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HEAT TRANSFER ANALYSIS OF NANOFLUIDS WITH VARIABLE STREAM CONDITIONS USING NUMERICAL APPROACH – RKF45

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Universiti Tun Hussein Onn Malaysia

Examiners:

DR. FATIMA AL ZAHRA BINTI MOHD SA'AT
Faculty of Mechanical Engineering
Universiti Teknikal Malaysia

DR. ASLAM BIN ABDULLAH
Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

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ASHWIN KUMAR ERODE NATARAJAN

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HEAT TRANSFER ANALYSIS OF NANOFLUIDS WITH VARIABLE STREAM CONDITIONS USING NUMERICAL APPROACH – RKF45

ASHWIN KUMAR ERODE NATARAJAN

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2016

I hereby declare that this thesis entitled "heat transfer analysis of nanofluids with variable stream conditions using numerical approach – RKF45" is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	
Name	:	ASHWIN KUMAR ERODE NATARAJAN
Matrix No.	:	HD130005
Date	:	JANUARY 2016

Supervisor :

Dr. Norasikin Binti Mat Isa

Co-Supervisor :

Prof. Dr. R. Kandasamy

I would like to dedicate this thesis to

ALMIGHTY "GOD"

(Who gave me strength, knowledge, patience and wisdom)

MY "PARENTS"

(Their pure love, devotion, cares and prayers had helped me to achieve this target)

MY "BROTHERS AND FRIENDS"

(Their love, care, encouragement and motivation made me finish this valuable work)

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ABSTRACT

Nanofluid is a stable, colloidal suspension of low volume fraction of ultrafine solid particles. These solid particles are in nano metric dimension, dispersed in conventional heat transfer fluids to offer a dramatic enhancement in conductivity. Three nanoparticles namely Alumina, Copper and Titanium dioxide; two base fluids - fresh water and sea water are selected to form nanofluids. The fluid dynamics equation for incompressible flow is selected. In the present study, the highly nonlinear partial differential equations of momentum and energy fields have been simplified using suitable similarity transformations. Both the momentum equation and energy equation are solved for steady, two-dimensional, stagnation-point, laminar flow of a viscous nanofluid past a stretching / shrinking porous plate. Stream functions pertaining to current research work is selected from literature reviews. Various stream conditions are introduced into the equations for better understanding of nanofluids' behavior. Finally, for executing the coupled equations, a new mathematical software known as MAPLE 18 is used. This software uses a fourth-fifth order Runge–Kutta–Fehlberg method as a default to solve boundary value problems numerically. Temperature and velocity profiles are obtained in the form of graphs for all nanofluids that are taken into consideration. Then the graphs are analyzed and compared amongst them. The results proved Copper nanoparticle to be more effective. The results of Cu-fresh water nanofluid and Cu-seawater nanofluid are compared, and it is proven that effectiveness depends on the stream conditions. The study has concluded that magnetic effect increases the heat transfer efficiency and Copper nanofluid is most suitable for stagnation-point flow. Studying sea water based nanofluids in multi-environment will increase the chance of using sea water as coolant in various applications.

ABSTRAK

Bendalir nano adalah suatu cecair elektrik yang stabil, penggantungan koloid yang mempunyai pecahan isipadu yang rendah daripada zarah pepejal ultra halus dalam nano dimensi metrik tersebar secara pemindahan haba konvesional untuk memberikan peningkatan yang maksima dalam kekonduksian. Terdapat tiga nanopartikel seperti Alumina, tembaga dan Titanium Diotsida, berdasarkan dua cecair asas iaitu air tawar dan air laut. Pengiraan persamaan dinamik bendalir untuk aliran yang tidak boleh dimampat telah dipilih. Kedua-dua persamaan momentum dan persamaan tenaga adalah ditentukan untuk memantapkan dua dimensi, titik genangan, aliran lamina daripada bendalir nano melalui regangan atau kecutan yang berliang. Berdasarkan kajian literatur fungsi aliran yang berkaitan untuk kajian telah dipilih. Pelbagai keadaan aliran diperkenalkan dalam persamaan untuk permahaman yang lebih baik daripada tingkah laku bendalir nano. Akhir sekali, untuk melaksanakan persamaan gandingan, satu perisian matematik baru MAPLE 18 telah digunakan. Perisian ini menggunakan tertib ke-empat dan ke-lima kaedah *Runge-Kutta-Fehlberg* sebagai tertib alpa untuk menyelesaikan masalah nilai sempadan berangka. Profil suhu dan halaju profil diperolehi dalam bentuk graf untuk semua bendalir nano yang diambil kira dalam pengiraan. Kemudian graf dianalisis dan dibandingkan. Keputusan membuktikan bahawa nanopartikel tembaga adalah lebih berkesan. Keputusan bendalir nano Cu-air tawar dan Cu-air laut telah dibandingkan dan dibuktikan bahawa keberkesanannya bergantung kepada keadaan aliran. Kajian ini menyimpulkan bahawa kesan magnet meningkatkan kecekapan pemindahan haba dan tenaga bendalir nano adalah sesuai untuk pelbagai aplikasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

a	Acceleration, constant (+ve)
A	Area
Al_2O_3	Alumina nanoparticle
b	Constants (+ve)
B_0	Magnetic field strength
c	Constants (+ve)
C_p	Specific heat at constant pressure
$(C_p)_s$	Specify heat of solid
$(C_p)_f$	Specific heat of fluid
$(C_p)_{nf}$	Specific heat of nanofluids
Cu	Copper nanoparticle
CuO	Copper oxide nanoparticle
DI	Deionized water
Ec	Eckert number
F	Force
$f'(\eta)$	Dimensionless velocity
$f''(\eta)$	Dimensionless skin friction
Gr_x	local Grashof number
g	Gravitational force
h	Enthalpy
h_x	Local heat transfer coefficient ($Wm^{-2}K^{-1}$)
K	Porous parameter
KCl	Potassium chloride
K_1	Permeability of the porous medium (m^2)
K^*	Roseland mean spectral absorption coefficient (m^{-1})

L	Length
m	Mass
M	Magnetic strength parameter (Nm $\Omega^{-1}A^{-2}$ s^{-1})
MHD	Magnetohydrodynamics
N	Thermal radiation parameter (s^3m^{-2})
Nu	Nusselt number
Nu_x	Local Nusselt number
ODE	Ordinary differential equations
Pr	Prandtl number
Pr_{fw}	Prandtl number for fresh water
Pr_{sw}	Prandtl number for sea water
Q	Heat transfer rate
Q_o	Dimensional heat generation/absorption coefficient ($kgm^{-1}s^{-3}K^{-1}$)
q_r	Thermal radiative heat flux (Wm^{-2})
Re_x	Local Reynolds number
RK4	Runge-Kutta method
RKF45	Runge-Kutta-Felhberg method
S	Suction/injection parameter ($kgs^{-1}m^{-3}$)
T	Fluid temperature in Cartesians co-ordinates (x,y)
TiO_2	Titanium dioxide nanoparticle
u	Velocity component in *x*-direction
u_w	Stretching/shrinking surface velocity
u_T	Tangential velocity
U	Free stream velocity in Cartesians co-ordinates (x,y)
U_T	Tangential boundary velocity
v	Velocity component in *y*-direction
x	Direction along the plate
y	Direction perpendicular to the plate
2-D	Two-dimensional
3-D	Three-dimensional
$^o/oo$	Parts per thousand

Greek symbols

α	Thermal diffusivity
α_{nf}	Thermal diffusivity of the nanofluid
α_{f}	Fluid thermal diffusivity
β	Thermal expansion coefficient
γ	Buoyancy parameter
δ	Boundary layer thickness
$\delta_{V(x)}$	Velocity boundary layer thickness in x-direction
$\delta_{T(x)}$	Thermal boundary layer thickness in x-direction
η	Similarity variable
$\theta(\eta)$	Dimensionless temperature of the fluid
θ_{w}	Wall temperature excess ratio parameter
$\theta'(\eta)$	Dimensionless heat transfer rate
κ	Thermal conductivity
κ_{eff}	Effective thermal conductivity
κ_{f}	Thermal conductivity of the fluid
κ_{nf}	Thermal conductivity of the nanofluid
κ_{s}	Thermal conductivity of solid
λ	Heat generation/absorption parameter
λ_{I}	Heat generation/absorption parameter for injection
λ_{S}	Heat generation/absorption parameter for suction
μ	Dynamic viscosity
υ	Kinematic viscosity
υ_{w}	Wall mass flux
ρ	Density
ρ_{f}	Density of fluid
ρ_{nf}	Effective density of the nanofluid
ρ_{s}	Density of solid
$(\rho C_{p})_{f}$	Heat capacitance of fluid
$(\rho Cp)_{nf}$	Heat capacitance of nanofluid
$(\rho C_{p})_{s}$	Heat capacitance of solid
σ	Electrical conductivity

σ^*	Stefan–Boltzmann constant
τ	Shear stress
ϕ	Nanoparticles volume fraction
ψ	Stream function

Superscripts

$'$	Differentiate with respect to y, x, η correspondingly

Subscripts

f	Fluid
fw	Fresh water
I	Injection
nf	Nanofluid
s	Solid
S	Suction
sw	Sea water
T	Tangential
w	Wall
∞	Free stream

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journal Articles

1. Impact of heat transfer on MHD boundary layer of copper nanofluid at a stagnation point flow past a porous stretching and shrinking surface with variable stream conditions
   Ashwin Kumar, Norasikin Binti Mat Isa, Kandasamy
   ARPN Journal of Science and Technology, 5(5), (2015), 219-231.

In Press

2. Impact of injection on a stagnation–point flow of copper nanofluids over a vertical porous shrinking or stretching plate in the presence of magnetic field
   Ashwin Kumar, Norasikin Binti Mat Isa, Vibhu Vignesh, Kandasamy
   ARPN Journal of Engineering and Applied Sciences (*Scopus Indexed)*

3. Heat transfer characteristic of nanofluids on MHD stagnation–point flow towards stretching or shrinking plate in the presence of injection or suction
   Ashwin Kumar, Norasikin Binti Mat Isa, Vibhu Vignesh, Kandasamy
   ARPN Journal of Engineering and Applied Sciences (*Scopus Indexed)*

4. Effect of injection on thermal and flow characteristics of copper MHD nanofluid in the presence of sea water/fresh water
   Ashwin Kumar, Norasikin Binti Mat Isa, Vibhu Vignesh, Kandasamy
   ARPN Journal of Engineering and Applied Sciences (*Scopus Indexed)*

5. Impact of suction on a stagnation–point flow of copper nanofluids over a vertical porous plate in the presence of magnetic field
   Ashwin Kumar, Norasikin Binti Mat Isa, Vibhu Vignesh, Kandasamy
   Australian Journal of Basic and Applied Science (*ISI/Thomson Reuters)*

CHAPTER 1

INTRODUCTION

1.1 Background

Heat transfer is one of the most important processes in many industrial and consumer products. The inherently poor thermal conductivity of conventional fluids puts a fundamental limit on heat transfer. Therefore, for more than a century since Maxwell in 1904, scientists and engineers have made great efforts to break this fundamental limit by dispersing millimeter- or micrometer-sized particles in liquids. However, the major problem with the use of such large particles is the rapid settling of these particles in fluids, clogging and erosion of pipes and channels. As extended surface technology has already been adapted to its limits in the designs of thermal management systems, technologies with the potential to improve a fluid's thermal properties are of great interest once again. The concept and emergence of nanofluids is related directly to the trend in miniaturization and nanotechnology. Maxwell's concept is old, but what is new and innovative in the concept of nanofluids is the idea that particle size is of primary importance in developing stable and highly conductive nanofluids.

Ultrahigh-performance cooling is one of the most vital needs of many industrial technologies. However, inherently low thermal conductivity is a primary limitation in developing energy efficient heat transfer fluids that are required for ultrahigh-performance cooling. Nanofluids are engineered by suspending nanoparticles with average sizes below 100 nm in traditional heat transfer fluids such as water, oil, and ethylene glycol. Nanofluids (nanoparticle fluid suspensions) is the term coined by Choi (1995) to describe this new class of nanotechnology-based heat transfer fluids that exhibit thermal properties superior to those of their host fluids or conventional particle fluid suspensions. Nanofluid technology, a new interdisciplinary field of great importance where nanoscience, nanotechnology, and thermal engineering meet, has developed largely over the past decades. The goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations (preferably < 1% by volume) by uniform dispersion.

Based on the above discussion of the versatile properties and applications of nanofluids, the research study has been narrowed and had made an approach to synthesize Al_2O_3, Cu and TiO_2 based nanofluids which can transfer heat more effectively. Fresh water and sea water are chosen as base fluids. The enhancement of heating or cooling in an industrial process may promote conservation of energy, reduce process time, raise thermal rating and lengthen the working life of equipment. A number of studies have been conducted to gain an understanding of the heat transfer performance for their practical application to heat transfer enhancement. Thus the advent of high heat flow processes has created significant demand for new technologies to enhance heat transfer.

There are several methods to improve the heat transfer efficiency. Some methods are utilization of extended surfaces, application of vibration to the heat transfer surfaces, and usage of micro channels. Heat transfer efficiency can also be improved by increasing the thermal conductivity of the working fluid. Commonly used heat transfer fluids such as water, ethylene glycol, and engine oil have relatively low thermal conductivity, as compared to the thermal conductivity of solids. High thermal conductivity of solids can be used to increase the thermal conductivity of a fluid by adding nanoparticles to that fluid. However, the emergence of modern materials technology provide the opportunity to produce nanometer-sized particles which are quite different from the parent material in mechanical, thermal, electrical, and optical properties.

1.2 Problem statement

There are many kinds of nanofluids which can efficiently and safely help the heat transfer process in industries, condensers and etc. A big unresolved issue for most environmental and industrial applications is to find the flow and heat transfer behaviors of nanofluids towards the stretching/shrinking surface on various stream conditions when injection/suction is present. This will help in understanding the heat transfer processes of the surfacing materials, hence improving the quality of the final products.

1.3 Aim of Study

The aim of the study is to obtain a mathematical derivation suitable to the stagnation-point flow and study the behaviors of four different nanofluids. The lack of knowledge on the behavior of nanofluids on stagnation-point flow over a stretching/shrinking permeable surface prevents the nanofluids from the widespread use in industrial applications.

1.4 Objectives of the study

The main theme of this study is to modify a mathematical equation for the stagnation-point flow of nanofluids. Based on the research gaps identified in literature review, this study has been done according to the following objectives:

1. To derive a mathematical equation for studying mechanical and thermal behavior of nanofluids in stagnation-point flow in the influence of mechanical field strength and Grashof number and various other parameters i.e. thermal radiation, heat sink/source, suction/injection parameter, Eckert number, Nusselt number, nanoparticle volume fraction and porous parameter.
2. Study the heat transfer rate, thermal and velocity distribution of Al_2O_3, Cu and TiO_2 nanoparticles in fresh water to predict the best and appropriate nanofluid for stagnation-point flow and comparing the results by changing the base fluid to sea water for various stream conditions.

1.5 Scope of study

This study is limited to the problem of steady convective heat transfer boundary layer flow and stagnation-point flow of viscous, incompressible nanofluid over a permeable shrinking/stretching surface under prescribed parameters effect. The surface of the wall is permeable in order to allow suction or injection. Some prescribed parameters, such as porous medium, heat radiation, variable viscosity and suction/injection parameter, are included in the study on the boundary layer behaviors. The governing partial differential equations are approximated by natural convective flow model, MHD flow model, laminar, stagnation-point flow model. Due to the use of a porous medium, it takes into account the effect of inertia on solid boundary and is simplified using boundary layer theory and Boussinesq approximations.

The partial differential equations governing the problem under consideration are transformed by similarity transformation into a system of ordinary differential equations with boundary conditions. The numerical scheme, Runge-Kutta-Fehlberg in conjunction with shooting method is used to find the dimensionless velocity and temperature profiles. Alumina, Copper and Titanium dioxide as nanoparticles, fresh water and sea water as base fluids are taken into consideration for studying the behaviour of nanofluids in laminar stagnation-point flow over porous surface. MAPLE 18 software is used to solve boundary layer equations, which uses Runge-Kutta-Fehlberg method for solving ordinary differential equations.

1.6 Contributions towards nanofluid field

The proposed mathematical equation for nanofluids in stagnation-point flow over a shrinking/stretching surface would provide better understanding in mechanical and also thermal behaviors of the nanofluids. The major contributions are:

1. A new mathematical derivation with magnetic field strength, Nusselt number and Grashof number helps to get better understanding of the mechanical and thermal behavior of nanofluids flowing horizontally under various governing parameters.
2. The study with four different nanofluids under similar stream conditions over a shrinking /stretching surface gives clear idea for the selection of nanofluids for numerous applications such as nuclear cooling system, solar water heating, defence and space application, electronics and bio-medical application, etc.

1.7 Research motivation

The study focuses on new mathematical equation for stagnation-point flow and boundary layer flow of nanofluids over a vertical permeable membrane under the influence of magnetic field strength. The study motivation chart is shown in Figure 1.1 that highlights the problem, its solution and outcomes.

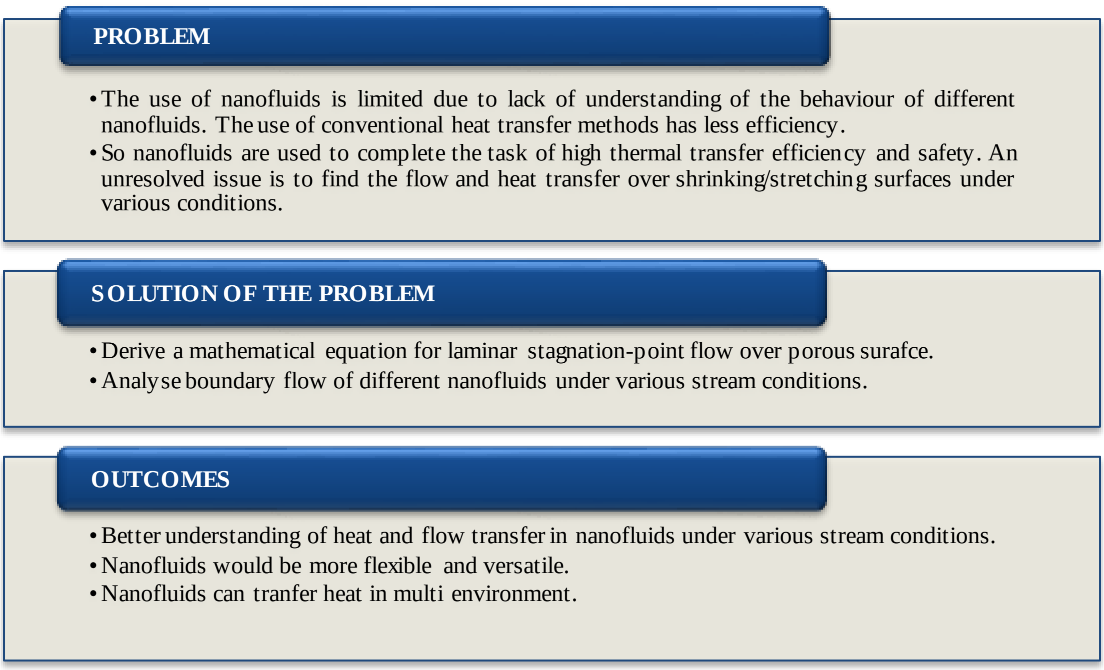

Figure 1.1 Research motivation

1.8 Thesis layout

This thesis is organized as follows:

In Chapter 1, the introduction, the very beginning of all the research works that has been done for the past year. The problems that are to be dealt with at the end of this research are listed in the problem statement. The aim and the objectives that have pushed this research work with numerous findings and data are provided consecutively. The contribution to the field of nanofluids by this research work are stated after that.

In Chapter 2, a collection of studies of existing works in several key areas of nanofluids research and background to the field of nanofluids along with examples of existing types of nanofluids are discussed. It also highlights the existing issues related to heat transfer, high pumping power problems. The data from the numerous existing researches from all over the world which are used for the research work purpose are provided in this chapter.

In Chapter 3, the way this project is carried out is explained. Mathematical modelling by which the general fluid dynamics equation suitable for incompressible flow is transformed into an equation suitable for stagnation-point flow is elaborated. The physical flow model is presented and discussed. The MAPLE software using which the governing equations is executed, is explained in this chapter. A unique program coding suitable for solving ODE is written exclusively for this situation. For validation of MAPLE software, data are analyzed with the previous presented results.

In Chapter 4, values and graphs obtained from the numerical calculation are presented and discussed briefly. At first the study of behavior of three nanofluids taking fresh water as base fluid. Then Cu-fresh water nanofluid extensive study of behavior in the presence of suction and injection for various governing parameters are discussed. At last, the behavior of Cu-sea water nanofluid in the presence of suction and injection is discussed and compared with the behavior of Cu-fresh water.

In Chapter 5, summary of this research work is given. Future recommendations are also discussed.

CHAPTER 2

LITERATURE REVIEW

Numerous researches on nanofluids have been carried out in the past two decades, the implementation of nano-meter sized particle to the heat transfer fluids to enhance their heat transfer rate. Nano fluids have been used for engine cooling, engine transmission oil, boiler exhaust flue gas recovery, cooling of electronic circuit, especially in nuclear cooling system, solar water heating, defense and space application and biomedical application, etc. To increase the thermal conductivity of base fluids, many factors have to be considered, such as the shape and size of nanoparticle, thermal conductivity of nanoparticle, concentration of nanoparticle, Prandtl number, and Reynolds number.

2.1 Fluid mechanics

The field of fluid mechanics is divided into two branches, fluid statics and fluid dynamics. Fluid statics, or hydrostatics, is concerned with the behavior of a fluid at rest or nearly so. Fluid dynamics involves the study of a fluid in motion (Anderson, 2012). Modern engineering science has the ability to create and solve mathematical models of physical systems. Fluid mechanics is a challenging subject, because the underlying mathematical model appears to be complex and difficult to apply. This study will show that the governing equation of fluid statics, called the hydrostatic equation, is actually relatively simple and may be solved to find the pressure distribution in the fluid.

On the other hand, the governing equation of fluid dynamics, called the Navier–Stokes equation, would never be described as simple. The common theme is to simplify the mathematical or experimental model used to describe the flow without sacrificing the relevant physical phenomena. The art of fluid mechanics is to know when it is safe to neglect the effects of physical phenomena that are judged to have little impact on the flow. Once it is decided that certain physical phenomena be neglected, the corresponding terms are dropped from the governing equations, thereby decreasing the difficulty in obtaining a solution (Shaughnessy *et al.*, 2005).

One of the intentions of this study is to integrate these modern computational aids into a first course in fluid mechanics. The use of symbolic mathematics codes, such as MATHCAD, MAPLE, Mathematica, and others like them, helps in learning fluid mechanics, to simplify calculations and to visualize the mathematics.

2.2 Fluid dynamics

There are three fundamental physical principles upon which all of fluid dynamics is based on (Anderson, 2012):

1. Mass is conserved.
2. Newton's second law, F= ma
3. Energy is conserved.

All of fluid dynamics is based on the three fundamental physical principles. These physical principles are applied to model a flow. This application results in equations which are mathematical statements of the particular physical principles involved, namely, the continuity, momentum and energy equations. Each different model of the flow directly produces a different mathematical statement of the governing equations, some in conservation form and others in non-conservation form. Boundary conditions and their appropriate mathematical statements will be developed. The governing equations must be solved subject to these boundary conditions. The physical aspects of the boundary conditions are fundamentally independent of the forms of the governing equations. However, the appropriate numerical form of the physical boundary conditions is dependent on the particular mathematical form of the governing equations as well as the particular numerical algorithm used to solve these equations.

2.2.1 Governing equations

In the current study, Navier-Stokes governing equations are used. The advantage of using a time-independent Navier-Stokes approach for incompressible flow is its inherent ability to evolve to the correct steady-state solution (Anderson, 2012). The steady, 2-D stagnation-point flow of a viscous and incompressible fluid over a stretching/shrinking vertical porous surface is placed in the plane $y = 0$ of a Cartesian system of coordinates with the x-axis along the sheet as shown in Figure 2.1. Figure 2.1 shows the flow configuration with conventional variables. The flow being confined to y > 0 that is fluid occupies the half plane (y > 0). It is assumed that the velocity $u_w(x)$ and the temperature $T_w(x)$ of the stretching/shrinking sheet is proportional to the distance x from the stagnation-point, where $T_w(x) < T_\infty$. g is the gravity acceleration.

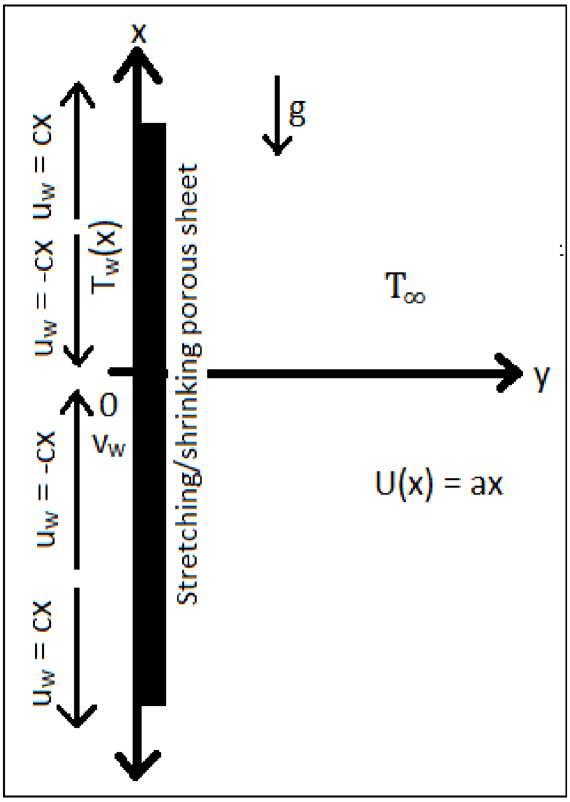

Figure 2.1 Flow configuration

Under these assumptions along with the Boussinesq and boundary layer approximations, the boundary layer equations for steady 2-D stagnation-point flow through a porous medium (highly permeable) over a heated porous stretching/shrinking surface (with the application of Darcy's law) are, in the usual notations,

1. **Continuity equation**

   Physical principal: Mass is conserved

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.1}$$

2. **Momentum equation**

   Physical principle: F = ma

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U(x)\frac{dU(x)}{dx} + \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial y^2} + \frac{\mu_{nf}}{\rho_{nf}K}(U(x) - u) \tag{2.2}$$

In equation 2.2, $U(x)$ stands for the stagnation-point velocity in the inviscid free stream, u and v are the components of velocity respectively in the x and y directions, K is the permeability of the porous medium, μ_{nf} is the dynamic viscosity of nanofluids, ρ_{nf} is the nanofluids' density.

By using the boundary layer approximations, the boundary layer equation of energy for fluid temperature T in the presence of heat source/heat sink, thermal radiation and viscous dissipation is

3. **Energy equation**

   Physical principle: Energy is conserved

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\frac{d^2 T}{dy^2} + \frac{Q_0}{(\rho C_p)_{nf}}(T - T_\infty) - \frac{1}{(\rho C_p)_{nf}}\frac{\partial q_r}{\partial y} +$$

$$\frac{\mu_{nf}}{(\rho C_p)_{nf}}\left(\frac{\partial u}{\partial y}\right)^2 \tag{2.3}$$

C_p is the specific heat at constant pressure of nanofluids, α is the thermal diffusivity coeficient of fluids, Q_0 is the dimensional heat generation/absorption coefficient of fluids and q_r is the radiative heat flux respectively. The equation 2.1 to equation 2.3 are subjected to the boundary conditions (for shrinking or stretching plate):

$$\left.\begin{array}{l} v = v_w, u = u_w(x) = \pm cx, T = T_w(x) \ at \ y = 0 \\ v = 0, \ u = U(x) = ax, T = T_\infty \ at \ y = \infty \end{array}\right\} \tag{2.4}$$

where a and c are positive constants. v_w is the wall mass flux. $T_w(x)$ and T_∞ are also constants with $T_\infty > T_w(x)$.

2.2.2 Similarity Solutions

The similarity solutions for equation 2.1 to equation 2.3 with boundary condtions are in the following form:

1. **Stream functions**

   Stream function is defined for incompressible flow in 2-D with axisymentry. It can be used to plot streamlines , which represent the trajectories of particles in steady flow. Stream functions will exclude pressure. Usefulness of stream functions is that the velocity components in (x,y) direction at any given point are given by partial derivatives of stream function at that point.

   Stream function, $\psi = \sqrt{c \cdot \nu_f} \cdot f(\eta) \cdot x$

2. **Similarity variable** (dimensionless distance), $\eta = \sqrt{\frac{c}{\nu_f}} \cdot y$

3. **Dimensionless temperature,** $\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}$

2.3 Heat transfer

Heat transfer and temperature distribution are of great importance to engineers because of its almost universal occurrence in many branches of science and engineering. Heat transfer is thermal energy transfer in transit due to a spatial temperature difference (Bergman, 2011). Fluid dynamics is closely associated with heat transfer. In a system, heat flow occurs wherever temperature gradient is present. Thus the knowledge of temperature distribution is essential in heat transfer studies. The energy transfer of heat takes place by three distinct modes (Sachdeva, 2010):

1. Conduction – Exists in a system, comprising molecules of a solid, liquid or gas.
2. Convection – Exists between fluid and solid.
3. Radiation – Exists between two bodies of different temperatures in an evacuated adiabatic

2.3.1 Convection

Convective heat transfer is one of the distinct modes of heat transfer for transferring heat between a solid surface and the fluid moving on it. Convection is only possible in the presence of a fluid medium. Transfer of energy in convection is mostly due to the bulk motion of fluid particles. This kind of heat transfer is present mostly in liquids and gases. Heat transfer by convection is always accompanied by conduction, because the transfer of energy between the solid surface and the fluid at the surface can take place only by conduction (Sachdeva, 2010).

2.3.1.1 Convection in nanofluids

The study on the heat transfer convection is very limited as compared to the experimental and theoretical study of the thermal conductivity of nanofluids. It is very important to know that enhancement in thermal conductivity of nanofluid does not necessarily increase the heat transfer capability of it. The physical properties of nanofluids compared to pure fluids such as viscosity, heat capacity, density and stability of nanoparticles in the fluid may deteriorate. Natural convection, force convection and mixed convection can be obtained in nanofluids. Natural convection is the type of convection which the flow is generated by buoyancy force during cooling or heating of the fluid. Force convection is the convection in which the flow is due to external forces such as a pump, fan, compressor and etc. The law of convection is Fourier's conduction law (Bergman, 2011):

$$Q = hA(T_w - T_f) \tag{2.5}$$

where Q is the amount of heat transfer between the wall and the fluid in motion, A is the solid-liquid interface area, T_w is the wall temperature, and T_f is the fluid temperature. In nanofluids two methods can be used for the study of heat transfer (Khanafer *et al.*, 2003) which is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity which is named as single phase model. In the other model, the fluid is considered to be a single fluid with two phases, and the coupling between them is strong which each phase has its own velocity vectors, and within a given volume fraction, there is a certain volume fraction of each phase which is named as mixture model. In nanofluids, due to the small particles being suspended in an ordinary fluid and their higher stability, the single phase model is more applicable.

2.3.1.2 Convective boundary layer flow over a porous surfaces

Single phase model has been used in several studies of convective heat transfer with nanofluids, (Khanafer *et al.,* 2003; Maiga *et al.,* 2004; Koo & Kleinstreuer, 2005). Convective flow, heat transfer in porous surface, has been a topic of interest for researchers, as it plays a crucial role in diverse applications, such as thermal insulation, extraction of crude oil and chemical catalytic reactors etc. Numerous authors proposed models and group theory methods to study convective boundary layer flow of fluids, which are (Birkhoff, 1948, 1960; Yurusoy *et al.,* 2001). Pak & Cho (1998) analyzed the heat transfer by convection in Al_2O_3-water and TiO2-water nanofluids. The flow of nanofluid is turbulent, and observes that increase in nanoparticle volume fraction and the Reynolds number, increases the Nusselt number of the nanofluids. However, in a nanofluid having 3% volume of nanoparticle, the convective heat transfer coefficient for an average fluid velocity was 12% lower than that of pure water. The result appears to disagree with the observation of (Lee & Choi, 1996). Lee & Choi (1996) investigated convective heat transfer in microchannel using an unspecified nanofluid. Laminar flow was selected as the flow of nanofluids and found a reduction in thermal resistance by a factor of 2. Heat power dissipation by nanofluids were measured to three times more than pure water.

Kuznetsov & Neild (2010) studied the influence of nanoparticles on natural convection boundary-layer flow past a vertical plate, using a model in which Brownian motion and thermophoresis are accounted. In this study, both temperature and nanoparticle volume fraction are assumed to be constant along the wall. Kuznetsov & Neild (2009) have examined natural convection boundary-layer flow past a vertical permeable plate and Darcy model was introduced in momentum equation. In a contemporaneous study, Bataller (2008) studied the boundary layer flow over a convectively heated flat plate with a radiation term in the energy equation. Aziz (2009) has recently studied the Blasius flow over a flat plate with a convective thermal boundary condition and established the condition which the convection heat transfer coefficient must meet for a similarity type solution to exist. Bachok *et al.* (2010) have studied theoretically the problem of steady boundary-layer flow of a nanofluid past semi-infinite flat plate in uniform free stream and it is found that dual solutions exist when the plate and the free stream flow move in opposite directions. The problems of laminar fluid flow resulting from the stretching of a flat plate in a nanofluid have been investigated by (Khan & Pop, 2010). Kuznetsov & Neild (2011) studied the double-diffusive natural convective boundary-layer flow of a binary nanofluid past a vertical plate incorporated it with the effects of Brownian motion and thermophoresis.

2.3.2 Important points about the heat transfer of nanofluids

It should be noted that the most important reason of using nanofluids is to improve the heat transfer of fluids. The experience in this field has showed that other properties besides the thermal conductivity, such as the C_p, α, heat fusion and etc. of the nanoparticle have great impact on nanofluids. This point has not been mentioned elsewhere. Most of the researchers have mainly focused on the thermal conductivity of nanofluids without considering these properties. This is the main key in making useful nanofluids for practical applications. Some other key points for nanofluids are (Kahar, 2014):

1. The thermal conductivity enhancement ratio increases with increasing particle volume fraction.
2. The sensitivity to volume fraction depends on particle material and base fluid (the sensitivity is higher for particle material with higher thermal conductivity and base fluid with lower thermal conductivity).
3. The thermal conductivity of nanofluids shows higher sensitivity to temperature than that of the base fluid, consequently the thermal conductivity enhancement ratio also shows high sensitivity to temperature.
4. The particle shape also affects the thermal conductivity. Elongated particles show higher thermal conductivity enhancement ratio than spherical particles.
5. The thermal conductivity enhancement ratio increases with acidity.

6. For the suspensions containing the same base liquid and nanoparticles, the thermal conductivity enhancements were highly dependent on the specific surface area of the nanoparticles.
7. For the suspensions using the same nanoparticles, the enhanced thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid.

2.4 Classification of flow

Flow is generally classified into uniform and non-uniform flow, compressible and incompressible flow, steady and unsteady flow, and laminar and turbulent flow. A steady flow is one in which the conditions (velocity, pressure and cross-section) may differ from point to point but do not change with time (Shaughnessy *et al.,* 2005). If at any point in the fluid, the conditions change with time, the flow is described as unsteady. Density of all fluids will change if pressure changes. Liquids are quite difficult to compress, so under most steady conditions they are treated as incompressible. In some unsteady conditions very high pressure differences can occur and it is necessary to take these into account.

2.4.1 Stagnation-point flow

At stagnation point, the local velocity of the fluid is zero (Clancy, 1975). When a flow strikes on a solid object, a stagnation-point occurs. The Bernoulli equation shows that the static pressure is highest when the velocity is zero and hence static pressure is at its maximum value at stagnation points. This static pressure is called the stagnation pressure (Clancy, 1975). The Bernoulli equation applicable to incompressible flow shows that the stagnation pressure is equal to the dynamic pressure plus static pressure. Total pressure is also equal to dynamic pressure plus static pressure so, in incompressible flows, stagnation pressure is equal to total pressure. In compressible flows, stagnation pressure is also equal to total pressure providing the fluid entering the stagnation point is brought to rest isentropically. In fluid dynamics, more attention has been given to the study of stagnation-point flows because of their importance in many engineering disciplines, for example cooling of electronic devices by fans, cooling of nuclear reactors, and many other hydrodynamics processes.

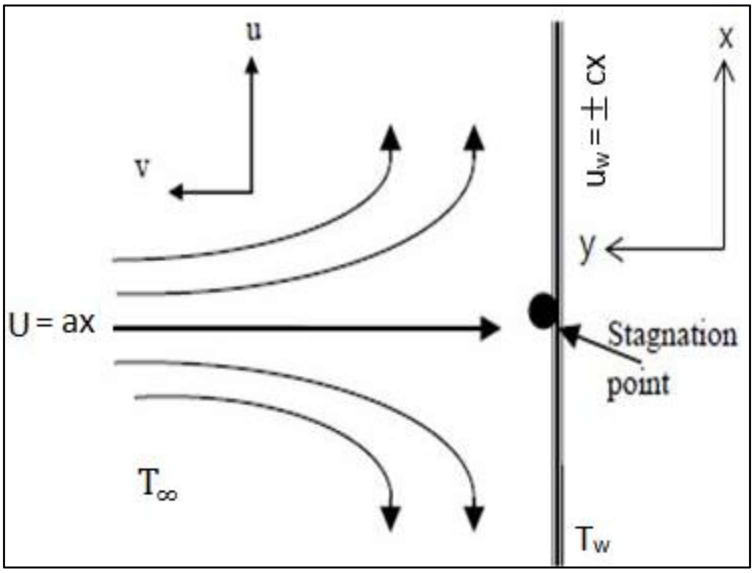

Figure 2.2 Stagnation-point flow (ABD-Elaziz & Ahmed, 2008)

Consider the development of the 2-D boundary layer flow of a micro polar fluid near the rear stagnation point of a vertical plane surface in a porous medium. For analysis, rectangular Cartesian coordinates (x,y) are used in which x and y are taken as the coordinates along the wall and normal to it, respectively. u and v are the components of fluid velocity in the x and y directions, respectively. The flow configuration is shown schematically in Figure 2.1.

Stagnation-point can be located in the region of flow passing any shape of body, i.e., pier and aerofoil. Hiemenz in 1911, was the pioneer in analyzing stagnation-point flow on a plate; keeping the plate at stationary position. Navier-Stokes equations which are reduced to highly nonlinear equations using similarity transformation, was first coined by Hiemenz in 1911. In the past two decades, many investigators have carried out researches on stagnation-point flow, due to the applications in engineering field. The popularity of stagnation-point flow is increasing among the scientists and researchers, as the stagnation-point flow is studied in various ways. The difference in the boundary layer thickness obtained from numerical simulation and similarity solution is small for low aspect ratio and close to the stagnation point.

Mahapatra & Gupta (2002) studied the behavior of flow and heat transfer over stretching plate using two-dimensional boundary layer flow, stagnation-point flow and heat transfer. The results showed that when stretching surface velocity is lower than the free stream velocity, boundary layer is formed. When the stretching surface velocity is higher than the free steam velocity, an inverted boundary layer is formed. Magentohydrodynamics stagnation-point flow and boundary layer flow is studied by (Mahapatra & Gupta, 2001; Ishak *et al.*, 2009) over a stretching surface. According to their results, it is clear that when stretching velocity is lower than that of free stream velocity, there is an increase in velocity at one point with an increase in magnetic field. Pal *et al.* (2014) analyzed the behavior of Cu, Al_2O_3 and TiO_2 nanoparticles taking fresh water as base fluid at a stagnation point flow on shrinking or stretching surface with thermal radiation. Pal *et al.* (2014) took the Prandtl number for water as 6.8. He studied the behavior of temperature, velocity profiles, skin friction and heat transfer rate and found that temperature profiles are high in the case of shrinking surfaces.

2.5 Flat plate boundary-layer concept

The concept of a boundary layer as proposed by Prandtl in 1904 forms the starting point for the simplification of the equations of motion and energy. Fluid at plate surface does not move relative to the plate. The effect of viscosity is to create a boundary layer near the plate in which the velocity changes smoothly and continuously from zero to free stream value (Shaughnessy *et al.*, 2005). In this concept, flow field over a surface is divided into two regions: First, by a thin region near the body, called the boundary layer, where the velocity and temperature gradients are large, and secondly by the region outside the boundary layer where the velocity and temperature gradients are very nearly equal to their free stream value. Outside the boundary layer, the flow is essentially the inviscid flow that had been studied for the previous two centuries. In general, both the velocity boundary layer and thermal boundary layer will exist simultaneously.

2.5.1 Velocity boundary layer

Consider the flow over a flat plate, the velocity here in front of the leading edge of the plate is uniform. Due to the no slip condition to be satisfied at the surface of the plate, the velocity of the fluid is reduced to zero relative to the surface. This results in the retardation of the fluid particles in the adjoining fluid layers until at a distance y = δ from the surface (called boundary layer thickness) this effect becomes negligible. The deceleration of the fluid particles in the boundary layer is associated with shear stress, τ. The effect of shear (viscous) forces originating at the surface extends into the body of the fluid, but with increasing distance, *y*, from the surface, the *x* velocity component of the fluid, u, increases until it approaches the free stream velocity, U_∞ (Kahar, 2014). $\delta_{V(x)}$ is the velocity boundary layer thickness in *x*-direction. The velocity and thermal boundary layer thickness is shown in Figure 2.2. The free stream velocity (U_∞) is zero in Figure 2.2.

It is most essential to distinguish between laminar and turbulent boundary layers. Initially, the boundary layer development is laminar for the flow over a flat plate. Depending upon the flow field and fluid properties, at some critical distance from the leading edge small disturbances in the flow begin to get amplified, a transition process takes place and the flow becomes turbulent. In laminar boundary layer, the fluid motion is highly ordered whereas the motion in the turbulent boundary layer is highly irregular with the fluid moving to and from all directions. Due to fluid mixing resulting from these macroscopic motions, the turbulent boundary layer is thicker and the velocity profile in turbulent boundary layer is flatter than that in laminar flow.

2.5.2 Thermal boundary layer

A thermal boundary layer will develop if the surface temperature and free stream temperature are different. In Figure 2.2, at the leading edge, the temperature profile is uniform with $T = T_\infty$. The wall is maintained at T_w. $\delta_{T(x)}$ is the thermal boundary layer thickness in *x*-direction. The fluid particles coming into contact with the surface exchange thermal energy with those in the neighboring layers and a thermal gradient is setup. With increasing distance, *y*, from the surface, the fluid temperature approaches the free stream temperature. The effects of heat transfer penetrate further into free stream resulting in the growth of thermal boundary layer thickness. Like the velocity boundary, the thermal boundary will also be defined as laminar or turbulent depending upon the critical value of Reynolds number (Kahar, 2014).

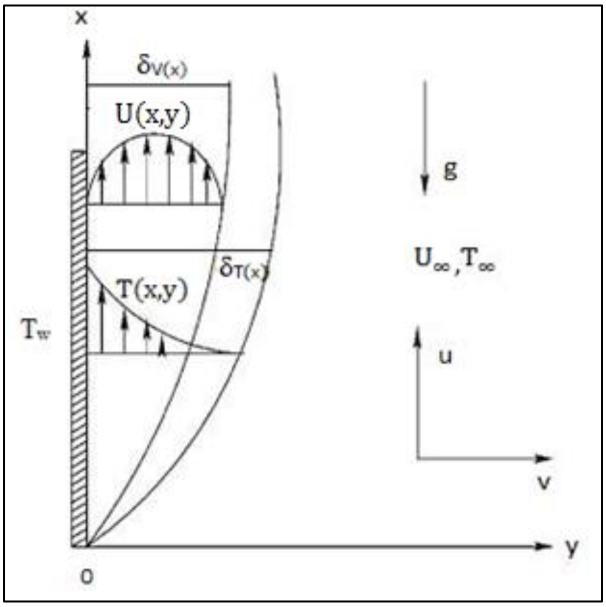

Figure 2.3 Velocity and thermal boundary layer (Kandasamy *et al.*, 2011)

2.5.3 No slip boundary conditions

In using the governing equations to solve a flow problem, it is necessary to specify conditions that model the behavior of the fluid and flow properties at boundaries of various types. The boundary conditions that apply specifically to the velocity field of the surface are referred to as the no-slip conditions. In nearly all flows encountered in engineering, observation shows that a fluid does not move relative to a solid surface in the tangential direction. Rather, the fluid sticks to the surface, a phenomenon referred to as no-slip. From this, it is concluded that the tangential component of velocity u_T is equal to the tangential component of boundary velocity, U_T. This boundary condition $u_T = U_T$ is called the no-slip condition in fluid dynamics. If a solid surface is not moving, $U_T = 0$, and the no-slip condition becomes $u_T = 0$. The no-slip condition is normally invoked for every solid–fluid interface (Shaughnessy *et al.*, 2005).

2.6 Porous surface

Porous surface consists of void spaces called pores distributed throughout solid matrix. Porous material are permeable to a variety of fluids that is fluids should be able to penetrate through one face of septum made of the material and emerge on the other side. They can be used as an insulator (for all temperature ranges) and can be used as a heat transfer promoter for either sensible or latent heat transfer. Porous medium is characterized by a very large surface area to a volume ratio. This peculiar feature of the porous media can be utilized to either distribute heat energy uniformly or to enhance the heat transfer in heat exchange systems. The fluid storage capacity of porous media, such as paper, is mainly determined by its porosity. Porosity is the geometrical property of porous medium. The absorption and spreading rate is determined by permeability. Permeability is the measure of ability of a porous media to transmit fluids. The unit of measurement is Darcy, named after a French scientist Darcy in 1856. Permeability is the most important physical property of a porous media. Different transport models are available in the literature, are used to model energy and momentum transport in porous media. These models are based upon governing equations which are inherited from the corresponding free-fluid flow.

Porous materials are encountered literally everywhere in everyday life, in technology and in nature. There is a large variety of natural and artificial porous materials encountered in practice, such as: soil, sandstone, limestone, ceramics, foam, rubber, bread, lungs, and kidneys. With the exception of metals, some dense rocks, and some plastics, virtually all solids and semi-solid materials are porous to varying degrees. Aquifers (from where water is pumped), sand filters (for purifying water), reservoirs (which yield oil or gas), packed and fluidized beds in the chemical engineering and the root zone in agricultural industry may serve as additional examples of porous media domains.

2.6.1 Momentum transport in porous surface

Several momentum flow models have been proposed to model the flow through a permeable medium. A small mistake in the velocity distribution will strongly affect the temperature distribution. Therefore, there is a need to focus on these momentum models before considering any model describing the temperature distribution. The first momentum equation which describes the transport phenomenon of the fluid flow through porous media were deduced experimentally by Darcy in 1856. Since then several flow models which are based on phenomenological observations rather than analytical approaches have been developed to match the same purpose.

2.6.2 Energy transport in porous surface

The knowledge of the heat transfer characteristics in porous media is of great importance in many applications. For example, in chemical reactor design it is important to know the thermal transport characteristics of the porous media in order to make accurate predictions of the variation in reaction rate caused by the inlet temperature disturbances. Temperature histories are also important for the design of packed bed thermal storage system. Therefore, it is desirable to have the proper values of the heat transfer coefficient and effective thermal conductivity, so that the time required to heat up the solid particles can be estimated (Grangeot *et al.*, 1984).

2.7 Magnetohydrodynamic (MHD)

The field MHD was initiated by Hannes Alfven in 1942, an astrophysicist. Magneto-hydrodynamics is the branch of continuum mechanics which deals with the flow of electrically conducting fluids in electric and magnetic fields. The word magentohydrodynamics (MHD) is derived from magneto which means magnetic field, hydro means liquid and dynamics which mean movement. The set of equations which describe MHD are a combination of the Navier-Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism. These differential equations have to be solved simultaneously, either analytically or numerically. When a conducting fluid moving through a magnetic field, a Lorentz force will act on the fluid and modify its motion. In MHD, the motion modifies the field and the field, in turn, reacts back and modifies the motion. This makes the theory highly non-linear. When nanofluids is in the influence of magnetic field a retarding force acts on the flow. This force moves in the opposite direction of the flow, and decelerates the velocity of the fluid motion.

2.7.1 Steady MHD flow over porous surfaces

Chamkla & Aly (2010) have analyzed MHD free convection flow of a nanofluid past a vertical plate in the presence of heat generation or absorption effects. Singh (2001) analyzed the MHD free convection and mass transfer flow with the heat source and thermal diffusion. The paper deals with the study of free convection and mass transfer flow of an incompressible, viscous and electrically conducting fluid past a continuously moving infinite vertical plate in the presence of large suction and under the influence of uniform magnetic field considering heat source and thermal diffusion. Rajeswari *et al.*, (2009) examined the governing equations for steady incompressible fluid past a semi-infinite vertical porous plate embedded in a porous medium and subjected to the presence of transverse magnetic field. Hamad & Pop (2011) have examined the unsteady MHD free convection flow past a vertical permeable flat plate in a rotating frame of reference with constant heat source in a nanofluid. Makinde (2009) used a shooting numerical technique to analyze MHD boundary-layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux at the plate surface. Except for a few, boundary layer flows have been studied using either a constant surface temperature or a constant heat flux boundary condition.

2.8 Thermal conductivity enhancement in nanofluids

Maxwell in 1904 and Hamilton & Crosser (1962) developed a classical model using the medium theory. This model is experimentally verified by the data for mixtures with lower volume fractions of micrometer and millimeter sized particles. The data obtained from the experiments showed that nanofluids have high thermal conductivity that cannot be predicted accurately by the models suggested by Maxwell in 1904 and (Hamilton & Crosser, 1962). Wang *et al.* (1999); Keblinski *et al.* (2002) have suggested few mechanisms that are not considered by classical models. These mechanisms elucidates the enhanced thermal conductivity of nanofluids.

Wang *et al.* (1999) told that enhanced thermal conductivity of nanofluids, is maybe due to the microscopic motion of nanoparticles, the surface properties, and the structural effects. Brownian motion, van der Waals force, and electrostatic force significantly causes the microscopic motion of nanoparticles in nanofluids. Keblinski *et al.* (2002) explained the increase in nanofluids heat transfer must be due to the four possible mechanisms and the mechanisms are:

1. Brownian motion of the nanoparticles,
2. Liquid layering at the liquid/particle interface,
3. Nature of the heat transport in the nanoparticles,
4. The effect of nanoparticle clustering.

From Eastman *et al.* (1997) report, nanoparticles induced in water, made a promising turning point of using nanofluids in heat transfer devices. The article showed that Copper Oxide (CuO) particles suspended in nanoparticle volume concentration of 0.05 in fresh water, the enhancement in thermal conductivity is almost 60% compared to fresh water. Murshed *et al.* (2005, 2009) found that nanofluids prepared by dispersing 5% volume fraction Titanium dioxide nanoparticles in deionized water, thermal conductivity enhancement is observed through hot wire technique to be nearly 33% and close to 30%, respectively over the base fluid.

A benchmark study on the thermal conductivity of nanofluids was made by (Buongiorno *et al.,* 2009). Variety of experimental approaches, including transient hot wire method, steady-state methods and optical methods are performed and it was found that the thermal conductivity increases with volume concentration and aspect ratio. The resulted thermal conductivities were then validated through effective medium theory developed for dispersed particles.

2.9 Impact and potential benefits of nanofluids

In industries, nanofluids technology is greatly considered, where the heat transfer characteristics of heat exchanger and cooling devise is vital. Choi *et al.* (2004); Zussman (1997) showed that when the nanoparticles are dispersed in conventional heat transfer fluids, nanofluids can offer variety of benefits. These benefits include (Murshed, 2008):

1. Improved heat transfer and stability
2. Microchannel cooling without clogging

3. Miniaturized systems
4. Pumping power reduction
5. Cost and energy savings

2.9.1 Applications of nanofluids

In the modern era of fast computers and battery operated devices, such as mobile phones and laptops, have accelerated the invention of new coolants and heat transfer fluids. In last two decades researchers have been working to find a new technology to perform this task. Many researches have been conducted over the years to understand the behavior of these fluids. Nanofluids are very important invention of this period which has wide applications, few are listed in Table 2.1.

Table 2.1 Applications of nanofluids

1. Engine cooling	2. Solar water heating
3. Engine transmission oil	4. Refrigeration
5. Boiler exhaust flue gas recovery	6. Defence and space application
7. Cooling of electronic circuit	8. Thermal storage
9. Nuclear cooling system	10. Bio-medical application

2.10 Nanoparticles

Nanotechnology is rapidly developing in the recent years. Particles that are in nano-meter size that is less than 100 nanometers normally, instead of micro-meter sized are suspended in conventional heat transfer liquids. Researchers have been working to increase the heat transfer capacity of conventional fluids by introducing different nanoparticles such as metals (Cu, Al, Au), oxides (CuO, Al_2O_3, TiO_2, ZnO), etc. and explained the heat transfer and flow characteristics of the different nanofluids. Li & Xuan (2002); Xuan & Li (2003) studied experimentally the convective heat transfer and flow features for Cu-water nanofluids flowing through a straight tube under laminar and turbulent flow regimes with a constant heat flux. The experimental results showed that addition of nanoparticles into the base liquid remarkably enhanced the heat transfer performance of the base liquid. Moreover, the friction factor of nanofluids coincided well with that of the water.