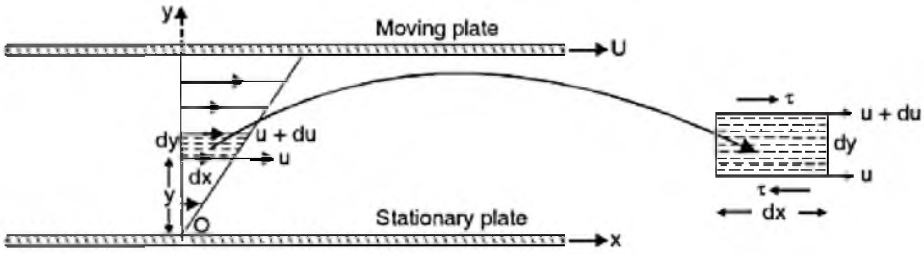

Figure 1.1: The shear rate between two layers [3]

The study of boundary layer flow of non-Newtonian fluids has received great attention from researchers due to its widespread in engineering applications such as chemical catalytic reactors, nuclear wastewater disposal, production of geothermal energy and groundwater hydrology [4]. In general, there are no single constitutive equation available in literature which describe the rheology of these fluids. Due to the distinct nature of these fluids, several models have been suggested by researchers to describe their rheological properties. Most common non-Newtonian models used are power law and second grade or third grade. However, these models are unable to predict the effect of elasticity and stress relaxation, respectively [5].

Casson fluid is categorized as one of non-Newtonian fluid due to its rheological behavior that related to shear stress and velocity gradient. It is a shear thinning fluid which exhibits an infinite viscosity at zero velocity gradient, no flow occurs when force applied below the yield stress and zero viscosity at infinite velocity gradient. Casson model was originally invented by Casson for printing inks and silicon suspension [6]. The model is an ideal model for studying the flow characteristics of blood. Some substances like red blood cells, protein, fibrinogen and globulin in aqueous base plasma need to be included in human blood in order to consider the blood as Casson fluid. Common examples of Casson fluid are tomato sauce, honey, jelly, concentrated fruit juices and soup [7].

There is another well-known fluid in the literature among non-Newtonian fluids known as Jeffrey fluid. It is a simple linear model which employed time derivatives instead of convective derivatives. The model able to describe the viscoelastic properties for the polymer industries due to the presence of the relaxation and retardation times parameter [8]. It constitutes a shear thinning fluid which possess high shear viscosity and yield stress. Figure 1.2 displays the effect of shear stress on viscosity of shear thinning fluid. Several authors have been used Jeffrey fluid model for the blood flow in narrow arteries [9], food bolus through esophagus [10] and movement of chyme in small intestine [11].

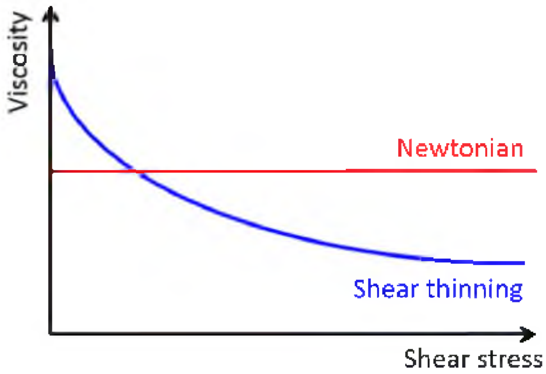

Figure 1.2: The effect of shear stress on viscosity of shear thinning fluid [12]

Ultrahigh-performance cooling is an important requirements for various industrial technologies. Basically, low thermal conductivity has become main limitation in establishing heat transfer fluids with higher energy efficiency that are necessary for cooling purposes. Hence, several attempts have been made to boost the thermal conductivity of fluids. The utilization of nanofluids in industrial cooling has shown good results in energy savings and emissions reductions [13]. Nanofluids are engineered colloids made of base fluid and nanoparticles. Choi and Eastman [14] were the first discovered the new class of heat transfer fluids created by suspending nanometer-sized particles in conventional heat transfer fluids such as ethylene glycol, water or kerosene oil. The conventional fluids also known as base fluids are poor heat transfer fluids because of its low thermal conductivity. They pointed out that suspended nanoparticles provide an effective way to enhance the heat transfer performance of base fluids. The nanoparticles employed in nanofluids are made of metals (Al, Cu), metal oxides, carbides, nitrides or non-metals (Graphite, carbon nanotubes). The main procedures in the preparation of nanofluid are presented in Figure 1.3.

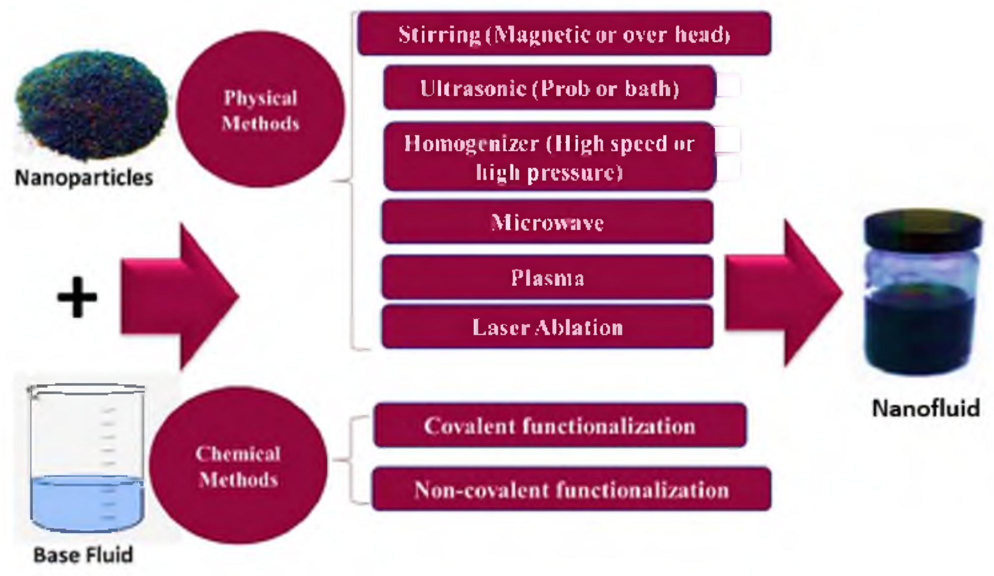

Figure 1.3: The main procedures in the preparation of nanofluid [15]

Nanofluids are predicted to possess high thermal conductivity compared to those base fluids because the suspended ultrafine particles significantly improve its capability in energy exchange [16]. Several researchers agreed that a small amount of nanoparticles volume fraction (5% or less) can increase the thermal conductivity of base fluid by more than 20%. These enhancements depend upon the shape, dimensions, thermal properties and volume fractions of suspended particles [17, 18].

After the seminal work of Masuda [19] on alteration of thermal conductivity by dispersing nanoparticles, many researchers have started showing their interest in this field. The primary proposed models for nanofluids behavior are twofold; homogeneous flow and dispersion models. However, Buongiorno [20] stated that the nanofluid heat transfer coefficient and the dispersion effect in the homogeneous model is assumed to be insignificant because of the nanoparticle size. Therefore, he developed an alternative model to overcome the limitations of those models. He asserted that the heat transfer enhancement in nanofluids happen due to movement of particle in fluids. Seven slip mechanisms including the inertia, gravity, Magnus forces, diffusiophoresis, fluid drainage, Brownian diffusion and thermophoresis are considered to investigate the nanoparticle migration. Later, he deduced that out of seven slip mechanisms, only Brownian motion and thermophoresis are responsible for heat transfer performance in nanofluids. Based on this outcome, he proposed non-homogeneous equilibrium model for convective transport in nanofluids known as Buongiorno's model. It is noteworthy that several researchers adopted the aforementioned model in their study [21–23].

The analysis on the effect of magnetic field in fluid flow is an active area of research caused by the geophysic and technology implementation. Magnetohydrodynamic (MHD) is the study that concerns the dynamic of magnetic fields in electrically conducting fluids. Examples of the fluids are plasma, liquid metals, saltwater and electrolytes [24]. Interest in MHD flow began when Hartmann invented the electromagnetic pump in 1918. However, the progress on MHD study become slower until it was initiated back by Hannes Alfven, a famous Swedish physicist. He received Nobel Prize in Physics in 1970 for his work in describing the class of MHD waves known as Alfven waves [25]. The research of magnetic field effects on the laminar flow of an incompressible electrically conducting fluid is a significant problem which correlated to several engineering applications, for example MHD power generator, MHD pump and boundary layer control in aerodynamics [26].

The study of MHD together with porous media has been a growing research interest because of its diverse engineering usages in groundwater flow, recovery of crude petroleum, irrigation problems, chemical catalytic reactors, chromatography, thermal and insulating engineering [27]. A porous medium is known as a material that consists of a solid matrix with an interconnected empty space. The porosity of a porous medium refers to the fraction of empty space in the total volume of material [28]. Figure 1.4 depicts the illustration of fluid flow through a porous medium. The first experimental study on the flow of mercury in porous media was conducted by Wallace, Pierce & Swayer in 1969. The experiments were performed either with the presence of magnetic field or combination of magnetic field and electric current. From the observations, it showed that the variation in the flow rate of mercury occurs when both magnetic field and electric current is applied. However, the presence of magnetic field alone did not affect the rate of the fluid flow [29].

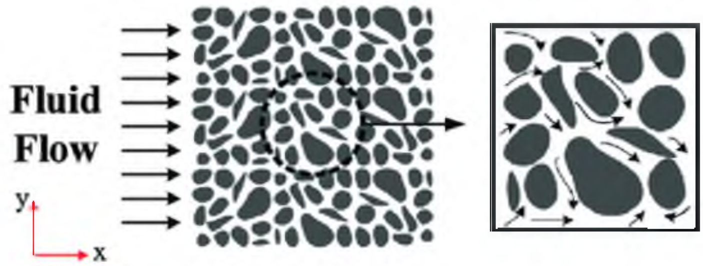

Figure 1.4: The fluid flow through a porous medium [30]

Another important mechanism that influences the behavior of fluid is heat transfer. Heat is a form of thermal energy and heat transfer takes place within a medium or among neighboring media due to temperature differences [31]. There are three basic modes of heat transfer namely conduction, convection and radiation. It is shown that convection has received great attention because of the practical usages in industries. Convection is the transfer of thermal energy between surface and moving fluid at different temperature. The convective heat transfer is divided into free, forced and mixed convection. Free or natural convection occurs when the fluid motion is induced by buoyancy forces that arises from density variation due to temperature and concentration differences. Meanwhile, the fluid motion generated by external resources such as pump, fan and fluid machinery is referred as force convection. The mechanism of mixed convection occurs when both free and force convection contribute to the heat transfer simultaneously. Mixed convection flow is used in many industrial problems such as cooling of nuclear reactors when emergency shutdown, cooling of electronic devices by fans, a heat exchanger at the low velocity environment and solar collectors [32].

The study of convection heat and mass transfer phenomenon in fluid flows has gained considerable attention from researchers as it occurs frequently in nature. It can occur due to the variation of temperature, concentration or combination of these two. The transport of substance or mass caused by concentration gradient is called mass transfer. Coupled heat and mass transfer plays a crucial role in absorption, evaporation, condensation, extraction and drying. In nature, the present of pure water or air is not achievable since the reaction between foreign substance and fluid cannot be refuted [33].

The effect of viscous dissipation is often neglected in low speed and viscosity fluid flow, yet its presence become significant when the fluid velocity and viscosity is high. Viscous dissipation is an irreversible process in which the conversion of mechanical energy to thermal energy occurs due to viscosity of fluid during the motion of fluid particles. The flow pattern is affected because of high velocity gradient closer to the surface. The main effect of dissipation is an increment in the fluid temperature [34]. The effect was initially considered by Brinkman in 1951. He examined the temperature profile of Newtonian fluid in straight circular tube. and noticed that the temperature rises caused by dissipation in the close region. The role of the viscous dissipation on heat transfer during fluid flow has become subject of interest in the industrial applications such as temperature rises in polymer processing, injection molding and high rates extrusion [35].

The fluid flow with chemical reaction has attracted the attention of engineers due to its importance in design of chemical processing equipment, food processing, generating electric power and damage of crops. There are two types of chemical reaction namely homogeneous and heterogeneous. The reaction is categorized as homogeneous or heterogeneous based on its occurrence in single phase (gaseous, liquid, or solid) or two phases (solid and gas, gas and liquid or solid and liquid), respectively [36]. Homogenous reaction occurs if the reactants and products are in the same phase while heterogeneous reactions have reactants in two or more phases. The formation of smog is a significant example representing the first order homogeneous chemical reaction. The first order reaction has a reaction rate proportional to the reactants concentration [37].

The fluid that exhibits slip effect at a fluid-solid interface have significant practical usages involving polish of artificial heart valves and internal cavities. Velocity slip is defined as the function of the Knudsen number and the velocity gradient at the wall. It is known as the non-adherence of the fluid to a solid boundary. Slip flow usually occurs when the size of flow system or the flow pressure is very small [38]. A numerous literature is devoted to the flow with no slip condition. However, the condition is only valid if the Knudsen number is small, while the velocity slip is valid for large Knudsen number. The difference of flow velocity with no-slip and slip boundary conditions are portrayed in Figure 1.5. The partial slip often involving the fluids like emulsions, suspensions, foams and polymer solutions. The idea of partial slip condition was proposed by Beavers and Joseph [39] for the flow past the permeable wall. The fluid flow with slip is implemented in the system of microelectromechanical. The behavior of flow exhibit slip condition due to the dimension of microscale [40].

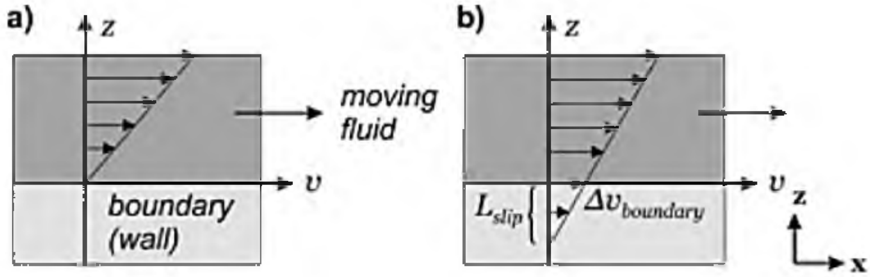

Figure 1.5: The flow velocity with no-slip and slip boundary conditions [41]

Squeeze flows are the flow in which constant mass of a material is compressed between two parallel plates or nearly parallel boundaries approaching each other. The fundamental analysis of squeezing flow has its origins in 18th century and continues to receive considerable attention following the pioneer work on basic formulation of squeeze flows of Newtonian fluids under lubrication approximation by Stefan [42]. Thereafter, various aspects of squeeze flows have been studied by researchers focusing on rheometry, parameter identification, constitutive equations and numerical simulation. The squeeze flow between parallel plates has promising applications in engineering and industrial such as hydraulic lifts, flow inside syringes and nasogastric tubes, moving pistons, electric motors and power transmission squeezed film [43].

1.3 Problem Statement

Experts worldwide are actively engaged in conducting experimental studies on nanofluids for heat transfer applications such as electronic cooling and heat exchangers. The high efficiency of electronic devices has caused heat dissipation occurs at a faster rate. Since the amount of heat to be dissipated is large, another heat transfer fluid is required instead of the conventional fluids. Several attempts have been made by researchers to overcome the limited heat transfer capability of conventional fluids due to their low thermal conductivity. A new class of fluids was developed by dispersing nanosized particles in the conventional fluids. This class offers better cooling and heating performance in industrial process. Existence of nanoparticles enhance the thermophysical properties and heat transfer rate of the conventional fluids. Although extensive research works have been devoted to the heat transfer in Newtonian fluids, it is well recognized that research in non-Newtonian fluids has gained considerable attention due to their potential in industries. The theoretical study on these fluids is more challenging and interesting due to the complexity of their constitutive equations. Consequently, the study of squeezing flow between two parallel plates involving non-Newtonian fluid has not been given much consideration compared to Newtonian fluid.

Based on the aforementioned matters, this study focuses on unsteady squeezing flow of non-Newtonian fluid and nanofluid, which are Casson and Jeffrey fluids between two parallel plates. The present study explores the following research questions:

(i) How do the mathematical models for MHD non-Newtonian fluid and nanofluid in the problem of unsteady squeezing flow through a porous medium with velocity slip condition can be formulated?
(ii) How does the combined effects of viscous dissipation and chemical reaction will affect the heat and mass transfer characteristics of non-Newtonian fluid and nanofluid?
(iii) How to develop a programming code in MATLAB software to find the numerical solutions of the problems?

Specifically, the problems considered in this study are as follow:

(i) Unsteady MHD squeezing flow of Casson fluid saturated in a porous medium with velocity slip.

(ii) Unsteady MHD squeezing flow of Casson fluid saturated in a porous medium with velocity slip in presence of viscous dissipation and chemical reaction.

(iii) Unsteady MHD squeezing flow of Casson nanofluid saturated in a porous medium with velocity slip in presence of viscous dissipation and chemical reaction.

(iv) Unsteady MHD squeezing flow of Jeffrey fluid saturated in a porous medium with velocity slip.

(v) Unsteady MHD squeezing flow of Jeffrey fluid saturated in a porous medium with velocity slip in presence of viscous dissipation and chemical reaction.

(vi) Unsteady MHD squeezing flow of Jeffrey nanofluid saturated in a porous medium with velocity slip in presence of viscous dissipation and chemical reaction.

1.4 Objectives of the Study

This study explores the unsteady squeezing flow of Casson fluid and Jeffrey fluid between two parallel plates. The presence of nanoparticles in the fluids are taken into account. Moreover, the effects of MHD, porous medium, viscous dissipation, chemical reaction and slip boundary condition are also analyzed. The governing nonlinear partial differential equations are converted into the system of nonlinear ordinary differential equations with the help of suitable transformation and then numerically solved using Keller-box method. The obtained results are displayed graphically and discussed in detail. In order to validate the present method, numerical results for skin friction, Nusselt and Sherwood numbers are compared with the existing literature results. The objectives of this study are:

(i) To derive the mathematical models of the problems which involve continuity, momentum, energy and concentration equations.

(ii) To solve the governing equations numerically using Keller-box method and develop numerical algorithm in MATLAB software to obtain the solutions of all problems.

(iii) To examine the effects of pertinent parameters including Casson, Jeffrey, Hartmann, porosity, magnetic, viscous dissipation and chemical reaction parameters on velocity, temperature and concentration profiles as well as skin friction, Nusselt and Sherwood numbers.

1.5 Scope of the Study

This study focuses on the unsteady flow of Casson fluid and Jeffrey fluid. The presence of nanofluid is considered. The flow is generated due to squeeze between two infinite parallel plates. Further, the effects of MHD, porous medium, viscous dissipation, chemical reaction and slip boundary condition are also taken into account. Buongiorno's nanofluid model is implemented in this study. Boundary layer approximation is employed to simplify the governing equations. The governing partial differential equations are transformed into a set of ordinary differential equations using suitable non dimensional variables. The dimensionless nonlinear ordinary differential equations are solved numerically via implicit finite difference scheme known as Keller-box method. The method is unconditionally stable with a second order convergence. It is also found to be very suitable in dealing with nonlinear parabolic problems. The detail of this method is described in Cebeci and Bradshaw [44]. The computation of numerical results is achieved and plotted graphically using algorithm developed in MATLAB software. In order to check the accuracy of present algorithm, the numerical results obtained is compared with previously published works as limiting cases. The framework for this study is displayed in Figure 1.6.

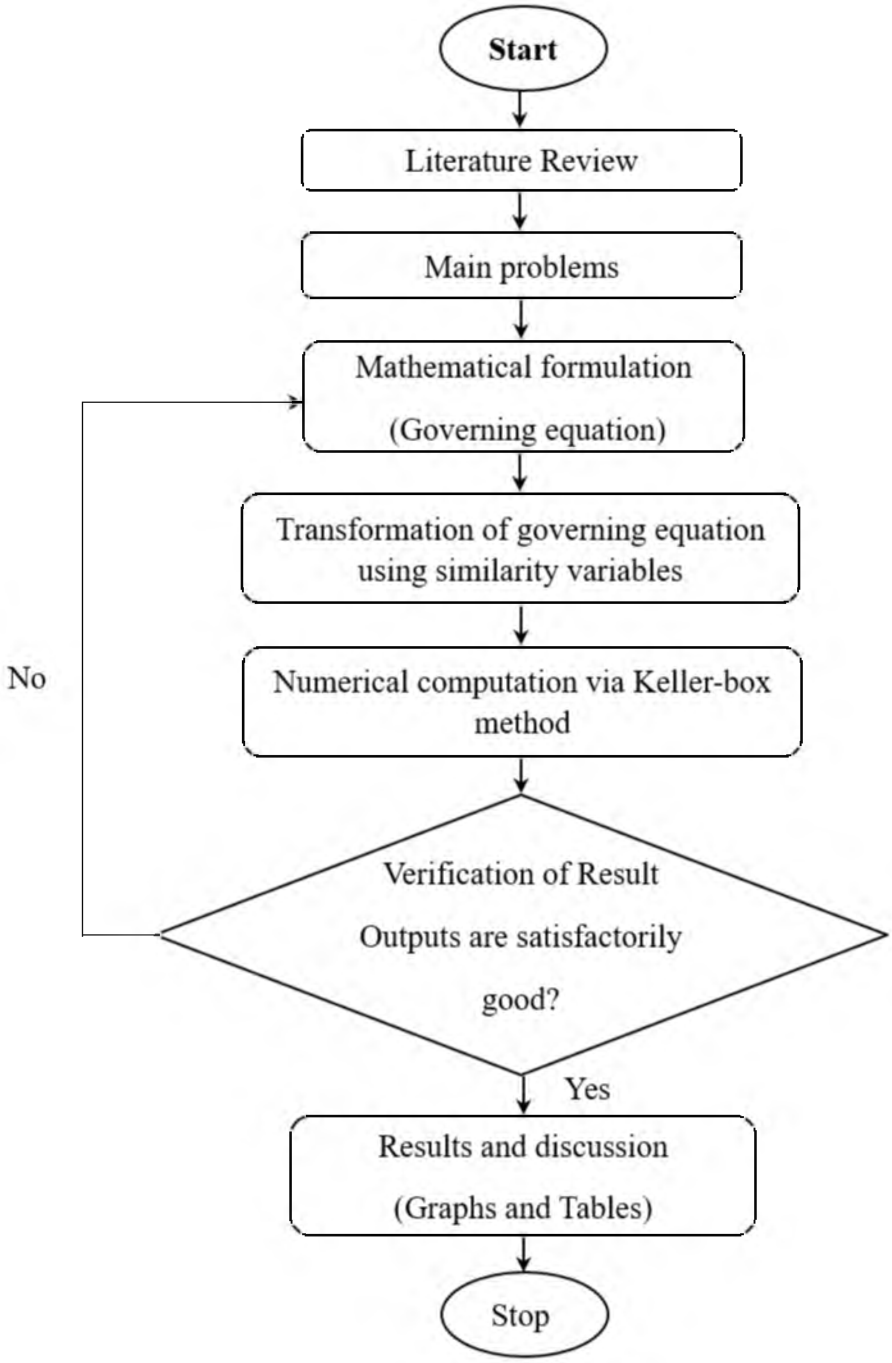

Figure 1.6: Research framework

1.6 Significance of the Study

Nanofluids have been a topic of great interest in the past decade due to their heat transfer attributes. The conventional heat transfer fluids like water, ethylene glycol and engine oil are unproductive and inadequate to fulfill the current industrial and technological demands because of their low heat transfer capability. It is well known that metals have thermal conductivities up to three times higher than those fluids [45]. Hence, the dispersion of metallic nanoparticles in the conventional fluid is implemented to improve the thermal conductivity and enhance the heat transfer characteristics of the fluid significantly. Nanofluids have novel properties that potentially useful in numerous applications involving heat transfer such as cooling of the microchips in computers, improve the performance of coolant in nuclear power system and vehicle engines, and biomedical in nano-drug delivery [46]. The classical Navier Stokes equations employed in viscous Newtonian fluids fail to simulate the critical characteristics of non-Newtonian fluids. The relationship between shear stress and rate of strain for non-Newtonian fluids are complicated compared to viscous fluid. Several constitutive equations of non-Newtonian fluids based on their empirical observations have been introduced. There are some famous non-Newtonian models in the literature such as Casson fluid, Jeffrey fluid, second grade fluid and viscoelastic fluid [47]. Among various of non-Newtonian fluids, the dynamic of Casson and Jeffrey fluids are gained attention due to its practical applications. The flow of blood in different geometries using Casson and Jeffrey fluids model is investigated by many researchers. The model describes the characteristics of blood flow more accurate when it flows through small blood vessels and low shear rate [48–50]. Generally, the significances of the study are as follows

(i) Enhance knowledge on the rheological behavior of non-Newtonian fluid, especially Casson fluid and Jeffrey fluid.
(ii) To give insight on the physical behavior of nanoparticles on the fluid velocity, temperature and concentration profiles.
(iii) Build a better understanding on squeezing flow of Casson and Jeffrey fluids between two parallel plates with and without nanoparticles.

(iv) Increase knowledge of heat and mass transfer on squeezing flow of Casson and Jeffrey fluids over porous medium under the influences of viscous dissipation and chemical reaction.

(v) Development of MATLAB codes that capable in solving unsteady flow of Casson and Jeffrey fluids problems.

(vi) The analysis on squeezing flow of Casson and Jeffrey fluids between two parallel plates with the presence and absence of nanoparticles can be used as future reference for researchers.

1.7 Thesis Organization

There are ten chapters in this thesis. Chapter 1 discusses the background of the study, statement of the problem, objectives, scope and significance of the study. The aim of this study is to explores the unsteady squeezing flow of Casson fluid and Jeffrey fluid between two parallel plates. The impacts of nanoparticles, MHD, porous medium, viscous dissipation, chemical reaction and velocity slip are examined. The literature review about MHD squeezing flow between two parallel plates in porous medium, heat and mass transfer in MHD squeezing flow with viscous dissipation and chemical reaction, squeezing flow of nanofluid and heat and mass transfer in MHD flow of Jeffrey fluid are described in Chapter 2. Next, Chapter 3 presents the derivation of governing equation of continuity, momentum, energy and mass equations for each problem in detail. The governing equation is simplified based on boundary layer approximations. Chapter 4 investigates the first problem in the study on time dependent MHD squeezing flow of Casson fluid through porous medium with slip condition. The second problem is extended by considering the impacts of viscous dissipation and chemical reaction on MHD squeezing flow of Casson fluid in porous medium as shown in Chapter 5. Meanwhile, Chapter 6 discovers the third problem on MHD squeezing flow of Casson nanofluid with viscous dissipation and chemical reaction in porous medium. Chapters 7 to 9 present the problems 4 to 6 focusing on Jeffrey fluid. The similar effects is discovered as described in problems 1 to 3. Chapter 7 studies the time dependent MHD squeezing flow of Jeffrey fluid across porous medium with slip condition. The MHD squeezing flow of Jeffrey fluid in porous medium with viscous dissipation and chemical reaction is analyzed in Chapter 8. Moreover, Chapter 9 is extended by considering Jeffrey nanofluid in the MHD squeezing flow under the influences of viscous dissipation and chemical reaction. All the references cited in this thesis are listed. The algorithm developed in MATLAB software is given in Appendix A, and the published articles and conferences attended are presented in Appendix B.

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APPENDIX B

List of publications

Journal with Impact Factor

1. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2021). Slip Effects on MHD Squeezing Flow of Jeffrey Nanofluid in Horizontal Channel with Chemical Reaction. Mathematics, 9(11), 1215. https://doi.org/10.3390/math9111215. **(Q1, IF:2.258)**
2. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2021). Heat and mass transfer on MHD squeezing flow of Jeffrey nanofluid in horizontal channel through permeable medium. PLoS ONE, 16(5), e0250402. https://doi.org/10.1371/journal.pone.0250402. **(Q2, IF:2.74)**
3. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2021). Impacts of chemical reaction on squeeze flow of MHD Jeffrey fluid in horizontal porous channel with slip condition. Physica Scripta, 96, 035216. https://doi.org/10.1088/1402-4896/abd821. **(Q2, IF:1.985)**
4. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2020). Effects of viscous dissipation and chemical reaction on MHD squeezing flow of Casson nanofluid between parallel plates in a porous medium with slip boundary condition. The European Physical Journal Plus, 135, 855. https://doi.org/10.1140/epjp/s13360-020-00868-w. **(Q1, IF:3.228)**
5. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2020). Unsteady MHD squeezing flow of Jeffrey fluid in a porous medium with thermal radiation, heat generation/absorption and chemical reaction. Physica Scripta, 95, 105213. https://doi.org/10.1088/1402-4896/abb695. **(Q2, IF:1.985)**

Indexed Journal

6. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2019). Unsteady MHD Flow of Cassonnano Fluid with Chemical Reaction, Thermal Radiation and Heat Generation/Absorption. MATEMATIKA, 35(4):33-52. http://dx.doi.org/10.11113/matematika.v35.n4.1262. **(Indexed by WOS)**
7. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2019). MHD Squeezing Flow of Casson Nanofluid with Chemical Reaction, Thermal Radiation and Heat Generation/Absorption. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 68(2): 94-111. http://dx.doi.org/10.37934/arfmts.68.2.94111. **(Indexed by Scopus)**
8. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2021). Heat Transfer on MHD Squeezing Flow of Jeffrey Fluid through Porous Medium with Slip Condition. Journal of Nanofluids, 11: 31-38. **(Indexed by WOS)**

Non-Indexed Conference Proceedings

9. **Mat Noor, N. A.**, Shafie, S., Admon, M. A. (2020). MHD Squeezing Flow of Jeffrey Fluid between Parallel Plates through Porous Medium with Slip Condition. 7th International Graduate Conference of Engineering, Science and Humanities 2020 (IGCESH 2020). 248-252.

Conferences Presentation

1. 8th International Graduate Conference on Engineering Science & Humanity 2020 (IGCESH 2020), 18th to 19th August 2020, Virtual conference. Title: MHD squeezing flow of Jeffrey fluid between parallel plates through porous medium.
2. 7th International Conference and Workshop on Basic and Applied Sciences (ICOWOBAS 2019), 16th to 17th July 2019, KSL Resorts, Johor Bahru. Title: Unsteady MHD Flow of Casson nanofluid with Chemical Reaction, Thermal Radiation and Heat Generation/Absorption.
3. 4th International Symposium on Fluid Mechanics and Thermal Sciences (IS-FMTS 2019), 14th December 2019, Palm Garden Hotel IOI Resort City, Putrajaya. Title: MHD Squeezing Flow of Casson Nanofluid with Chemical Reaction, Thermal Radiation and Heat Generation/Absorption.