UNIVERSITI PUTRA MALAYSIA

MARANGONI BOUNDARY LAYER FLOW OVER A PERMEABLE SURFACE IN THE PRESENCE OF THERMAL RADIATION

NORFARAHANIM MOHD ARIFFIN

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By

NORFARAHANIM BINTI MOHD ARIFFIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

October 2017

DEDICATIONS

To all of my love;
Abah & Ma
Along, Amirul, K. Baby, Adik, Na

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Master of Science

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October 2017

Chairman: Norihan Md. Arifin, PhD
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Marangoni convection is a flow induced by the surface tension gradients associated with either thermal or concentration gradients. In this study, the problem of Marangoni boundary layer is derived in three different types of fluid over a permeable surface, where there is suction or injection effect. The scope of this thesis is restricted to two dimensional, steady, incompressible and laminar flow considered in micropolar fluid, nanofluid and viscous fluid. Each problem is considered in different type of fluid with respect to the parameters interest. The effect of thermal radiation is considered due to its vast applications and large contribution in the field of science and technology and it is occurring in the heat equations. The consumption of suction or injection effect is also utilized to determine the effect of it on the flow and heat transfer characteristics. The governing nonlinear partial differential equations are transformed into a system of nonlinear ordinary differential equations using similarity transformation. Then the resulting systems of equations are solved numerically. Numerical results are presented in tables and graphs for the velocity, temperature and concentration profiles are analysed with respect to the involved parameter interest namely types of concentration (weak and strong), radiation, magnetic field and suction or injection parameter. Comparisons with known results from the previous literature have been made in order to ratify the numerical results obtained in this thesis and the injunction showing very good agreements. All the governing parameters affect the flow and heat transfer characteristics of the fluid except for the radiation parameter. It only affects the heat transfer rate of the fluid as it decreases the flow rate. While the suction gave a decrement to the heat transfer and injection proposed an opposite results.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Sarjana Sains

ALIRAN LAPISAN SEMPADAN MARANGONI ATAS PERMUKAAN TELAP DENGAN KEHADIRAN RADIASI HABA

Oleh

NORFARAHANIM BINTI MOHD ARIFFIN

Oktober 2017

Pengerusi: Norihan Md. Arifin, PhD
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Olakan Marangoni adalah aliran yang disebabkan oleh kecerunan permukaan berkaitan dengan kecerunan haba atau kepekatan. Dalam kajian ini, masalah aliran lapisan sempadan Marangoni diterbitkan dalam tiga jenis bendalir yang berbeza di atas permukaan telap, dimana terdapat kesan sedutan atau semburan. Skop kajian tesis ini dihadkan kepada dua dimensi, mantap, tidak boleh mampat dan aliran lapisan sempadan berlamina yang dipertimbangkan dalam bendalir mikropolar, nanobendalir dan bendalir likat. Setiap masalah adalah dipertimbangkan dengan jenis bendalir yang berbeza tertakluk kepada parameter yang dikaji. Kesan radiasi haba dipertimbangkan disebabkan oleh aplikasinya yang luas dan sumbangan yang besar di dalam bidang sains dan teknologi dan ianya berlaku dalam persamaan haba. Penggunaan kesan sedutan atau semburan juga dimanfaatkan bagi mengetahui kesannya terhadap ciri-ciri aliran dan pemindahan haba. Persamaan terbitan separa tak linear dijelmakan kepada sistem persamaan terbitan biasa tak linear menggunakan penjelmaan keserupaan. Kemudian sistem persamaan yang terhasil diselesaikan secara berangka. Keputusan berangka yang diperoleh dibentangkan dalam bentuk jadual dan graf untuk profil halaju, suhu dan kepekatan dianalisis berkaitan dengan parameter yang terlibat iaitu jenis kepekatan (lemah dan kuat), parameter radiasi, medan magnet dan sedutan atau semburan. Perbandingan dengan hasil yang diketahui dari kajian sebelumnya telah dilakukan untuk mengesahkan keputusan berangka yang diperoleh dalam tesis ini dan perbandingan menunjukkan kesepakatan yang sangat baik. Semua parameter yang terlibat mempengaruhi ciri-ciri aliran dan pemindahan haba bendalir kecuali parameter radiasi. Ia hanya mempengaruhi kadar pemindahan haba kerana ia mengurangkan kadar aliran. Sementara sedutan memberikan pengurangan pada pemindahan haba dan semburan mengusulkan hasil sebaliknya.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful. Alhamdulillah. Thanks to Almighty Allah for graciously blessed me with the ability to undertake and finally complete this thesis.

I would like to express my sincere gratitude and deepest appreciation to my supervisor, Assoc. Prof. Dr. Norihan Md. Arifin. The door to Dr. Norihan office was always open whenever I ran into a trouble spot or had a question about my research or writing. She consistently allowed this research to be my own work, but steered me in the right direction whenever she thought I needed it. I would also like to thanks my co-supervisor, Assoc. Prof. Dr. Norfifah Bachok@Lati for the encouragement and stimulating suggestions throughout the course of this study.

I would also like to acknowledge with much appreciation the crucial role of the staffs and lecturers of Department of Mathematics, specifically and Faculty of Sciences for their great assistance and continuous help. Nevertheless, I want to thanks School of Graduate Studies (SGS) and Universiti Putra Malaysia (UPM), for giving me the opportunity to pursue my study and get Graduate Research Fellowship (GRF) and also to the Ministry of Higher Education (MOHE) for the financial of my studies.

Furthermore I would like to express my very profound gratitude to my father, Abah, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. Not to forget my late mother, Ma for the memories that I will always cherish. This accomplishment would not have been possible without them. Thanks to my siblings for unconditionally love and keep supporting me in study through ups and downs.

Special thanks go to my friends and all my colleagues in Faculty of Sciences and Institute of Mathematical Research for this unforgettable journey.

I certify that a Thesis Examination Committee has met on 16 October 2017 to conduct the final examination of Norfarahanim binti Mohd Ariffin on her thesis entitled "Marangoni Boundary Layer Flow Over a Permeable Surface in the Presence of Thermal Radiation" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for Master of Science. The members of the Supervisory Committee were as follows:

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I hereby confirm that:

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LIST OF ABBREVIATIONS

A	constant
B_0	magnetic induction
c	dimensional concentration
C_0	dimensional constant
C_1	similarity transformation coefficient
C_2	similarity transformation coefficient
c_p	specific heat constant
$C(\eta)$	dimensionless concentration
D	mass diffusivity
f_0	normal component of the dimensional interface velocity
$f(\eta)$	stream function similarity variable
$g(\eta)$	microrotation function similarity variable
j	spin gradient viscosity
k	thermal conductivity
k^*	mean absorption coefficient
K	micropolar or material parameter
K_o	dimensionless chemical reaction coefficient
L	reference length
M	magnetic parameter
m	constant exponent of the temperature
n	concentration of microelements
N	microrotation or angular velocity
Nr	thermal radiation parameter
$\Pr$	prandtl number
q_r	radiative heat flux
Q_0	dimensional heat generation or absorption coefficient
r	ratio of the solutal and thermal marangoni number
R	dimensional chemical reaction parameter
S	suction or injection parameter
Sc	schmidt number, $Sc = v / D$
t	time
T	temperature
T_0	dimensional constant
u	x component of the dimensional velocity
$u_e(x)$	velocity of the external flow
v	y component of the dimensional velocity
v_0	dimensional suction or injection parameter
X	constant

Greek symbols

α	thermal diffusivity
α_{nf}	thermal diffusivity for nanofluid
κ	vortex viscosity
η	location similarity variable
σ	surface tension
σ^*	stefan-boltzmann constant
ϕ	dimensionless heat generation or absorption coefficient
φ	unknown eigenvalue parameter
ρ	density
ρ_f	density for fluid
ρ_{nf}	density for nanofluid
ρ_s	density for solid
ρC_p	heat capacity
$\left(\rho C_p\right)_f$	heat capacity for fluid
$\left(\rho C_p\right)_{nf}$	heat capacity for nanofluid
$\left(\rho C_p\right)_s$	heat capacity for solid
τ	constant variable
μ	dynamic viscosity
μ_f	dynamic viscosity for fluid
μ_{nf}	dynamic viscosity for nanofluid
ν	kinematic viscosity
γ	thermal
γ_c	concentration coefficient of the surface tension
γ_T	temperature coefficient of the surface tension
$\theta(\eta)$	temperature similarity variable
Δ	discriminant

CHAPTER 1

INTRODUCTION

1.1 Research Background

The research about fluid dynamics is considered in this thesis theoretically. The main focused is on the mathematical modeling by computational without experiment. The mathematical model used is resembled the reality with the use of mathematical language. The model used can be fixed, altered or as a reference to build a more good model.

A fluid is anything that flows, usually liquid or gas, the latter being distinguished by its great relative compressibility. Fluids are treated as continuous media, and their motion and state can be specified in terms of the velocity, pressure, density, etc. evaluated at every point in space and time. Fluid dynamics is part of fluid mechanics that deals with the fluid flow and can be divided into two major sections which is aerodynamics and hydrodynamics. Aerodynamics is the flow of the fluid related to gases while hydrodynamics is the fluid flow entangled with liquids. There are two type of fluid flow existed which is the laminar flow and the turbulent flow. Laminar flow is the flow at which the motion of particles in the fluid flow is predictable and it follows the streamlines. It occurs at the low flow rates at which the fluid particles moving in straight lines along the tube and by symmetry, all fluid particles at the same distance from the axis of the tube would have the same velocity so that the fluid could be thought as flowing in layers or laminar. The turbulent flow indicated a flow which characterized by an unpredictable, pseudo random behavior, some very-strong mixing properties and a broad spectrum of time and length scales. In this thesis, we are considering the laminar flow type.

Heat is the exchange of energy between two medium and the energy exchange is called as thermal energy. It occurs because of two different temperatures between two mediums which basically the transfer of heat happened from the higher temperature to the lower one in a medium or across a medium. In a solid body, liquids or gases the flow of heat is the result of the transfer of internal energy from one molecule to another. This process is called conduction. In addition there is still another mode of heat transfer in liquids and gases. In such a medium, motion of a macroscopic nature may exist and heat may be transported from one point to another by being carried along as internal energy with the flowing medium. This process is called heat transfer by convection. A third mode of heat transfer is the result of radiation. Solid bodies, as well as liquids and gases, are capable or radiating thermal energy in the form of electromagnetic waves and of picking up such radiant energy by absorption. In this thesis we are dealing with the heat transfer by convection.

A fluid motion can either be set up by some external source like a blower or be caused by temperature differences in the fluid which is developed as a result of local heating. Heat exchange between a wall and a fluid when the flow is forced along the wall by external means is called heat transfer by forced convection. The heat exchange between a wall and a fluid when the fluid is set in motion by temperature differences between the wall surface and the surrounding fluid is called heat transfer by free or natural convection. Free or natural convection flow arises in various ways, for instance, when a heated object is placed in a fluid, otherwise at rest, the density of which varies with temperature. Heat is transferred from the surface of the object to the fluid layers in its neighborhood. The density decrease which in a normal fluid is connected with a temperature increase causes these layers to rise and create the free-convection flow which now transports heat away from the object. Physically such a flow is described by stating that it is caused by body forces. For this thesis, we are considering the free or natural type convection of heat transfer.

1.2 Marangoni Convection

Convection can be understood as the transfer of heat from one place to another location by mean of the movements of groups of molecules either within fluids or rheids, a non-molten solid. The transfer of heat can happen either through advection, known as the heat transfer by bulk fluid flow or can be either through conduction which is the heat diffusion or can be happened through combination of both. Marangoni convection is generally known as a phenomenon resulted from the flow of the liquids from the lower surface tension area to the higher one. The name of Marangoni is taken after an Italian physicist in nineteenth century name Carlo Marangoni, 1965. It can be divided into two general cases which is solutal Marangoni convection on which the flow is caused by the surface tension gradients originating from the concentrations while the other case is the thermocapillary flow on which it is induced by surface tension gradients originating from the temperature gradients. It can be either through gas-liquid or liquid-liquid interface. It was believed that Napolitano (1979) is the first person who works on this area and consequently then gives a bunch of contribution within wide range of area including industries, engineering, bio-medical, etc., due to the ability of the Marangoni convection to be applied for the fluid movements when there is no gravity exist, see Zhang and Zheng (2014). Marangoni became an important part in microgravity science and space craft due to its possibility of material processing in space craft, where the gravity force is very small in comparison with the thermo-capillary, see Zheng et al. (2004) and Chen (2007).

Marangoni is widely used in the applications of semiconductor processing and drying silicon wafers (Sastry, 2015). Moreover it has a vast contribution in the industrial field especially in the art work of dyeing on the ground, see Kuroda (2000) and in the field of crystal growth, see Arafune and Hirata (1999). The elementary mechanism of Marangoni convection can be seen from Gelles

(1978) and Okano et al. (1989). Then a more details analysis of Marangoni boundary layer was done by Napolitano and Golia (1981). Their investigation is basically on the structure, properties and the behaviour of Marangoni boundary layers. Then the further development of theory of Marangoni flow was done by Napolitano (1986) and focused on the study of the main features of the flow regimes. Currently, there are two type of models exist for Marangoni boundary layer which are model for non-isobaric discussed by Golia and Viviani (1986) and model for Marangoni boundary layer over a flat plate studied by Christopher and Wang (2001). The models of Marangoni boundary layer flow been studied in this thesis is Marangoni boundary layer over a flat plate. For a flat plate, the external flow for velocity, $u_e(x)$ in Golia and Viviani (1986) is neglected. In this thesis, we are considering the Marangoni boundary layer flow in three different types of fluids which are micropolar fluid, nanofluid and vicsous fluid.

1.3 Boundary Layer Flow

In fluid dynamics, boundary layer emerges in many situations. A boundary layer is defined as the flow region next to a solid boundary where the flow field is affected by the presence of the boundary. In other word, boundary layer is the layer of fluid in the immediate vicinity of the bounding surface where the effects of viscosity cannot be ignored. The concept was originally introduced by Ludwig Prandtl in 1904 (Anderson, 2005), a German physicist and aerodynamicist, when he explained that the viscosity of a fluid plays a role in a very thin layer adjacent to the surface, which he called as boundary layer. It occurs when a molecule stick to the surface, as the fluid passes through an object; collide with the molecules just above the surface area. It is called a boundary layer because of it occurs on the boundary of the fluid. Boundary layer flow can be simplified into two major disciplines which are laminar boundary layer flow and turbulent boundary layer flow. The different between laminar and turbulent flow is that laminar creates less skin friction drag than the turbulent flow. The case of laminar boundary layer flow is taking into account in this thesis. Prandtl says that the flow can be divided into two types which are inviscid flow at the main section and thin layers adjacent to body surface (boundary layer). In the thin layers, friction force needs to be considered but for the outer thin layers, the friction forced can be neglected, see Schlichting (1979). Boundary layer theory is an extensively developed sub-area of fluid mechanics.

1.4 Micropolar Fluid

Microfluids are a class of fluids which exhibit a certain microscopic effects arising from the local structure and micro-motions of the fluid elements. These fluids are influenced by the spin inertia and can support stress moments and body moments. Micropolar fluids are a subclass of these fluids which exhibit the micro-rotational effects and micro-rotational inertia and it is consist of randomly oriented molecules where it named by Eringen (1966). These micropolar fluids however can support couple stress and body stress only. It may represent fluids consisting of bar-like or sphere-like elements, physically. Eringen (1964) was the first to propose the micropolar fluid theory which takes into account the inertial characteristics of the substructure particles which are allowed to undergo rotation and was continued to develop by Eringen. He proposed new kinematic variables for example the gyration tension and micro inertia. Many classical flows are being re-examined to determine the effects of the fluid microstructure.

The prolongation of the main equations for Newtonian fluids, so that more complex fluids such as particle suspensions, liquid crystals, animal blood, lubrication and turbulent shear flow can be described by this theory, is the gist of the theory of the micropolar fluids. Through this theory, a transport equation which represents the principle of conservation of local angular momentum must be added to the usual transport equations for the conservation of mass and momentum, and additional local constitutive parameters are also introduced in practice. Non-Newtonian fluid specifically micropolar fluids has been part of the research fields that are widely studied due to its contribution especially in the area of industrial important fluids like paints, polymeric suspensions and in the field of physiological fluids for instance human blood and synovial fluids. It has become a great assist to many research related to this complex fluids convenient to its special capability and for such Peddieson (1972) claimed that the model is capable of predicting results which exhibit some characteristics found in the turbulent wall shear layers when he investigated the problems of axisymmetric stagnation-point flow of micropolar fluids over a flat plate. Arimen et al. (1973) discussed the special features of micropolar fluids in the reviewed paper of the subject and application of micropolar fluid mechanics.

1.5 Nanofluid

The main restriction in enhancing the performance and the succinctness of many engineering electronic devices is due to the low thermal conductivity of conventional heat transfer fluids such as water, oil, and ethylene glycol mixture. To cope with the limitation in enhancing the performances and the compactness of such system, scientist has found an innovative way to improve the thermal conductivities of a fluid by suspended metallic nanoparticles within it. The resulting mixture which is called as nanofluid is the concept believed to be done first by Choi (1995). Nanoparticles have been made of various materials such as ceramics, nitride ceramics, etc. The used of nanofluids is to achieve a better possible thermal properties with the least possible $(<1\%)$ volume fraction of nanoparticles in base fluid (Godson et al., 2010). Nanofluids generally own a substantially larger thermal conductivity compared to that of the traditional fluids (Eastman et al., 2001). The presence of the nanoparticles in the fluids increases appreciably the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics. There exist a few nanofluid models considered in studies and among them, the well-known models are the model proposed by Buongiorno (2006) and Tiwari and Das (2007). For Buongiorno’s model the nanoparticle absolute velocity can be viewed as the sum of the base fluid velocity and a relative velocity. He discussed all the convective properties of nanofluids by developing a more generalize model. While the model by Tiwari and Das (2007) take the solid volume fraction into account while studied the behavior of the nanofluids.

Nanotechnology is widely used in industry since materials with sizes of nanoparticles possess unique physical and chemical properties. Convective heat transfer in nanofluids has a wide range of applications in both sciences and engineering especially in the technology that involving the heat transfer fluids, solar energy and nuclear reactors. The importance of nanofluids leads to many researches and studies related to nanotechnology. Trisaksri and Wongwises (2007) presented a critical review about heat transfer characteristics of nanofluids. Some numerical and experimental studies on nanofluids including the thermal conductivity, convective heat transfer boiling heat transfer and natural convection. Through the model existed, research about nanofluid has been furthered for various factor in many areas. For such, Santra et al. (2004) analysed the laminar natural convection in a square cavity using nanofluid and Oztop and Abu-Nada (2008) studied the effect of using nanofluid in the natural convection flow field and temperature distributions in partially heated square enclosure. They claimed that the type of nanoparticles used is the key factor to gain a better enhancement in heat transfer.

1.6 Viscous Fluid

Viscous fluids are the fluid that can resist movements or the movements of object through it, depending on how viscous they are. In general, all fluids have viscosity, but viscous fluid is the type of fluid that has high level of viscosity. It can move slowly or does not budge at all depending on their level of viscosity. Viscosity of the fluids can be measured between 1 to 1000 millipascal seconds. The more viscous the fluid is, the higher the value measure. The viscosity of the fluids can be measured by the type of fluid is made up, temperature, pressure and other surrounding factors. Basically, for liquids, the higher the temperature applied the less viscous it will become. Butter and glass is an example of extremely viscous fluid which make them behave like a solid than a liquid. Viscosity has been long understood as a friction force tending to destroy a velocity gradient. The simple description of this effect, known as Newtonian viscosity, considers the force between neighbouring laminar planes of fluid in differential motion. The flow is assumed to be unidirectional and the velocity gradient normal to the planes containing the flow. The force is proportional to the area of the planes and to the velocity gradient normal to the planes. The generally form for viscosity was first given by Navier in 1827 based on a model of dubious validity.

Viscous fluids are categorized in the type of Newtonian fluid. Simple examples of Newtonian fluids are water and air. Newtonian fluids are the simplest mathematical models of fluids that account for viscosity. While a non-Newtonian fluid, is a fluid with properties that are different in any way from those of Newtonian fluids for example micropolar fluids and nanofluids. Viscous fluids are the most type of fluid that being studied by plentiful of researchers. Thus numerous of work and publication have been manifested such as from Zaturska et al. (1988) where they analysed theoretically the flow of a viscous incompressible fluid driven along a channel by steady uniform suction through porous parallel rigid walls by considering asymmetric flows, unsteady flows and three-dimensional perturbations. Arifin and Abidin (2009) considered the effect of feedback control on the commencement of Marangoni convection in their study under the influence of variation viscosity and surface deformation. Puvi Arasu et al. (2011) where they studied to obtain the solutions for heat and mass transfer from natural convection flow along a vertical surface with temperature-dependent fluid viscosity embedded in a porous medium due to thermal-diffusion (Soret) and diffusion-thermo (Dufour) effects.

1.7 Thermal Radiation

There are two primary goals of scientists throughout the world which is to control the spreading of ferocious disease and the cultivation of plenteous energy sources. To achieve this goal, the manipulation and the control of ionizing radiation is taking into account. This makes the science of radiation chemistry more significant than ever before. Radiative effect generally has important applications through many different fields such as physics and engineering particularly in the high temperature processes and space technology (Mukhophadyay and Layek, 2008). This is basically due to their ability to transfer the heat when there is no medium existed between two locations for the radiant interchange to occur. Some of the important applications of radiation are in the area related to diagnosis and therapy, medical studies and research and agriculture and environment, Hurst and Turner (1970). By Siegel and Howell (1981), the radiation-convection interaction problems are found in consideration of the cooling high temperature components, furnace design where the heat transfer from surfaces occurs by parallel radiation and convection, convection cells and their effect on radiation from stars, the interaction of incident solar radiation with the earth's surface to produce complex free convection patterns and thus to complicate the art of weather forecasting and marine environment studies for predicting free convection patterns in the oceans and lake. Technology of solar energy utilization, reject waste heat from a power plant operating in space, wavelength region that give mankind heat, light, photosynthesis and all the attendant benefits are some of the factors why radiation is important. Combination or coupling of radiative heat transfer with convection or conduction was considered by several authors.

1.8 Permeable Surface (Suction or Injection)

Suction is the process of sucking while injection is the act of injecting through the plate. One of the applications of suction or injection is in the field of aerodynamic and space sciences (Singh, 1984). It can control the fluid flow on the surface of subsonic craft which can be benefit properties for the other important aspects such as

fuel saving and operating costs, see Shojaefard et al. (2005) and Braslow in (1999). Basically, suction acts as the factor that reduces the skin friction and heat transfer coefficients while injection serves an opposite manner, Al-Sanea (2004). An approximate solution to the uniform suction has been given by Ariel (1994). Generally, suction or injection gave a physical effect on the local Nusselt number, (Afify, 2009). The studied with the consideration of suction or injection has been widely investigated by many researchers.
For example, Attia (2005) studied the effect of suction and injection on the unsteady flow between two parallel plates with variable viscosity and thermal conductivity. Suali et al. (2012) utilize the influence of suction or injection in their study of unsteady stagnation point flow where both stretching and shrinking sheet is taking into consideration.

1.9 Magnetohydrodynamic (MHD)

Magnetohydrodynamic (MHD) is the study of the feature of magnetic in the electrically conducting fluid such as liquid metals and plasmas. Electric currents induced in the fluid as a result of its motion modify the field; at the same time their flow in the magnetic field leads to mechanical forces which modify the motion. The beginning creation on the field of MHD about the basic properties and work related to it was proposed by Alfvén (1942). Magnetohydrodynamic set a main role in many applications especially in industrial and technologies applications and it can control the quality of the product demand in industrial applications due to its feature that it can control the rate of cooling. Furthermore, in general magnetic field can degrade the fluid velocity, heat transfer rate and surface concentration gradient. Magnetic field can reduce the fluid velocity, the rate of heat transfer and concentration gradient at the surface. Magnetic field somehow became a primary factor that could control the rate of cooling which consequently the quality of the product desired can be characterized as demand. Due to that necessity, many researchers tend to investigate a problem related to electrically conducting fluid. Especially in the metallurgical processes that involved the cooling of continuous strips or filaments. Another important application of hydromagnetics to metallurgy lies in the purification of molten metals from non-metallic inclusion by the application of magnetic field (Datti et al. (2004)). Magnetic field can reduce the fluid velocity, the rate of heat transfer and concentration gradient at the surface.

1.10 Stability Analysis

Stability analysis is a study to determine the stability of solutions whenever non-unique solutions exist. It arises after the existence of more than one solution in computational results which give a resistance on which of the solution is stable to be applied. Hence, it is important to determine which of the solution is stable and physically realizable. Thus, a stability analysis is performed to specify the physical realizable of a multiple solutions in the computations. It is known that Merkin (1985) developed a stability analysis to determine the stability of the solutions exist in his work and he stated that the solution is not stable when the eigenvalue obtained is negative which indicated the instability. Later, Weidman et al. (2006) improved the work done by Merkin (1985) by proposed a new parameter related to the initial value problem. In this thesis, we consider the stability analysis developed by Weidman et al. (2006). For mathematical formulation of stability analysis it deals with the unsteady-flow. Flows with unsteady effects dealt with large-scale fluctuations, including those leading to transition and oblique waves. Driven unsteadiness effects included forced flow oscillations, sudden injection and immersion, and other variations in thermal heating boundary conditions.

1.11 Objectives and Scope

The objective of the thesis is to analyse the following three problems:

1. Marangoni boundary layer flow in micropolar fluid with the effects of thermal radiation where the flow is assumed to be laminar and the wall is permeable.
2. Marangoni boundary layer flow in nanofluid with the effects of thermal radiation and MHD where the nanofluids were made by dispersion of Cu, Al_2O_3 and TiO_2 in a water-based fluid.
3. Stability analysis of Marangoni boundary layer flow in viscous fluid with the effects of thermal radiation and MHD under the influence of heat and mass generation or consumption.

The scope of the study is restricted to two-dimensional, steady compressible laminar boundary layer flows in micropolar fluid, nanofluid and viscous fluid with the effect of radiation or MHD through a permeable surface to allow the case problem of suction or injection. Problem 1 is related with the micropolar fluid while problem 2 is associated with nanofluid cases where it followed the model by Tiwari and Das (2007) and problem 3 is related to viscous fluids.

1.12 Outline of the Thesis

This thesis consists of seven different chapters. Begin with Chapter 1, describing the introduction of the thesis, including the brief introduction of background of the research, objectives, scope of the research and the outline of the thesis.

Chapter 2 is basically the literature review related to the problem studied including the Marangoni convection, the fluid considered and the parameters involved in the study. There are some summary of books and journals been discussed in this chapter.

Chapter 3 is about the general mathematical formulation used in this thesis and the numerical methods are given. It is worth to mention that, this thesis is the extending work by the previous authors on the Marangoni boundary layer problem.

Next, Chapter 4 to Chapter 6 is the further discussion of the problem considered in this thesis. Beginning with the brief introduction of each problem involved as the first section. Then, the second section is the mathematical formulation of the problem and the method of solution applied. Continued with the third section about numerical results and discussion of each problem and finally followed by the conclusion as the final section.

In Chapter 4, we analyze the effect of radiation on the micropolar fluid of Marangoni boundary layer flow with suction/injection. While in Chapter 5, we studied the influence of magnetohydrodynamic (MHD) on the flow of Marangoni boundary layer in nanofluid through a permeable surface. The stability analysis of thermosolutal Marangoni boundary layer flow of a viscous Newtonian fluid with the effect of radiation and suction/injection is considered and discussed in Chapter 6.

The summary of the study in the thesis is in Chapter 7 with the possible further research that can be carried out in future.

REFERENCES

Abdullah, A. A., & Lindsay, K. A. (2017). Marangoni convection in a thin layer of nanofluid: application to combinations of water or ethanol with nanoparticles of alumina or multi–walled carbon nanotubules. *International Journal of Heat and Mass Transfer*, *104*, 693–702.

Abidin, N. H. Z., Mokhtar, N. F. M., Arbin, N., Said, J. M. & Arifin N. M. (2012). Marangoni convection in a micropolar fluid with feedback control. *IEEE Symposium on Business, Engineering and Industrial Applications, ISBELA 2012*, Article number 6422949, 558-562.

Abu Bakar, N. A., Hamid, R. A., & Zaimi, W. M. K. A. W. (2013). Marangoni mixed convection boundary layer flow with suction and injection. *AIP Conference Proceedings*, *1522*(1), 55.

Afify, A. (2009). Similarity solution in MHD: effects of thermal diffusion and diffusion thermo on free convective heat and mass transfer over a stretching surface considering suction or injection. *Communications in Nonlinear Science and Numerical Simulation*, *14*, 2202–2214.

Ahmad, N., Kechil, S. A., & Basir, N. M. (2012). Thermal and solutal mixed Marangoni boundary layers with suction or injection effects. *Journal of Science and Technology*, *4*(2).

Ahmadi, G. (1976). Self–similar solution of incompressible micropolar boundary layer flow over a semi–infinte plate. *International Journal Engineering Sciences*, 14, 639–646.

Al-Amri, F. G., & El–Shaarawi, M. A. I. (2010). Combined forced convection and surface radiation between two parallel plates. *International Journal of Numerical Methods for Heat and Fluid Flow*, *20*, 218–239.

Alfvén, H. (1942). Existence of electromagnetic–hydrodynamic waves. *Nature*. *150*, 405–406.

Ali, F. M., Nazar, R., Arifin, N. M., & Pop, I. (2011). MHD stagnation–point flow and heat transfer towards stretching sheet with induced magnetic field. *Appl. Math. Mech.*, *32*(4), 409–418.

Alloui, Z. & Vasseur, P. (2011). Onset of Bénard-Marangoni convection in a micropolar fluid. *International Journal of Heat and Mass Transfer*, *54*, 2765-2773.

Al-Sanea, S. A. (2004). Mixed convection heat transfer along a continuously moving heated vertical plate with suction or injection. *Int. J. Heat Mass Transfer*, *47*, 1445–1465.

Aly, E. H., & Ebaid, A. (2016). Exact analysis for the effect of heat transfer on MHD and radiation Marangoni boundary layer nanofluid flow past a surface embedded in a porous medium. *Journal of Molecular Liquids*, *215*, 625–639.

Andersson, J. D. (2005). Ludwig Prandtl's boundary layer. *Physics Today*.

Andersson, H. I., Bech, K. H., & Dandapat, B. S. (1992). Magnetohydrodynamic flow of a power-law fluid over a stretching sheet. *Int. J. Nonlinear Mechanics*, *27*(6), 929–935.

Anjali Devi, S. P., & Kandasamy, R. (2002). Effects of chemical reaction heat and mass transfer on non–linear MHD laminar boundary-layer flow over a wedge with suction or injection. *International Communications in Heat and Mass Transfer*, *29*, 707–716.

Arafune, K., & Hirata, A. (1999). Thermal and solutal Marangoni convection in In–Ga–Sb system. *Journal of Crystal Growth*, *197*(4), 811–817.

Ariel, P. D. (1994). Hiemenz flow in hydromagnetics, *Acta Mechanica*, *103*, 31–43.

Arifin, N. M. & Abidin, N. H. Z. (2009). Marangoni convection in a variable viscosity fluid layer with feedback control. *WSEAS Transactions on Mathematics*, *8*(8), 373-382.

Arifin, N. M., Nazar, R., & Pop, I. (2010). Marangoni boundary layer flow in nanofluids. In *International Conference on Theoretical and Applied Mechanics, International Conference on Fluid Mechanics and Heat and Mass Transfer-Proceedings*, 32-35.

Arifin, N. M., Nazar, R. & Pop, I. (2011). Non–isobaric Marangoni boundary layer flow for Cu, Al_2o_3 and Tio_2 nanoparticles in a water based fluid. *Meccanica*, *46*, 833–843.

Arifin, N. M., Nazar, R. & Pop, I. (2013). Similarity solution of marangoni convection boundary layer flow over a flat surface in a nanofluid. *Journal of Applied Mathematics*, *2013*, Article number 634746.

Arimen, T., Turk, M. A. & Sylvester, N. D. (1973). Microcontinuum fluid mechanics - A review. *International Journal of Engineering Science*, *11*, 905– 930.

Attia, H. A. (2005). The effect of suction and injection on the unsteady flow between two parallel plates with variable properties. *Tamkang Journal of Science and Engineering*, *8*, 17–22.

Azmi, H. M. & Idris, R. (2014). Effects of controller and nonuniform temperature profile on the onset of rayleigh-bénard-marangoni electroconvection in a micropolar fluid. *Journal of Applied Mathematics*, *2014*, Article number 571437.

Bakar, S. A., Arifin, N. M., Ali, F. M., Bachok, N. & Nazar, R. (2017). A stability analysis on unsteady mixed convection stagnation-point ow over a moving plate along the flow impingement direction. *Journal of Physics: Conference Series*, *890*, Article number 012041.

Bejan, A. (1984). Convection heat transfer. *New York: A Wiley–Interscience Publication*.

Braslow, A. (1999). A history of suction type laminar flow control with emphasis on flight research. *Washington, Wash, USA: American Institute of Aeronautics and Astronautics*.

Buongiorno, J. (2006). Convective transport in nanofluids. *ASME J. Heat Transfer*, *128*, 240–250.

Cess, R. D. (1961). The effect of radiation upon forced–convection heat transfer. *Appl. Sci. Res.*, *10*, 430–438.

Chamkha, A. J., Takhar, H. S. & Soundalgekar, V. M. (2001). Radiation effects on free convection flow past a semi–infinite vertical plate with mass transfer. *Chemical Engineering Journal*, *84*, 335–342.

Chen, C. H. (2007). Marangoni effects on forced convection of power–law liquids in a thin film over a stretching surface. *Phys. Lett. A.*, *370*, 51–57.

Choi, S. U. S. (1995). Enhancing thermal conductivity of fluids with nanoparticles. In *Proc of the ASME Int. Mech. Eng. Cong. and Exp.*, *66*, 99–105.

Christopher, D. M., & Wang, B. (2001). Prandlt number effects for Marangoni convection over a flat surface. *Int. J. Therm. Sci.*, *40*, 564–570.

Damseh, R. A., Al-Odata, M. Q., Chamkha, A. J. & Shannak, B. A. (2009). Combined effect of heat generation or absorption and first–order chemical reaction on micropolar fluid flows over a uniformly stretched permeable surface. *International Journal of Thermal Sciences*, *48*, 1658–1663.

Datti, P. S., Prasad, K. V., Abel, M. S., & Joshi, A. (2004). MHD visco–elastic fluid flow over a non–isothermal stretching sheet. *International Journal of Engineering Science*, *42*, 935–946.

Eastman, J. A., Choi, S. U. S., Li, S., Yu, W., & Thompson, L. J. (2001). Anamolously increased effective thermal conductivities of ethylene glycolbased nanofluids containing copper nanoparticles. *Phys. Lett. Appl.*, *78*(6), 718–720.

Ellahi, R., Zeeshan, A., & Hassan, M. (2016). Particle shape effects on Marangoni convection boundary layer flow of a nanofluid. *International Journal of Numerical Methods for Heat and Fluid Flow*, *26*(7), 2160–2174.

Eringen, A. C. (1964). Simple microfluids. *Int. J. Engng Sci.*, *2*, 205.

Eringen, A. C. (1966). *Proc. of the Eleventh Int. Cong. Appl. Mech., Munich Germany, 131. Springer.*

Gelles, S. H. (1978). Microgravity studies in the liquid–phase immiscible system: aluminium–indium. *AIAA J., 16*(5), 431–438.

Godson, L., Raja, B., Lal, D. M., & Wongwises, S. (2010). Enhancement of heat transfer using nanofluid – an overview. *Renew. Sust. Energy Reviews, 14,* 629–641.

Golia, C., & Viviani, A. (1986). Marangoni–bouyant boundary layers. *L' Aerotecnica Missili e Spazio*, *65*(6), 29–35.

Guram, S. G., & Smith, A. C. (1980). Stagnation flows of micropolar fuids with strong and weak interactions. *Computers and Mathematics in Applications,* 6, 213–233.

Hamid, R. A., & Nazar, R. (2016). Stability analysis of MHD thermosolutal Marangoni convection boundary layer flow. *AIP Conference Proceedings*, *1750*.

Hamid, R. A., Arifin, N. M., Nazar, R., & Pop, I. (2011). Radiation effects on Marangoni boundary layer flow past a flat plate in nanofluid. *Proc. of the International Multi Conference of Engineers and Computer Scientists, 2*.

Hamid, R. A., Arifin, N. M., Nazar, R., Ali, F. M., & Pop, I. (2011). Dual solutions on thermosolutal Marangoni forced convection boundary layer with suction and injection. *Mathematical Problems in Engineering*, *2011*, 19 pages.

Harris, S. D., Ingham, D. B., & Pop, I. (2009). Mixed convection boundary-layer flow near the stagnation point on a vertical surface in a porous medium: Brinkman model with slip, *Transport Porous Media*, *77*, 267–285.

Hurst, G. S., & Turner, J. E. (1970). Elementary radiation physics, *John Wiley and Sons, Inc.*

Ishak, A. (2010). Thermal boundary layer flow over a stretching sheet in a micropolar fluid with radiation effect. *Meccanica*, *45*, 367–373.

Ishak, A. (2014). Flow and heat transfer over a shrinking sheet: a stability analysis. *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*, *8*(5), 902.

Ishak, A., Nazar, R., & Pop, I. (2009). Dual solutions of the extended blasius problem. *Matematika*, *25*(2), 107–111.

Ishak, A., Nazar, R., Arifin, N. M., & Pop, I. (2007). Dual solutions in magnetohydrodynamic mixed convection flow near a stagnation–point on a vertical surface. *Journal of Heat Transfer*. *129*, 1212–1216.

Ishak, A., Nazar, R., Arifin, N. M., & Pop, I. (2008). Dual solutions in mixed convection flow near a stagnation point on a vertical porous plate. *International Journal of Thermal Sciences*, *47*, 417–422.

Ismail, N. S., Arifin, N. M., Bachok, N. & Mahiddin, N. (2016). Stagnation-point flow and heat transfer over an exponentially shrinking sheet: A stability analysis. In *AIP Conference Proceedings*, *1739*, Article number 020023.

Ismail, N. S., Arifin, N. M., Nazar, R. & Bachok, N. (2017). The stagnation-point flow and heat transfer of nanofluid over a shrinking surface in magnetic field and thermal radiation with slip effects: a stability analysis. *Journal of Physics: Conference Series*, *890*, 012055.

Katagiri, M. (1969). Magnetohydrodynamic flow with suction or injection at the forward stagnation point. *Journal of the Physical Society of Japan*, *27*(6), 1677-1685.

Keshtekar, M. M., Asadi, M. H., Samareh, R., & Poor, H. M. (2014). numerical study on the effects of Marangoni-driven boundary layer flow for different nanoparticles with variable based fluids. *Journal of International Academic Research for Multidisciplinary*, *2*(5).

Khaled, S. M. (2016). The exact effects of radiation and joule heating on MHD Marangoni convection over a flat surface. *Thermal Science*, 2016(00), 50–50.

Khan, M., & Malik, R. (2016). Forced convective heat transfer to sisko nanofluid past a stretching cylinder in the presence of variable thermal conductivity. *Journal of Molecular Liquids*, *218*, 1–7.

Kuroda, T. (2000). The Marangoni effect and its artistic application. *Forma*, *15*(3), 203-204.

Lichtenbelt, J. H., Dijkstra, H. A., & Drinkenburg, A. A. H. (1986). Marangoni convection and mass transfer from the liquid to the gasphase. *Adv. Space Res.*, *6*(5), 61–64.

Lin, Y., Li, B., Zheng, L., & Chen, G. (2016). Particle shape and radiation effects on Marangoni boundary layer flow and heat transfer of copper-water nanofluid driven by an exponential temperature. *Powder Technology*, *301*, 379–386.

Lin, Y., Zheng, L., & Zhang, X. (2014). Radiation effects on Marangoni convection flow and heat transfer in Pseudo–Plastic non–newtonian nanofluids with variable thermal conductivity. *International Journal of Heat and Mass Transfer*, *77*, 708–716.

Liu, L., Tan, H., & He, Z. (2001). Inverse radiation problem of source term in three-dimensional complicated geometric semitransparent media. *Int. J. Therm. Sci*, *40*, 528–538.

Maekawa, T., & Tanasawa, I. (1986). Onset of Marangoni convection in an infinite layer of an electrically conducting liquid under magnetic field. *Adv. Space Res.*, *6*(5), 41–44.

Magyari, E., & Chamkha, A. J. (2007). Exact Analytical results for the thermosolutal MHD Marangoni boundary layers. *International Journal of Thermal Sciences*, *47*, 848–857.

Mahapatra, T. R., & Nandy, S. K. (2011). Stability analysis of dual solutions in stagnation-point flow and heat transfer over a power-law shrinking surface. *International Journal of Nonlinear Science*, *12*(1), 86–94.

Mahapatra, T. R., & Gupta, A. S. (2001). Magnetohydrodynamic stagnation-point flow towards a stretching sheet. *Acta Mechanica*, *152*, 191–196.

Mahapatra, T. R., Nandy, S. K., & Gupta, A. S. (2014). Dual solution of MHD stagnation-point flow towards a stretching surface. *Engineering*, *2*(4), 299–305.

Mahdy, A., & Ahmed, S. E. (2015). Thermosolutal Marangoni boundary layer magnetohydrodynamic flow with the soret and dufour effects past a vertical flat plate. *Engineering Science and Technology, an International Journal*, *18*, 24–31.

Mahmud, M. N., Idris, R., & Hashim, I. (2009). Effects of magnetic field and nonlinear temperature profile on Marangoni convection in micropolar fluid. *Differential Equations and Nonlinear Mechanics*, *2009*, 11 pages.

Mat, N. M., Arifin, N. M., Nazar, R., Ismail, F., & Pop, I. (2012). Radiation effects on Marangoni convection boundary layer over a permeable surface. *Meccanica*, *48*, 83–89.

Mbeledogu, I. U., Amakiri, A. R. C., & Ogulu, A. (2007). Unsteady MHD free convective flow of a compressible fluid past a moving vertical plate in the presence of radiative heat transfer. *International Journal of Heat and Mass Transfer*, *50*, 1668–1674.

Merkin, J. H. (1985). Free convection above a uniformly heated horizontal circular disk. *J. Eng. Math*. *20*, 171–179.

Mishra, U., & Singh, G. (2014). Dual solutions of mixed convection flow with momentum and thermal slip flow over a permeable shrinking cylinder. *Computer Fluids*. *93*, 107–115.

Mokhtar, N. F. M., Khalid, I. K. & Arifin, N. M. (2012). Effect of internal heat generation on benard-marangoni convection in micropolar fluid with feedback control. *Journal of Physics: Conference Series*, *435*, Article number 012029.

Mudhaf, A., & Chamkha, A. J. (2005). Similarity solutions for MHD thermosolutal Marangoni convection over a flat surface in the presence of heat generation or absorption effects. *Heat Mass Transfer*, *42*, 112–121.

Mukhophadyay, S., & Layek, G. C. (2008). Effects of thermal radiation and variable fluid viscosity on free convective flow and heat transfer past a porous stretching surface. *Int. J. Heat Mass Transfer*, *51*, 2167–2178.

Napolitano, L. G., & Golia, C. (1981). Coupled Marangoni boundary layers. *Acta Astronautica*, *8*(5), 417–434.

Napolitano, L. G. (1979). Marangoni boundary layers. *In Proc. 3rd European Symp. on Material Science in Space, Grenoble, ESA SP–142*.

Napolitano, L. G. (1986). Recent development of Marangoni flows theory and experimental results. *Adv. Space Ret*., *6*(5), 19–34.

Okano, Y., Itoh, M., & Hirata, A. (1989). Marangoni convections in a two–dimensional rectangular open boat. *J. Chem. Eng. Jpn*., *22*, 275–281.

Oztop, H. F., & Abu–Nada, E. (2008). Numerical study of natural convection in partially heated rectangular enclosures filled with nanofluids. *International Journal of Heat and Fluid Flow*, *29*, 1326–1336.

Peddieson, J. (1972). An Application of the micropolar fluid model to the circulation of a turbulent shear flow. *Int. J. Engng. Sci*., *10*, 23– 32.

Puvi Arasu, P., Loganathan, P., Kandasamy, R., & Muhaimin, I. (2011). Lie group analysis for thermal–diffusion and diffusion–thermo effects on free convective flow over a porous stretching surface with variable stream conditions in the presence of thermophoresis particle deposition. *Nonlinear Analysis: Hybrid Systems*, *5*, 20–31.

Rashad, A. M., Rashidi, M. M., Lorenzini, G., Ahmed, S. E., & Aly, A. M. (2017). Magnetic field and internal heat generation effects on the free convection in a rectangular cavity filled with a porous medium saturated with cu-water nanofluid. *International Journal of Heat and Mass Transfer*, *104*, 878–889.

Ridha, A. (1992). On the dual solutions associated with boundary–layer equations in a corner. *Journal of Engineering Mathematics*, *26*, 525–537.

Roşca, N. C., Roşca, A. V., & Pop, I. (2016). Lie group symmetry method for MHD double–diffusive convection from a permeable vertical stretching/shrinking sheet. *Journal Computers and Mathematics with Applications*, *71*(8), 1679–1693.

Saleh, S. H., Arifin N. M., Nazar R., Ali F. M. & Pop I. (2014). Marangoni Boundary Layer Flow in Micropolar Fluid. Australian Journal of Basic and Applied Sciences, 8(22): 12–23.

Santra, A. K., Sen, S., & Chakraborty, N. (2004). Analysis of laminar natural convection in a square cavity using nanofluid. *31st National Conference on Fluid Mechanics and Fluid Power (FMFP)*, 240–248.

Saravanan, S., & Sivaraj, C. (2014). Surface radiation effect on convection in a closed enclosure driven by a discrete heater. *International Communications in Heat and Mass Transfer*, *53*, 34–38.

Sastry, D. R. V. S. R. (2015). MHD thermosolutal Marangoni convection boundary layer nanofluid flow past a flat plate with radiation and chemical reaction. *Indian Journal of Science and Technology*, *8*(13).

Sastry, D. R. V. S. R. K. (2016). Thermosolutal MHD Marangoni convective flow of a nanofluid past a flat plate with viscous dissipation and radiation effects. *WSEAS Transactions on Mathematics*, *15*.

Sastry, D. R. V. S. R. K., Murti, A. S. N., & Kantha, T. P. (2013). The effect of heat transfer on MHD Marangoni boundary layer flow past a flat plate in nanofluid. *International Journal of Engineering Mathematics, 2013*, 6 pages.

Sastry, D. R. V. S. R. K., Srinivasu, M., Murty, A. V. S. N. & Srinivas, M. N. (2017). MHD viscous chemically reacted marangoni convective nanofluid flow over a flat plate with suction/injection. *International Journal of Civil Engineering and Technology*, *8*, 1039-1045.

Schlichting, H. (1979). Boundary–layer theory. *New York (USA): McGraw-Hill, 7 editions.*

Shojaefard M. H., Noorpoor A. R., Avanesians A. & Ghaffapour M. (2005). Numerical Investigation of Flow Control by Suction and Injection on a Subsonic Airfoil. The American Journal of Applied Sciences, 20: 1474–1480.

Siegel, R., & Howell, J. R. (1981). Thermal radiation heat transfer. *Series in Thermal and Fluid Engineering, Hemisphere Publishing Corporation, United State of America.*

Singh, A. K. (1984). Stokes problem for a porous vertical plate with heat sinks by finite difference method. *Astrophysics and Space Science*, *2*, 241–248.

Sreenivasulu, P., Reddya, N. B., & Reddy, M. G. (2013). Radiation and viscous dissipation effects on steady MHD Marangoni convection flow over a permeable flat surface with heat generation/absorption. *International Journal of Mathematical*, *4*(2), 174–183.

Suali, M., Nik Long, N. M. A., & Arifin, N. M. (2012). Unsteady stagnation point flow and heat transfer over a stretching/shrinking sheet with suction or injection. *Journal of Applied Mathematics*, *2012*, 12 pages.

Tiwari, R. K., & Das, M. K. (2007). Heat transfer augmentation in a two-sided lid-driven differentially heated square cavity utilizing nanofluids. *International Journal of Heat and Mass Transfer*, *50*, 2002–2018.

Trisaksri, V., & Wongwises, S. (2007). Critical review of heat transfer characteristics of nanofluids, *Renewable and Sustainable Energy Reviews*, *11*, 512–523.

Uwanta, I. J., & Hamza, M. M. (2014). Effect of suction/injection on unsteady hydromagnetic convective flow of reactive viscous fluid between vertical porous plates with thermal diffusion. *International Scholarly Research Notices*, *2014*, 14 pages.

Verma, S., & Balaji, C. (2007). Multi-parameter estimation in combined conduction-radiation from a plane parallel participating medium using genetic algorithms. *International Journal of Heat and Mass Transfer*, *50*, 1706–1714.

Watanabe, T. (1993). Magnetohydrodynamic free convection flow over a wedge in the presence of a transverse magnetic field. *Int. Commun. Heat Mass Transfer*, *20*(6), 871.

Weidman, P. D., Kubitschek, D. G., & Davis, A. M. J. (2006). The effect of transpiration on self-similar boundary layer flow over moving surfaces. *Int. J. Eng. Sci*., *44*, 730–737.

Yina, S., Xinhui, S., Yanan, S., & Zheng, L. (2013). The analytical solution for the flow and heat transfer of a nanofluid over a nonlinearly stretching sheet. *International Journal of Applied Mathematics and Statistics*, *46*(16), 366–373.

Zaturska, M. B., Drazin, P. G., & Banks, W. H. H. (1988). On the flow of a viscous fluid driven along a channel by suction at porous walls. *Fluid Dynamics Research*, *4*, 151–178.

Zhang, Y., & Zheng, L. (2012). Analysis of MHD thermosolutal Marangoni convection with the heat generation and a first–order chemical reaction. *Chemical Engineering Science*, *69*, 449–455.

Zhang, Y., & Zheng, L. (2014). Similarity Solutions of Marangoni convection boundary layer flow with gravity and external pressure. *Chinese Journal of Chemical Engineering*, *22*(4), 365–369.

Zheng, L. C., Chen, X. H., Zhang, X. X., & He, J. C. (2004). An approximately analytical solution for the Marangoni convection in an In–Ga–Sb system. *Chinese Phys. Lett.*, *21*, 1983–1985.

LIST OF PUBLICATIONS

Jurnal

Ariffin, N. M., Arifin, N. M., & Bachok, N. (2017). Radiation effects on MHD marangoni boundary layer flow past a flat plate in nanofluid with permeable. *Advances and Applications in Fluid Mechanics*, *20*(3), 407-420

Proceeding

Ariffin, N. M., Arifin, N. M., & Bachok, N. (2017). Marangoni boundary layer flow in micropolar fluid with suction/injection. In *AIP Conference Proceedings* 1795, 020011 (2017); doi: 10.1063/1.4972155

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