g-JITTER INDUCED MIXED CONVECTION FLOW OF NEWTONIAN AND NON - NEWTONIAN NANOFLUID PAST AN INCLINED STRETCHING SHEET

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Special dedication to my beloved:

my first and forever hero,

Rawi Ismail (uya)

my strength and lifetime supporter,

Hasimah Mohd Hashim (umi)

and

my loving siblings

my great listener after my mother,

Nurul Najihah Rawi (nuyu)

my future travel partner,

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the most harworking person in family,

Nurul Hanani Rawi

my only lil brother,

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ABSTRACT

A new class of heat transfer fluid based on nanotechnology known as nanofluid has attracted much attention of many researchers due to its potential to improve the thermal properties of conventional fluids. This new approach which significantly enhance the heat transfer is becoming popular in many industrial applications such as cooling applications, nuclear reactors, transportation industry, electronics and instrumentation and biomedical applications. In this thesis, a mathematical model of mixed convection flow of nanofluid is developed based on Tiwari and Das model to study the influence of solid nanoparticles volume fraction on the Newtonian and non-Newtonian fluid flow with heat transfer. Specifically, the flow of nanofluid past an inclined stretching sheet for viscous, second grade, Jeffrey and Casson fluids with the effect of g-jitter is considered. The velocity and temperature of the sheet are assumed to vary linearly with distance through the sheet. The governing equation which consist of coupled non-linear partial differential equations are solved numerically using an implicit finite-difference scheme known as Keller-box method. The numerical results of surface shear stress in terms of skin friction and heat transfer coefficient in terms of Nusselt number as well as the velocity and temperature profiles for amplitude of modulation, frequency of oscillation, solid nanoparticles volume fraction, inclination angle, second grade parameter, Deborah number, ratio of relaxation to retardation times and Casson parameter for assisting and opposing flows are presented graphically and analyzed in details. Numerical result shows that, the presence of solid nanoparticles in all types of fluid enhance the temperature profiles and consequently increase the heat transfer coefficients. It is also found that, the second grade parameter and Deborah number give rise to the values of the heat transfer coefficient but to a contradiction for the inclination angle, ratio of relaxation to retardation times and Casson parameter. Comparative results amongst all types of fluids also show that, Casson nanofluid has the highest heat transfer coefficient but the lowest for skin friction coefficient.

ABSTRAK

Suatu kelas baru bendalir pemindahan haba berasaskan nanoteknologi yang dikenali sebagai nanobendalir telah menarik perhatian banyak penyelidik kerana potensinya untuk bertambah baik sifat terma bendalir konvensional. Pendekatan baru ini yang nyata sekali meningkatkan kadar pemindahan haba menjadi popular dalam banyak aplikasi perindustrian seperti aplikasi penyejukan, reaktor nuklear, industri pengangkutan, elektronik dan instrumentasi dan aplikasi bioperubatan. Dalam tesis ini, model matematik aliran olakan campuran nanobendalir dibangunkan berdasarkan model Tiwari dan Das untuk mengkaji pengaruh pecahan isipadu pepejal zarah nano pada aliran bendalir Newtonan dan bukan Newtonan dengan pemindahan haba. Khususnya, aliran nanobendalir merentasi helaian regangan condong untuk bendalir likat, gred kedua, Jeffrey dan Casson dengan kesan ketar-g dipertimbangkan. Halaju dan suhu permukaan diandaikan berubah secara linear dengan jarak disepanjang permukaan. Persamaan menakluk yang terdiri daripada persamaan pembezaan separa tak linear berganding diselesaikan secara berangka menggunakan skim beza terhingga tersirat yang dikenali sebagai kaedah kotak-Keller. Nilai berangka tegasan ricih dalam sebutan geseran kulit dan pekali pemindahan haba dalam sebutan nombor Nusselt serta profil halaju dan suhu untuk perubahan amplitud, frekuensi bagi ayunan-satu harmonik, pecahan isipadu zarah nano, sudut condongan, parameter gred kedua, nombor Deborah, nisbah masa pengenduran kepada masa rencatan dan parameter Casson untuk membantu dan menentang aliran dipersembahkan secara grafik dan dianalisa secara terperinci. Analisis berangka menunjukkan bahawa, kehadiran pepejal zarah nano dalam semua jenis bendalir meningkatkan profil suhu dan seterusnya meninggikan pekali pemindahan haba. Didapati juga, parameter gred kedua dan nombor Deborah menaikkan nilai pekali pemindahan haba tetapi menimbulkan percanggahan bagi sudut condongan, nisbah masa pengenduran kepada masa rencatan dan parameter Casson. Keputusan komparatif di antara semua jenis bendalir juga menunjukkan, Casson nanobendalir mempunyai pekali pemindahan haba tertinggi tetapi paling rendah untuk pekali geseran kulit.

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CMC	-	carboxymethyl cellulose
FDM	-	finite difference method
FEM	-	finite element method
HAM	-	homotopy analysis method
MEMS	-	micro-electromechanical systems
MHD	-	magnetohydrodynamics
PEST	-	prescribed exponential order surface temperature
PHF	-	prescribed heat flux
PST	-	prescribed surface temperature
PEHF	-	prescribed exponential order heat flux
UCM	-	upper convected Maxwell

LIST OF SYMBOLS

$\mathbf{a}$	-	acceleration
a, c	-	constant
Ag	-	silver
$\mathbf{A_1}$	-	first Rivilin-Ericksen tensor
$\mathbf{A_2}$	-	second Rivilin-Ericksen tensor
Al_2O_3	-	aluminium oxide
C_p	-	specific heat at constant pressure
$(C_p)_f$	-	specific heat at constant pressure of base fluid
$(C_p)_{nf}$	-	specific heat at constant pressure of nanofluid
$(C_p)_s$	-	specific heat at constant pressure of nanoparticle
Cu	-	copper
e_{ij}	-	(i, j) - th components of deformation rate
$\mathbf{F}$	-	body force
F_x	-	body force along x-direction
F_y	-	body force along y-direction
$\mathbf{g}$	-	gravitational force
g_0	-	time averaged value of gravitational acceleration
Gr_x	-	Grashof number
H_2O	-	water
$\mathbf{I}$	-	identity tensor
k	-	thermal conductivity
K	-	non-dimensional second grade parameter
k_f	-	thermal conductivity of base fluid
k_{nf}	-	thermal conductivity of nanofluid

k_s	-	thermal conductivity of nanoparticle
L	-	stream wise distance
m	-	mass of element
Nu_x	-	Nusselt number
p	-	pressure
p_d	-	dynamic pressure
p_h	-	hydrostatic pressure
p_y	-	fluid yield stress
Pr	-	Prandtl number
q_w	-	wall heat flux
Re_x	-	Reynold number
$\mathbf{S}$	-	extra tensor
t	-	time
T	-	temperature
T_w	-	temperature of sheet
T_∞	-	uniform temperature of ambient fluid
TiO_2	-	titanium oxide
U_∞	-	free stream velocity
u_w	-	velocity at surface
u	-	velocity in x-direction
v	-	velocity in y-direction
$\mathbf{V}$	-	velocity vector field

Greek Letters

α	-	inclination angle
α_1, α_2	-	normal stress moduli
β	-	Deborah number
β_T	-	coefficient of thermal expansion of fluid at constant pressure
$(\beta_T)_f$	-	coefficient of thermal expansion of base fluid at constant pressure

$(\beta_T)_{nf}$	-	coefficient of thermal expansion of nanofluid at constant pressure
$(\beta_T)_s$	-	coefficient of thermal expansion of nanoparticle at constant pressure
γ	-	Casson parameter
δ	-	boundary layer thickness
δ_t	-	thermal boundary layer thickness
ε	-	amplitude of modulation
λ	-	mixed convection parameter
λ_1	-	ratio of relaxation to retardation times
λ_2	-	retardation time
μ	-	dynamic viscosity
μ_B	-	plastic dynamic viscosity of non-Newtonian fluid
μ_f	-	dynamic viscosity of base fluid
μ_{nf}	-	effective viscosity of nanofluid
π	-	product of component of deformation rate with itself
π_c	-	critical value of product based on non-Newtonian model
ρ	-	density
ρ_f	-	density of base fluid
ρ_{nf}	-	density of nanofluid
ρ_s	-	density of nanoparticle
ρ_∞	-	fluid density in ambient medium
τ	-	non-dimensional time
τ_w	-	wall shear stress
τ_{xx},τ_{xy},τ_{yy}	-	component of Cauchy stress tensor
υ	-	kinematic viscosity
υ_f	-	kinematic viscosity of base fluid
ϕ	-	nanoparticle volume fraction
ω	-	frequency of oscillation
Ω	-	non-dimensional frequency of oscillation

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Recent advancement in nanotechnology has led to the development of a new innovative class of heat transfer in fluids known as nanofluid. Nanofluid can be described as solid-liquid composite materials consisting of solid nanoparticles with size typically of 1-100 nm, which is suspended in conventional fluids such as oil, water and ethylene glycol mixture. This concept introduces advanced heat transfer with substantially higher conductivity to enhance thermal characteristics. Pioneer studies carried out by Choi (1995) and Choi $et\ al.$ (2001) successfully showed that the addition of a small amount of nanoparticles to convectional heat transfer liquids can increase thermal conductivity of the fluid up to approximately two times. Based on the experimental studies, it can be concluded that, the reason for the increase in thermal conductivity of the fluid is not only attributed to the higher thermal conductivity of the added nanoparticles, but also other mechanisms contributing to the increase in performance. After this discovery, nanofluid has been considered by many researchers to be one of the significant forces that could drive the next major industrial revolution in this century especially in biological sciences, physical sciences, electronic cooling and transportation. Broad range of current and future applications involving nanofluid has been reviewed by Wong and De Leon (2010). Recently, suspensions of metal nanoparticles are also being developed for other purposes, such as medical applications including cancer therapy (Huang and El-Sayed (2010); Ellis $et\ al.$ (2017); Kang

$et\ al.$ (2017); Mekheimer $et\ al.$ (2018)).

Numerous models and methods have been proposed by different authors to study convective flows of nanofluid, including the most popular models proposed by Buongiorno (2006) and Tiwari and Das (2007). Buongiorno considered seven slip mechanisms that can produce a relative velocity between the nanoparticles and the base fluid. Conclusively, among all the mechanisms, only Brownian diffusion and thermophoresis are found to be important factors in the convective transport process in nanofluid. Based on that, Buongiorno proposed a mathematical model by treating nanofluid as a two-component mixture which are Brownian diffusion and thermophoresis, and introduced these terms in the conservation equations for mass and energy. On the other hand, Tiwari and Das (2007) had proposed a theoretical model to analyze the behaviour of nanofluid by taking into account the solid volume fraction. It is worth mentioning that both proposed nanofluid models were recently used by Habibi Matin $et\ al.$ (2012), Mahdy (2012), Subhashini and Sumathi (2014), Imtiaz $et\ al.$ (2014), Uddin $et\ al.$ (2015), Hayat $et\ al.$ (2016b), Othman $et\ al.$ (2017), and Besthapu $et\ al.$ (2017) in their papers. Several other researchers further proposed the studies of nanofluid in different types of fluid, for example, Sandeep $et\ al.$ (2015), Abbasi $et\ al.$ (2016), Madhu and Kishnan (2016), Nabwey $et\ al.$ (2017) and Naseem $et\ al.$ (2017). All previous works used Newtonian fluid as the base fluid. Ellahi $et\ al.$ (2012) pointed out that, non-Newtonian nanofluids have potential roles in physiological transport as biological solutions, as well as in polymer melts and paints. Therefore, for this research, convective heat transfer behaviour of nanofluid with Newtonian and non-Newtonian base fluids have been considered, by applying Tiwari and Das model.

In the study of science, fluids can be classified into two categories, known as Newtonian and non-Newtonian fluids. Basically, a Newtonian fluid is a fluid in which the viscous stresses arising from its flow, at every point, are linearly proportional to the local strain rate or the rate of change of its deformation over time (Kirby, 2010). The relation defines the Newtonian fluid behaviour is known as Newton' s Law of viscosity, given by

$$\tau = \mu \frac{\partial u}{\partial y}$$

where τ denotes the shear stress exerted by the fluid, μ is the dynamic viscosity of the fluid and $\partial u/\partial y$ is the rate of the strain or velocity gradient. On the other hand, fluids which do not obey or opposite of the Newton' s law of viscosity, are defined as non-Newtonian fluid. This type of fluid is typically not independent on the shear rate, and classified on the basis of their properties. In fact, the mathematical systems for non-Newtonian fluid are much more complicated due to the higher order of equation, compared to the Newtonian fluid.

Due to the diversity of non-Newtonian fluids in nature, there is no single constitutive relationship available in the literature that can describe the rheology of all the non-Newtonian fluids. Therefore, various constitutive equations which exhibit different rheological effects have been suggested to predict the behaviour of non-Newtonian fluids, by describing the nonlinear relationship between stress and the rate of strain. Recently, many types of non-Newtonian fluid models have become very popular in the literature, such as Casson fluid, Jeffrey fluid and viscoelastic fluid.

The simplest subclass of viscoelastic fluid, known as second grade fluid model, was proposed by Coleman and Noll (1960). It is found in polymer fluids, where these fluids exhibit both viscous and elastic characteristics. Viscous materials, like honey, resist shear flow and strain linearly with time when a stress is applied. Meanwhile, elastic materials strain instantaneously when stretched and quickly return to their original state once the stress is removed. This fluid model is useful in explaining normal stress effects but is not applicable for predicting the shear thinning or shear thickening effects (Hayat and Qasim, 2011). Another subclass of non-Newtonian fluids, known as Jeffrey fluid, is attractive to researchers due to its simplicity. Theoretically, Jeffrey fluid model exhibits both characteristics of relaxation and retardation times (Nadeem *et al.*, 2014), which are significant in studying the viscoelastic properties for polymer industries (Ali and Asghar, 2012). This model constitutes a viscoelastic fluid model which exhibits shear-thinning characteristics, yields stress and has high shear viscosity. It can also be degenerated to a Newtonian fluid at a very high wall shear stress, especially when the wall stress is much greater than yield stress (Bird *et al.*, 1987). This fluid model also approximates reasonably well the rheological behavior of other liquids including physiological suspensions, foams, geological materials, cosmetics, and syrups (Gaffar *et al.*, 2017).

Among non-Newtonian fluids, Casson fluid has received attention of researchers due to its unique properties. Casson fluid is a subtype of viscoplastic fluid (Hussanan *et al.*, 2016) which was originally introduced by Casson (1959) for the prediction of the flow behaviour of pigment-oil suspensions. Casson fluid model can be defined as a shear thinning liquid which is assumed to have an infinite viscosity at zero rate of shear, a yield stress below which no flow occurs, and a zero viscosity at an infinite rate of shear (Dash *et al.*, 1996). It means that, if a shear stress less than the yield stress is applied to the fluid, it behaves like a solid, whereas if a shear stress greater than the yield stress is applied, the fluid will start to move. Some examples of Casson fluid are jelly, tomato sauce, honey, soup, concentrated fruit juice, as well as human red blood cell which can form a chainlike structure known as aggregates or rouleaux. In addition, the shear stress shear rate relation given by Casson also satisfactorily describes the properties of many polymers over a wide range of shear rates (Vinogradov *et al.*, 1980).

The study of nanofluid flow along stretching surfaces is also attractive for many practical applications such as the production of sheeting materials (which includes both metal and polymer sheets) in industrial manufacturing processes. These investigations are helpful to enhance the quality of resulting sheeting materials, as well as to lower the cost of production, which is clearly affected by the speed of collection and heat transfer rate. The pioneering study was carried out by Crane (1970), who presented an exact analytical solution for a steady two-dimensional stretching surface in a quiescent fluid. Since then, many authors have considered this problem from various aspects. Recently, problems involving boundary layer flow due to a stretching surface in the inclined direction in a steady or unsteady, viscous and incompressible nanofluid, when the buoyancy force is taken into account, have been considered by many researchers, such as Rana $et\ al.$ (2012), Rasekh and Ganji (2013), Devi and Suriyakumar (2013), Rudraswamy and Gireesha (2014), Rudraswamy $et\ al.$ (2015), Srinivasacharya and Vijay Kumar (2015) and Gupta $et\ al.$ (2018).

Heat transfer can be described as the transport of the thermal energy, driven by thermal nonequilibrium within a medium or among neighboring media (Kaviany, 2002), and can be grouped into three broad categories, namely conduction, convection and radiation. The convective mode of heat transfer can generally be divided into three types, which are free (natural), forced and mixed convections. Free convection happens when the flow arises naturally, simply due to the effect of a density difference resulting from temperature or concentration difference. Meanwhile, forced convection happens if the fluid motion is caused by an external agent, such as the externally-imposed flow of a fluid stream over a heated object. However, in any forced convection situation, free convection effects are also present under the influence of gravitational body forces. This process is called as mixed convection, in which flow occurs when both forced and free convection effects are significant and contribute to the heat transfer. Mixed convection flow is applied in many technological and industrial applications, such as solar central receivers exposed to wind currents, electronic devices cooled by fans, nuclear reactors cooled during emergency shutdown, and heat exchangers placed in a low velocity environment (Abbas $et\ al.$ (2010); Makinde (2011); Hayat $et\ al.$ (2015b)).

In the study of fluid flow over heated surfaces specifically for vertical or inclined surfaces, the buoyancy forces exert strong influence on the flow field, which makes it impossible to neglect the effect of buoyancy forces for vertical or inclined surfaces (Chamkha *et al.*, 2004). The theoretical procedure for obtaining heat transfer rate from an inclined surface was suggested by Rich (1953). According to the procedure, the problem of free convection on an inclined surface is identical to that of flow over a vertical surface except the addition of term $\cos\alpha$, where α is the inclination angle. Meanwhile, Kierkus (1968) carried out the first order approximation and obtained a perturbation solution for an inclined plate of finite length. Results showed that, the upper and lower sides of the inclined surface were different in terms of heat transfer due to the difference in orientation, with respect to the two sides of the component of the buoyancy force being normal to the surface (Jaluria, 1980). The importance of buoyancy force on an inclined, continuously moving sheet, depends not only on the angle of orientation, but also on the mixed convection parameter which indicates the strength of free (natural) and forced convection flow effects.

Generally, the presence of a temperature gradient and a gravitational field can generate buoyancy convective flows in many situations. In low-gravity or microgravity environments, it can be expected that the reduction or elimination of free (natural) convection may enhance the properties and performance of materials such as crystals. For example, low gravity situation, in which the effects of gravity is greatly reduced, offers an environment conductive to growing crystals with more uniform solute distribution and in a diffusion controlled regime. However, aboard orbiting spacecraft, all objects will experience low-amplitude perturbed accelerations, or so called as g-jitter, caused by crew activities, orbiter maneuvers, equipment vibrations, solar drag and other sources (Antar and Nuotio-Antar (1993); Hirata $et\ al.$ (2001)) which makes it difficult to achieve diffusion controlled single crystal growth in space. Recent technological implications have given rise to increasing interest in oscillating natural or mixed convection driven by g-jitter force associated with microgravity environment. Therefore, the effect of g-jitter on convection flow is interesting to study, especially when involving g-jitter induced flow in different types of Newtonian and non-Newtonian fluids.

g-Jitter or periodical gravity modulation can be defined as the inertia effects due to quasi-steady, oscillatory or transient accelerations arising from crew motions and machinery vibrations in parabolic aircrafts, space shuttles or other microgravity environments. Antar and Nuotio-Antar (1993) showed that, the specific amplitude and frequency of the g-jitter accelerations depend on the dynamic behaviour of the spacecraft structure, location of the body, and type and location of the sources generating contributing forces. Other studies on g-jitter effects also indicate that, convection in microgravity is related to the magnitude and frequency of g-jitter and to the alignment of the gravity field, with respect to the growth direction or the direction of the temperature gradient (Shu $et\ al.$ (2001); Pan $et\ al.$ (2002)). Recently, Uddin $et\ al.$ (2014) investigated the effects of g-jitter on two-dimensional mixed convection boundary layer flow of water-based nanofluid past a permeable stretching sheet. Later, Uddin $et\ al.$ (2015) extended their work by using Buongiorno-Darcy porous medium model, by taking into account the effect of constant convective thermal and mass boundary conditions. Both studies considered viscous fluids to investigate the flow behaviour past over a vertical stretching sheet. Besides vertical plate, the flow behaviour along an inclined stretching sheet also needs to be explored. Convection flow along inclined surfaces has received much attention due to its frequent encounter in engineering devices and many industrial applications such as electroplating, chemical processing of heavy metals, ash or scrubber waste treatment (Devi and Suriyakumar, 2017). At present, this matter has yet to be studied. Therefore, this study aims to make such an attempt.

1.2 Problem Statement

Interest in studying nanofluid flow has increased substantially over the past decades due to attribution of heat transfer. It is well known that conventional heat transfer fluids are unable to meet the growing challenges of modern world due to their low thermal conductivity. To overcome this limitation, nanoscale solid particles have been proposed for suspension in conventional heat transfer fluid to change the thermophysical characteristic of the fluid, aiming to enhance the heat transfer dramatically. Some researchers have successfully shown that presence of nanoparticles in water cooled nuclear system can improve the safety margins and produce substantial economic gains (Buongiorno *et al.*, 2008). Although extensive research works have been devoted to heat transfer in viscous (Newtonian) fluids, recently, research in non-Newtonian fluids has gained considerable attention among researchers as well. Nevertheless, theoretical study on these fluids is more challenging and interesting due to the complexity of their constitutive equations.

Based on the aforementioned matters, this research has been conducted to study the effects of inducing g-jitter on mixed convection flow of nanofluid past an inclined stretching sheet of Newtonian and non-Newtonian fluids, which are second grade, Jeffrey and Casson fluids. This study explores the following research questions:

1. How does the mathematical model of g-jitter mixed convection model describe the nature of mixed convection boundary layer flow of nanofluid past an inclined stretching sheet for different types of fluid model?

2. How would the skin friction and Nusselt number be affected due to the presence of amplitude of modulation, frequency of oscillation, nanoparticles volume fraction and inclination angle parameters for assisting and opposing flows?

3. How would the skin friction and Nusselt number be affected due to the presence of physical parameters which are second grade parameter, Deborah number, ratio of relaxation to retardation times, and Casson parameter with or without the presence of nanoparticles?

4. How does the presence of nanoparticles volume fraction, inclination angle, second grade parameter, Deborah number, ratio of relaxation to retardation time, and Casson parameter affect the fluid flow characteristics of the g-jitter mixed convection flow of Newtonian and non-Newtonian nanofluids?

1.3 Research Objectives

This study numerically investigates the effect of inducing g-jitter on two-dimensional boundary layer flow of nanofluid past an inclined stretching sheet in Newtonian viscous, second grade, Jeffrey and Casson fluids. Specifically, the main objectives of this research are:

1. to derive mathematical models of the problems, consisting of continuity, momentum and energy equations,
2. to carry out mathematical formulation and develop numerical algorithms for computation in order to analyze the problems,
3. to obtain the numerical results of the velocity and temperature profiles, as well as the skin friction and heat transfer coefficients, and
4. to investigate the behaviour of flow and heat transfer characteristics influenced by the amplitude of modulation, frequency of oscillation, inclination angle, nanoparticle volume fraction, Deborah number, second grade parameter, ratio of relaxation to retardation time, mixed convection, and Casson parameter.

1.4 Scope of Research

This thesis is focused on the mixed convection flow in the Newtonian viscous, second grade, Jeffrey and Casson nanofluids driven by g-jitter forces over an inclined stretching sheet. Boussinesq and boundary layer approximations have been considered to simplify the governing equations. The governing partial differential equations have been transformed into a set of coupled dimensionless nonlinear partial differential equations by using appropriate similarity transformation. In this study, water ($\mathrm{H_2O}$) has been selected to represent the Newtonian fluid model, while carboxymethyl cellulose (CMC) water has been used to represent the non-Newtonian fluid model, as proposed by Lin $et\ al.$ (2014). Copper (Cu) has been chosen as the dispersing nanoparticle.

Characteristics of fluid flow such as velocity and temperature profiles, the surface shear stress in terms of skin friction coefficient, and heat transfer coefficient in terms of Nusselt number, have been thoroughly analysed according to each proposed problem. In this research, the inclination angle has been considered up to a maximum angle of 60° (Jaluria, 1980) and the range of nanoparticles volume fraction has been considered to be in range $0 \leq \phi \leq 0.2$ (Uddin *et al.*, 2014). The following problems are discussed in Chapters 4 to 7 of this thesis:

1. the effect of inducing g-jitter on mixed convection flow of nanofluid past an inclined stretching sheet,

2. the effect of inducing g-jitter on mixed convection flow of second grade nanofluid past an inclined stretching sheet,

3. the effect of inducing g-jitter on mixed convection flow of Jeffrey nanofluid past an inclined stretching sheet, and

4. the effect of inducing g-jitter on mixed convection flow of Casson nanofluid past an inclined stretching sheet.

Consequently, the obtained dimensionless nonlinear partial differential equation (PDE) have been solved numerically using the implicit finite-difference method known as Keller-box method, with the help of FORTRAN 77 software for the iterated computational program, and then continued using MATLAB to plot the graphs. The research framework of this study is shown in Figure 1.1.

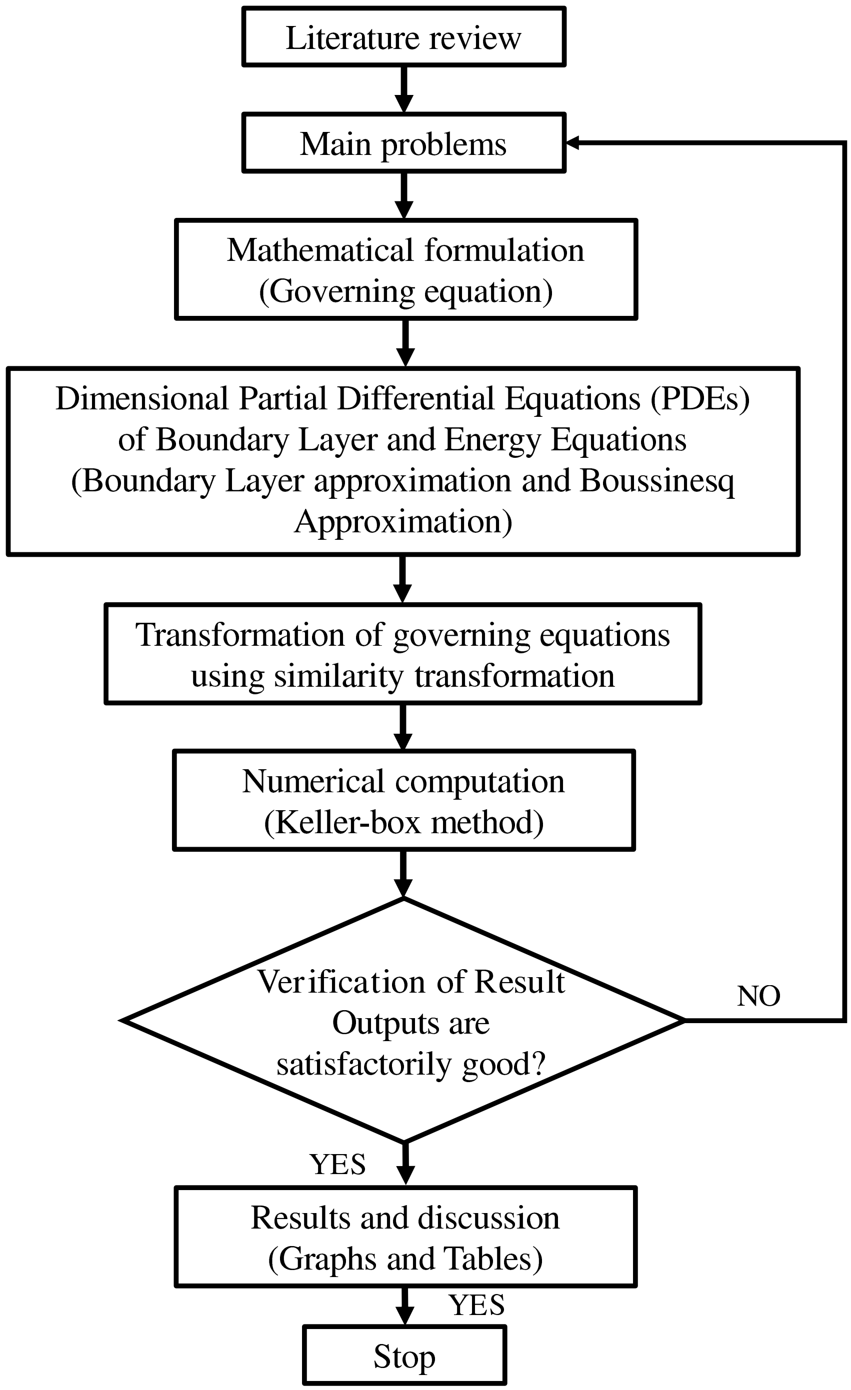

Figure 1.1 Research framework

1.5 Significance of Research

Conventional heat transfer fluids such as water, ethylene glycol, and engine oil have limited heat transfer capabilities due to their low heat transfer properties. In contrast, metals have thermal conductivities up to three times higher than these fluids, so it is naturally desirable to combine the two substances to produce a heat transfer medium that behaves like a fluid, but has the thermal properties of a metal. Innovative class of heat transfer fluids, namely nanofluid, has the potential to significantly increase the heat transfer rates in a variety of areas such as industrial cooling applications, nuclear reactors, transportation industry (automobiles, trucks and airplanes), micro-electromechanical systems (MEMS), electronics and instrumentation, as well as biomedical applications such as nano-drug delivery, cancer therapeutics and cryopreservation (Wong and De Leon, 2010).

Furthermore, mechanics of non-linear fluids are unable to be described by the classical Navier-Stokes model, therefore study of boundary layer flow using non-Newtonian models will present a special challenge to researchers due to its many practical applications. Therefore, the study on convective boundary layer flow of non-Newtonian fluid problems, particularly in nanofluid, is important due to its imperative applications in real life. The results or output of this research shall enhance the understanding on the fluids flow phenomenon and improve the development of related industries, for example the manufacturing industries. Besides that, the generation of efficient algorithm of the non-Newtonian problem shall help in solving the problem of computational fluid dynamics in the future.

In low gravity environment such as space environment, where heat transfer in the fluid medium is expected to be only affected by pure diffusion, the existence of perturbation accelerations or called as g-jitter caused by mechanical vibration, orbiter maneuvers and crew activities will affect the heat and mass transfer, which can lead to detrimental effects on the microgravity experimentation, for example space-based crystal growth. Carotenuto (2004) stated that, data on mass transport in microgravity could give insights on gravity-independent effects, like the second order transport mechanisms or kinetic effects, which on the ground could be superimposed on gravity-driven convection. Such knowledge is a prerequisite for optimizing crystal quality and growth rates in terrestrial production, thus more information regarding the effect of g-jitter on fluid behaviour specifically in low gravity environment is needed, so that the better engineering design for low gravity condition could be made in the future.

1.6 Thesis Organization

This thesis consists of eight chapters, focusing on the problem of g-jitter induced mixed convection flow of nanofluid past an inclined stretching sheet using different types of fluid model. In the first chapter, the introduction is given, followed by the statement of problem, objectives of research, scope of research and significance of research. Literature review for the proposed problems is presented in Chapter 2. In Chapter 3, the mathematical formulations involving the derivation of the governing equations, which consist of continuity, momentum and energy equations for each problem, together with the Boussinesq and boundary layer approximations, are discussed in detail.

Chapter 4 discusses the first problem in this study; about the effect of g-jitter induced mixed convection flow of nanofluid past an inclined stretching sheet. Chapter 5 discusses the second problem of this study, which is the effect of inducing g-jitter on mixed convection flow of second grade nanofluid past an inclined stretching sheet. Next, the problem of g-jitter induced mixed convection flow of Jeffrey nanofluid past an inclined stretching sheet is discussed in Chapter 6. Meanwhile, Chapter 7 encloses the final problem of this study; about the effects of inducing g-jitter on mixed convection flow of nanofluid past an inclined stretching sheet by taking the Casson fluid model into account. In each chapter, the obtained numerical results which include the velocity and

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