BOUNDARY LAYER FLOW, HEAT AND MASS TRANSFER OVER A STRETCHING OR SHRINKING SURFACES IN A NANOFLUID

By

MAHANI BINTI AHMAD KARDRI

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

June 2023

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DEDICATIONS

To my beloved;

father,
Ahmad Kardri bin Katiso
&
late mother,
Norhuda binti Palengah

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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June 2023

Chair : Norfifah binti Bachok @ Lati, PhD
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The purpose of this study is to solve five different problems focused on the nanofluid model, Tiwari-Das model (2007) and related to the steady laminar free and mixed convection boundary layer flow on a linear, exponential, or nonlinear stretching or shrinking surface in a nanofluid. This study considers flow that occurs over a flat surface or at the top of a cylinder. Three types of nanoparticles, namely copper, alumina, and titania, were investigated. The governing partial differential equations are reduced into nonlinear ordinary differential equations using the similarity transformation technique. The system of equations will then be numerically solved using the bvp4c solver in MATLAB software. The present study was validated by comparing it to previous literature and found to be in good agreement. The influence of governing parameters, including stretching or shrinking, nanoparticle volume fraction, curvature, suction, mixed convection, first-order and second-order velocity slip, chemical reaction, buoyancy ratio, magnetic field, Soret number, Dufour number, nonlinear parameter, radiation, heat generation, and Eckert number, are analyzed. The physical quantities of interest are the skin friction coefficient, Nusselt and Sherwood numbers, velocity, temperature, and concentration profiles, which are presented graphically for further discussion. A certain range of solutions reveals the existence of dual solutions. The stability analysis has been performed to determine which solutions are linearly stable and physically reliable. Dual solutions exist within a certain range of solutions. Copper has the highest thermal conductivity compared to alumina and titania. The lowest skin friction coefficient goes to alumina, while titania is for the lowest heat transfer. Increases in the skin friction coefficient and heat transfer rate reduced the values of the suction parameter, while there was an increase in the magnetic field parameter, nanoparticle volume fraction, and slip parameters. An increase in the nanoparticle volume fraction helps to increase the chemical reaction parameter. The upper branch solution was found to be stable by stability analysis performed

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in two problems of study, while the lower branch solution was unstable.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALIRAN LAPISAN SEMPADAN, PEMINDAHAN HABA DAN JISIM TERHADAP SUATU PERMUKAAN YANG MEREGANG ATAU MENGECUT DALAM NANOBENDALIR

Oleh

MAHANI BINTI AHMAD KARDRI

Jun 2023

Pengerusi : Norfifah binti Bachok @ Lati, PhD
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Kajian ini dijalankan adalah bertujuan untuk menyelesaikan lima permasalahan kajian yang berbeza memfokuskan kepada model nanobendalir, model Tiwari-Das (2007) dan berkenaan dengan aliran lapisan sempadan yang mantap berlamina dan olakan campuran pada permukaan atau plat meregang atau mengecut yang linear, eksponen dan tak linear dalam nanobendalir . Kajian ini mempertimbangkan aliran di atas permukaan yang rata atau di atas silinder. Tiga jenis nanobendalir iaitu tembaga, aluminium, dan titanium dikaji. Persamaan pembezaan separa menakluk telah dijelmakan kepada persamaan pembezaan biasa tak linear dengan menggunakan teknik penjelmaan keserupaan. Sistem persamaan berkenaan seterusnya diselesaikan secara berangka menggunakan pakej bvp4c yang dibina dalam perisian MATLAB. Pengesahan kajian ini dilakukan dengan membandingkan penyelesaian semasa dengan kajian terdahulu dan didapati hasil perbandingan adalah sangat baik. Pengaruh parameter menakluk yang merangkumi parameter meregang atau mengecut, pecahan isipadu nanozarah, kelengkungan, sedutan, olakan campuran, gelinciran peringkat pertama dan kedua, tindak balas kimia, nisbah apungan, medan magnet ke atas ciri-ciri aliran, nombor Soret, nombor Dufour, parameter tak linear, radiasi, penjanaan haba, dan nombor Eckert. Kuantiti fizikal seperti pekali geseran kulit, kadar pemindahan haba dan jisim serta profil halaju, suhu dan kepekatan ditunjukkan secara bergraf melalui rajah untuk perbincangan lanjut. Penyelesaian dual didapati wujud bagi julat tertentu. Analisis kestabilan dijalankan untuk menentukan penyelesaian yang stabil dan bermakna secara fizikal. Tembaga mempunyai kekonduksian haba yang lebih tinggi berbanding aluminium dan titanium. Pekali geseran kulit dan halaju yang tinggi akan merendahkan parameter sedutan dan meninggikan parameter medan magnet ke atas ciri-ciri aliran, pecahan isipadu nanozarah, dan parameter-parameter gelinciran. Peningkatan dalam pecahan isipadu nanozarah mempengaruhi

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kenaikan pada parameter tindak balas kimia. Penyelesaian untuk cabang atas adalah sentiasa stabil menerusi analisis kestabilan dalam dua permasalahan yang dikaji, manakala penyelesaian untuk cabang bawah didapati tidak stabil.

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Last but not least, I am so grateful for my family's unwavering support, my UiTM colleague's cooperation and patience in light of my duty as a worker and a part-time student, and not forgotten my UPM friends for their knowledge sharing and help whenever needed.

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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 the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date: 14 March 2024

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LIST OF ABBREVIATIONS

a, c	constants
Al_2O_3	alumina
B	transverse magnetic field
B_0	uniform magnetic field strength
C	nanofluid concentration
C_f	skin friction coefficient
C_p	specific heat at constant pressure
C_w	surface concentration
C_∞	ambient concentration
Cr	chemical reaction parameter
Cu	copper
Du	Dufour number
Ec	Eckert number
f	dimensionless stress functions
g	acceleration due to gravity
Gr	Grashoft number
k	thermal conductivity
L	characteristic length
M	magnetic parameter
n	nonlinear parameter
Nr	buoyancy ratio parameter
Nu_x	Nusselt number

p	pressure
Pr	Prandtl number
Q_0	uniform volumetric heat generation constant
q_m	surface mass flux
q_w	surface heat flux
r	Cartesian coordinate in radial direction
Rd	radiation parameter
Re_x	Reynolds number
S	suction parameter
Sc	Schmidt number
Sh_x	Sherwood number
Sr	Soret number
T	fluid temperature
T_0	reference temperature
T_w	wall temperature
T_∞	ambient temperature
TiO_2	titania
U_w	stretching or shrinking surface velocity
u	fluid velocity along the x-axis
v	fluid velocity along the y-axis
w	fluid velocity along the z-axis
x	Cartesian coordinate in x direction
y	Cartesian coordinate in y direction
z	Cartesian coordinate in z direction

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Greek Symbols

α	thermal diffusivity
β	thermal expansion coefficient
ε	stretching or shrinking parameter
ϕ	dimensionless concentration
Φ	heat generation parameter
γ	curvature parameter
η	dimensionless variable
φ	nanoparticle volume fraction parameter
λ	mixed convection parameter
μ	fluid dynamic viscosity
ν	fluid kinematic viscosity
θ	dimensionless temperature
ρ	fluid density
ρC_p	volumetric heat capacity
σ	electrical conductivity
τ	dimensionless time variable
τ_w	surface shear stress
ω	eigenvalue parameter
ψ	stream function
l	characteristic length

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Subscripts

c	critical value
f	fluid
nf	nanofluid
s	solid nanoparticles
w	condition at the wall
0	reference condition
∞	condition at infinity

Superscript

$'$	differentiation with respect to η

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CHAPTER 1

INTRODUCTION

1.1 Fluid Dynamics

This study is related to the benefit of fluid dynamics in real-life situations. The mathematical models obtained can represent the physical phenomena in fluid dynamics that can contribute to solving industrial problems. Aerospace engineers, for example, should study fluid flow to construct aeroplanes with low resistance but significant lift force to sustain the plane's weight. Besides, engineers can use fluid dynamics knowledge to develop dams and water supply systems, turbines and heat exchangers, efficient sewage systems, and efficient devices in industrial chemicals. Fluid dynamics requires mathematical analysis and experimental to reach a simple and accessible answer to a problem. Usually, some assumptions are needed while performing a mathematical model, but the mathematical model may or may not match the assumption made. As a result, the model must have some modifications to produce a good model.

One of the branches of fluid mechanics is fluid dynamics which is concerned with the movement of liquids and gases with the existence of the pressure force. The other one is fluid statics which the condition of the fluid is at rest. Many researchers are interested in exploring fluid dynamics for studying blood circulation, airflow in the lungs, weather patterns, star evolution, and the application of technology in oil pipelines, radiators, refrigerators, vacuum cleaners, dishwashers, washing machines, water and gas metres, air conditioning systems, rocket engines, and wind turbines. Since most fluid dynamics issues are hard to solve with calculations alone, a mix of numerical computation and computer simulation is necessary.

1.2 Boundary Layer

Aerodynamics encompasses a wide range of applications, including in planes and rockets, that necessitate a grasp of boundary layer flow concepts. Besides, meteorology, oceanography, and hydrology all employ a similar notion. In 1904, a German engineer named Ludwig Prandtl discovered the boundary layer concept. According to his research, when a fluid flows over a stationary solid boundary with high Reynolds numbers with a no-slip condition, the flow is divided into two regions. In most circumstances, he added, the viscosity is negligible when the kinematic viscosity is low. A thin layer adjacent to the solid boundary is a boundary layer where viscous forces dominate over inertia forces. An outer region away from the object's surface where the viscosity effect is too small can be neglected. Figure 1.1 shows the formation of the boundary layer on a flat plate (retrieved from https://cfdflowengineering.com/cfd-modelling-of-boundary-layer/).

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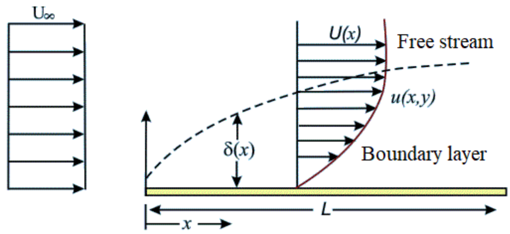

Figure 1.1: Boundary layer on a flat plate

1.3 Heat Transfer

Another aspect of fluid dynamics that is crucial in industrial and environmental challenges is the heat transfer rate. It includes an energy transition from a higher to a lower temperature. The pressure difference is the driving force for fluid movement, while the magnitude of the temperature gradient influences the rate of heat transmission in a particular direction. The faster the exchange of heat, the higher the temperature gradient (Ozisik, 1985). Figure 1.2 illustrates the three types of heat transfer: conduction, convection, and radiation (retrieved from https://www.vectorstock.com/royalty-free-vector/diagram-showing-how-heat-transfer-vector-27755208).

The process of energy transmission from more energetic to less energetic particles of a substance across a solid or fluid medium is known as thermal conduction. Cooking utensils with wooden handles and double-walled Eskimo dwellings made of ice blocks are examples of how it is applied. Convection is a heat transmission mechanism in liquids and gases in which heat is transferred from one location to another by heated particles moving around. Ventilation, electric lighting, and hot water circulation heating of buildings are some of the applications, as are environmental phenomena such as the formation of land and sea breezes. Heat is transferred via radiation in space or vacuum when there are no particles that may move or transfer heat. The electromagnetic spectrum, the sun's and light's radiation, are part of the radiation process.

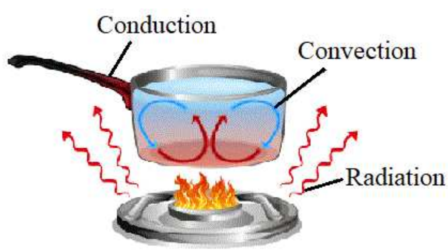

Figure 1.2: Types of heat transfer

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1.4 Mass Transfer

There is a tendency of mass transfer whose concentration fluctuates from one point to another by lowering the concentration discrepancies when a system consists of two or more components. The transition from higher to lower concentration is known as mass transfer (refer Figure 1.3 retrieved from https://en.wikipedia.org/wiki/Chemiosmosis). This phenomenon can be seen in industrial processes, including gas dispersion from stacks, pollutant removal from plant discharge fluxes through absorption, gas stripping from wastewater, neutron diffusion in nuclear reactors, and air conditioning, depending on mass transfer across a boundary or within a fluid process. Meanwhile, in daily life, it occurs when adding sugar to coffee to make the concentration more uniform, when water evaporates from ponds to increase the humidity of passing air, and when fragrances release an alluring scent into the environment. The mechanism of mass transfer involves both molecular diffusion and convection.

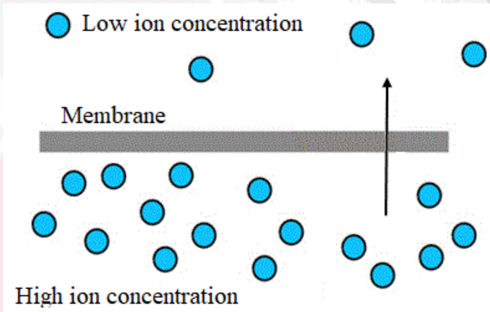

Figure 1.3: Mass transfer from high concentration to low concentration

1.5 Stagnation Point

A "stagnation point" is a point in a fluid's path around a plate where the flow velocities are zero. There are two types of stagnation point flow: plane and axisymmetrical. Hiemenz flow is another name for laminar flow in a plane with a stagnation point (Schlichting and Gersten, 2016). Figure 1.4 illustrates the physical interpretation of the stagnation point flow field in the neighbourhood of a stagnation point (retrieved from https://www.transtutors.com/questions/potential-flow-near-a-stagnation-point-fig-4b-6-a-show-375083.htm). There is a point ($x = y = 0$) known as the stagnation point where fluids are at rest state on the plate surface. A stagnation point flow is characterised by a high rate of deposition of mass, transfer of heat, and pressure of fluid as it approaches a stagnation point where the free streams head in different directions after passing through the stagnation point and approaching the plate surface.

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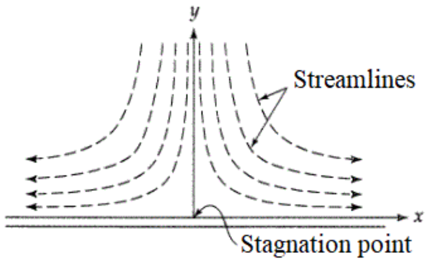

Figure 1.4: Physical interpretation of stagnation point flow field

1.6 Stretching and Shrinking Surface

The ”stretching flow” is the flow produced from stretching an elastic flat sheet that moves in its plane with a velocity that varies with distance from a fixed point resulting from the force applied. Crane (1970) was the first to introduce the analytical solution over a stretched sheet for the boundary layer flow of an incompressible viscous fluid. The study of a viscous fluid’s flow problem over a stretching sheet was driven by numerous industrial applications, for example, in cooling and extrusion operations, paper production, the boundary layer along material handling conveyors, a chemical plant’s polymer processing unit, and the metalworking process in metallurgy, the flow resulting from a stretching sheet occurs. The boundary layer flow problem on a shrinking sheet was initially studied by Wang (2008). The boundary layer cannot accommodate the vorticity of the shrinking sheet. As a result, a constant flow over a diminishing sheet is impossible unless an opposing force is applied to prevent vorticity diffusion and preserve the boundary layer structure. Figure 1.5 depicts the stretching or shrinking scenario on a flat plate (Zaimi et al., 2014b).

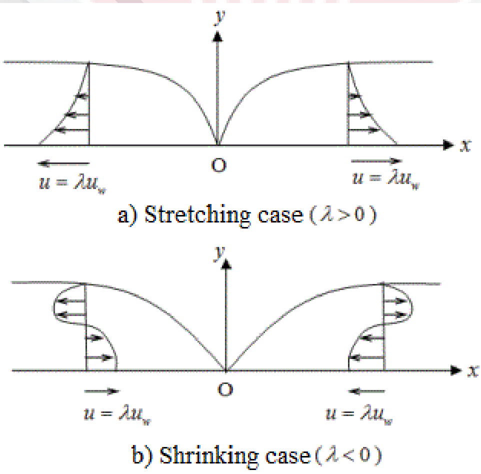

Figure 1.5: Stretching or shrinking on a flat plate

1.7 Magnetohydrodynamics

The study of the dynamics of electrically conducting fluids is known as magneto-hydrodynamics (MHD), often known as magnetofluid dynamics or hydromagnetics. These fluids include plasmas, liquid metals, and salt water or electrolytes, as example. The words magnetohydrodynamic refer to magnetic fields, liquids, and movement, respectively. Alfvén (1942) founded the field of MHD, for which he was awarded the physics Nobel Prize in 1970. The core idea behind MHD is that magnetic fields can induce currents in conductive fluids that are flowing, which in turn exerts forces on the fluid and affect the magnetic field. MHD effects are multi-physics issues that, like electrokinetics, require for the coupling of many fields. The Navier-Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism combine to provide the set of equations that describe MHD. It is necessary to simultaneously solve these differential equations, either analytically or numerically. There are numerous uses for MHD in physics, chemistry, and engineering. Figure 1.6 describes a state of moving conductive fluid with induced current in the presence of a magnetic field (Sheikholeslami and Ganji, 2016).

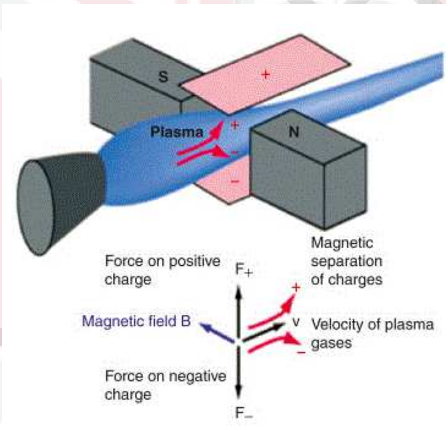

Figure 1.6: A moving conductive fluid with induced current in the presence of a magnetic field

1.8 Flow on a Cylinder Surface

The problem of the boundary layer flow and heat transfer over a cylinder surface gained attention among researchers due to its significant application in industry. The discovery of boundary layer flow and heat transfer problems due to stretching cylinders benefits the extrusion process and fibre technology. Other examples include the manufacturing process of polymer sheets and plastic films, paper making, glass blowing, and metal spinning. No matter how minimal the viscosity, a viscous flow over a cylinder, can result in a thin boundary layer adjacent to the cylinder surface.

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There will be a boundary layer separation and a trailing wake in the flow behind the cylinder. The pressure at any point on the wake side of the cylinder would be lower than the upstream side, resulting in a drag force in the downstream direction. Figure 1.7 (Waini et al., 2021) depicts the nanofluid flow configuration on a shrinking cylinder, with u and v representing velocities along the $x-$ and $r-$ axes, respectively. The nanofluid flow on a stagnation point of a shrinking cylinder of radius a is considered, with u_e as the free stream velocity, u_w as the surface velocity, q_w as the prescribed heat flux and T_∞ is the fluid's constant ambient temperature.

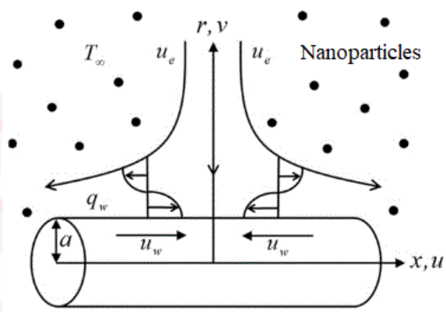

Figure 1.7: Nanofluid flow configuration on a shrinking cylinder

1.9 Nanofluid

Researchers have spent many years finding a method to enhance the thermal conductivity of the fluid. In 1995, Choi discovered a new class of heat transfer fluid which suspended nanoscale particles in size less than 100 nanometres into conventional fluid, namely nanofluid (Choi and Eastman, 1995). The word "nanofluid" is well-known among scientists, particularly in engineering. They agreed that nanofluids have so much potential in enhancing the thermophysical heat transfer of fluid and are very efficient in the heat transfer process. Nanofluid has significantly higher thermal conductivities than the conventional fluid (Huminic and Huminic, 2012). Figure 1.8 shows a schematic representation of the nanofluid (Gupta et al., 2012). Besides that, nanofluids with small-sized particles can surpass any obstacle

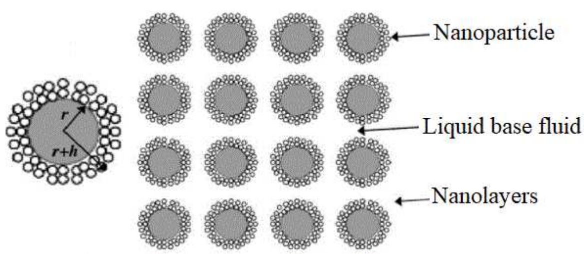

Figure 1.8: Schematic model of nanofluid

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and flow smoothly through mini or microchannels. They also can increase the heat transfer rate with the large surface area that encourages the heat transfer mechanism with the surrounding. A nanofluid is a popular choice among researchers as a heat transfer agent for all of these reasons. Copper (Cu), aluminium (Al), titanium (Ti), zinc (Zn), magnesium (Mg), silver (Ag), silicon (Si), iron (Fe), gold, and diamond are the most prevalent uses of nanofluids.

The nanofluid formulation used water, ethylene glycol (EG), and oils as base fluids. Heat exchange systems, cooling and heating systems, vehicle air conditioning, and plant processes cooling are examples of nanofluids applications. The instability of particle interaction with one another and the surrounding liquid, which can affect operational performance, is one of the difficulties in nanofluids.

1.10 Tiwari and Das Model

Assuming thermal equilibrium and uniform velocity for the base fluid and nanoparticles, the Tiwari-Das model describes a one-phase system free of slippage. The Tiwari-Das model primarily focuses on the impact of nanoparticle volume fraction. The results of the prior research show that as the volume percentage of nanoparticles grows, so does the thermal conductivity of the nanofluid. Furthermore, a small proportion of the solid volume fraction is needed to guarantee its efficacy (Jang and Choi, 2007). In conclusion, nanofluid can improve thermal conductivity and heat transfer efficiency on the wall surface.

Over the last few years, many researchers have tackled various practical issues to improve thermal conductivity. The model Tiwari and Das (Tiwari and Das, 2007), as well as the model Buongiorno (Buongiorno, 2006), are two well-known models of nanofluid. It's worth noting that the Buongiorno model is referred to as a non-homogenous two-phase model because the base fluid and nanoparticles have non-zero slip velocity. Meanwhile, the Tiwari-Das model is a single-phase (homogeneous) model where the base fluid's thermophysical properties can be improved by adding nanoparticles that contribute to the nanofluid's high thermal conductivity. Many researchers used these two models to explore a variety problems of nanofluids flows, including Hsiao (2017), Alarifi et al. (2019), and Moradikazerouni et al. (2019).

1.11 Stability Analysis

One method to determine if a flow is stable or unstable is to subject it to various forms of perturbation and observe its behaviour afterwards. The flow is steady and achievable if all perturbations decay and unstable if the perturbations increase. It would not happen in real life unless an external mechanism suppresses the growth

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of the unstable perturbations. In some circumstances, evaluating the behaviour of the perturbations can be done using simple physical explanations, but more often, it requires thorough analysis and numerical computation. The behaviour of the perturbations can be studied theoretically from solving the continuity equation and the equation of motion subject to the appropriate boundary conditions. The equation of motion subject to the velocity of the base state can be linearized and solved for a broad range of initial conditions using the Laplace transform. The general solution (analytical form) can be obtained only for limited class of flows after performed linearization, which examines the behaviour of perturbations with exponential growth or decay in time.

The flow is unstable if linear stability analysis indicates that perturbations grow in time. The base flow is linearly stable if the magnitude of the disturbance decays. The unstable flow can be realized in practice only when the disturbances are screen off from the physical system by some externally controlling mechanism. However, a flow that is stable according to the theory of linear stability may not always exist in actuality because of nonlinear influences and slight variations from the flow's stated domain.

Stability is a branch of fluid dynamics that studies the stability and onset of instability in fluid flows. The goal of a stability study is to determine whether a flow is stable or unstable. If an unsteady flow occurs, it is critical to understand the instabilities that cause turbulence to form. Escoffier and Boyd (1962) established the stability criterion. Analytical methods are required to solve nonlinear differential equations in boundary layer flow analysis over a shrinking sheet due to the difficulty to obtain an analytical solution.

In 1985, Merkin (1986) obtained dual solutions for his study on the problem of mixed convection flow with simple time-dependent. He concluded that the upper and lower branches solutions of possible steady states for general time-dependent are stable and unstable, respectively. The performance of nanofluids is frequently influenced by their stability. The thermophysical features of nanofluids are altered by their lack of stability, resulting in nanofluids with poor heat transmission capability. To obtain high thermal conductivity nanofluids, it is necessary to have a way to analyse and measure stability.

1.12 Dimensionless Parameters

Dimensionless parameters are the parametric study in engineering and physics. They are used to understand the similarity between issues of the same problem so that the researcher can avoid a lot of experimental data runs caused by the data collection that correlated to a similar problem. The time used to collect data also can be minimised. Besides, dimensionless parameters are widely used in fluid dynamics to

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determine fluid behaviour. Common examples of dimensionless parameters such as the Reynolds, Sherwood, Lewis, Nusselt, Prandtl, and Schmidt numbers, which describe as ratios the relative magnitude of fluid and physical system characteristics, such as density, viscosity, speed of sound, and flow speed. There are various dimensionless parameters used in this study as in details can be explained below:

1. **Prandtl number**.

   The "Prandtl number" often used to describe fluid flows, especially in forced convection heat transfer and boundary layer flow issues. It assists in determining the comparative significance of momentum diffusivity versus heat diffusivity in a fluid. Ludwig Prandtl, a researcher from the early twentieth century, was the one who introduced the Prandtl number (1875-1953). He is the pioneer who created the mathematical foundation for the core ideas of subsonic aerodynamics (Coulson, 2000). His study leads to the boundary layer, thin airfoils, and lifting-line theories.

   $$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu C_p}{k} = \frac{\text{rate of viscous diffusion}}{\text{rate of thermal diffusion}}, \tag{1.12.1}$$

   where,
   k is the thermal conductivity of the fluid,
   μ is the dynamic viscosity coefficient,
   $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity coefficient,
   C_p is the specific heat at constant pressure, and
   $\alpha = \frac{k}{\rho C_p}$ is the thermal diffusivity coefficient.

2. **Reynolds number**

   The "Reynolds number" is a ratio of inertial (non-moving) forces to viscous forces. George Gabriel Stokes proposed it in 1851, but it was Osborne Reynolds $(1842-1912)$ who popularised its use in 1883 (Rott, 1990). The Reynolds number is applied to compare dynamic similitude between different experimental examples, especially in liquid dynamics problems, and to distinguish between different flow regimes of laminar and turbulent. The laminar flow has low Reynolds numbers with viscous forces in smooth and constant liquid motion, whilst turbulent flow has high Reynolds numbers with inertial forces that tend to produce chaotic eddies, vortices and other flow instabilities. In general, flows with $Re < 2000$ are considered laminar, $Re > 4000$ are considered turbulent, and flows with Re between 2000 and 4000 are in a transitional state.

   $$Re = \frac{\rho u L}{\mu} = \frac{uL}{\nu} = \frac{\text{inertial forces}}{\text{viscous forces}}, \tag{1.12.2}$$

   where,
   u is the velocity of the fluid,

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ρ is the density, and
L is the characteristic length.

3. **Nusselt number**

The ratio of convective to conductive heat transfer at a fluid's boundary is called the Nusselt number. Advection (fluid motion) and diffusion are both types of convection (conduction). The "Nusselt number" is named after Wilhelm Nusselt $(1882-1957)$, who made a significant contribution to the research of convective heat transfer (Çengel and Ghajar, 2002). It is commonly used in the analysis and design of heat exchangers and other heat transfer applications. As the volume of the fluid body is divided by the surface area, a higher Nusselt number indicates more active convection, with turbulent flow often in the 1001000 range.

$$Nu = \frac{h}{\frac{k}{L}} = \frac{hL}{k} = \frac{\text{convective heat transfer}}{\text{conductive heat transfer}}, \tag{1.12.3}$$

where,
h is the convective heat transfer coefficient of the fluid.

Local Nusselt number,

$$Nu_x = \frac{h_x x}{k}. \tag{1.12.4}$$

where,
x is the distance from the surface boundary to the local point of interest.

4. **Sherwood number**

The "Sherwood number" also known as the mass transfer Nusselt number used in mass-transfer operations. It is named after Thomas Kilgore Sherwood $(1903-1976)$ and measures the ratio of convective mass transfer to diffusive mass transport (Heldman and Moraru, 2010). In many cases, the Sherwood number is correlated with the Reynolds number (Re) and the Schmidt number (Sc) for different flow conditions. It is commonly used in the design and analysis of processes involving mass transfer, such as absorption, distillation, and chemical reactions.

$$Sh = \frac{h}{\frac{D}{L}} = \frac{\text{convective mass transfer rate}}{\text{mass diffusion rate}}, \tag{1.12.5}$$

where,
D is the mass diffusivity of the fluid, and
h is the convective mass transfer coefficient.

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5. **Schmidt number**

The "Schmidt number" describes fluid flows with simultaneous momentum and mass diffusion convection processes. It was computed by dividing the momentum diffusivity (kinematic viscosity)by the mass diffusivity. Ernst Heinrich Wilhelm Schmidt (1892 – 1975), a German engineer, was the one to introduce it. It physically connects the hydrodynamic layer's thickness to the mass-transfer boundary layer's thickness (Incropera et al.). The Schmidt number is often used in the analysis of mass transfer processes, particularly in cases where both momentum and mass transfer occur simultaneously, such as in chemical reactions or the diffusion of a component in a flowing fluid.

$$Sc = \frac{\nu}{D} = \frac{\text{viscous diffusion rate}}{\text{mass diffusion rate}}, \tag{1.12.6}$$

6. **Grashof number**

In fluid dynamics and heat transfer, the "Grashof number" is a dimensionless parameter that approximates the ratio of buoyancy to the viscous force acting on a fluid. It is similar to the Reynolds number and commonly used in the study of natural convection scenarios. Franz Grashof (1826 – 1893) is known to be the inspiration for the name (Sanders and Holman, 1972). For natural convection from vertical flat plates, the transition to turbulent flow occurs in the range ($108 < Gr < 109$). The boundary layer is turbulent at higher Grashof numbers; at lower Grashof numbers, the boundary layer is laminar in the range ($103 < Gr < 106$). The Grashof number helps determine whether natural convection in a fluid will be significant compared to forced convection.

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^3} = \frac{\text{buoyancy force}}{\text{viscous force}}, \tag{1.12.7}$$

where,
T_s is the surface temperature,
g is the acceleration due to gravity,
β is the volumetric thermal expansion coefficient (equal to approximately $\frac{1}{T}$, for ideal fluids, where T is the absolute temperature), and
T_∞ is the bulk temperature.

7. **Eckert number**

The "Eckert number" is a unitless parameter used in continuum mechanics. The Eckert number expresses the flow's kinetic energy of the enthalpy differential across the thermal boundary layer. It is named after Ernst R. G. Eckert (1904 – 2004) and is used to characterize heat dissipation in

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high-speed flows for which viscous dissipation is significant. The temperature profile in a fluidic system at high flow velocities is dominated not only by the temperature gradients existing in the system but also by the effects of dissipation due to internal fluid friction (Rapp, 2022).

$$Ec = \frac{u^2}{C_p \Delta T} = \frac{\text{kinetic energy}}{\text{enthalpy}}, \tag{1.12.8}$$

where,
u is the local flow velocity of the continuum, and
$\Delta T = T_s - T_\infty$ is the temperature difference between the surface and the free stream.

1.13 Problem Statement

Numerous industrial processes depend on commonly used fluids like water, ethylene glycol, and oil. These fluids are essential for activities like power production, heating or cooling operations, chemical processes, and microelectronics. However, due to their limited thermal conductivity, these fluids incompetent to achieve high heat exchange rates in thermal engineering systems. There is a technique to overcome this obstacle by using ultra-tiny solid particles suspended in common base fluids to improve the thermal conductivity. A nanofluid is a suspension of nano-sized particles (1100 nm) in a regular base fluid. In 1995, Choi and Eastman (1995) coined the term ”nanofluid”. Nanofluids outperform micrometre-sized particles in improving stability, rheological properties, and thermal conductivities. Different nanomaterials alter parameters to various extents.

Two techniques for studying nanofluids in assessing the effective thermal conductivity of nanofluids are experimental research (Thomas and Balakrishna Panicker Sobhan, 2011) and computational modelling through computational fluid dynamics (CFD) (see Abouali and Ahmadi (2012), Kamyar et al. (2012) and Seon Ahn and Hwan Kim (2012)). The research on nanofluids was conducted based on three categories: influencing factors, prediction models, and applications.

The Tiwari and Das nanofluid model, possess multi-directional applications including nano drug delivery, cooling of computer microchips, and optical devices (Ramzan et al., 2023). Rapid heat dissipation is a big obstacle in developing smaller microchips. Nanofluids are beneficial for the liquid cooling of computer chips because of their high thermal conductivity. The next generation of computer chips has a localized heat flux of over 10 MW/m^2 and total power of more than 300 watts. Nanofluid oscillating heat pipe (OHP) on the cooling system will be able to remove heat fluxes of over 10 MW/m^2 and will be used as a next-generation cooling device to handle heat dissipation created by new technologies (see Ma et al. (2006a) and

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Ma et al. (2006b)).

In industrial applications such as process heating, space heating, and power generation, heat is released from the bottom of the solar pond at a temperature around 50 to 60 degrees Celcius higher than the top surface of the solar pond (see Andrews and Akbarzadeh (2005) and Singh et al. (2011)). Nanofluids help increase the rate of heat removal from the bottom of the solar pond when nanofluids travel through a heat exchanger positioned at the bottom of the solar pond to absorb heat (Mahian et al., 2013).

Nanofluids could be used in nearly every disease treatment procedure by reengineering the properties of nanoparticles. The anti-cancer medication docetaxel was bound to the nanoparticles, then dissolved in the cells' internal fluids and released at a controlled rate. The nanoparticles contain aptamers that target molecules that recognise the surface molecules on cancer cells and prevent the nanoparticles from hitting healthy cells. Polyethene glycol molecules are included in the nanoparticles to prevent them from being destroyed by macrophages, which are cells that protect our bodies from foreign toxins. Nanoparticles are effective medication delivery vehicles because they are so small that they are absorbed by living cells when they reach their surface (Wong and De Leon, 2010).

Industrial technology increasingly acknowledges the importance of flow through a stretching or contracting cylinder in fluid dynamics applications. Flow past a cylinder is occurred in many technical applications, including mooring lines, risers, bundled cylinders at offshore installations, bridge piers, and tube bundles in heat exchangers. Researchers have a good understanding of the flow patterns in a single cylinder. Fluid flow problems due to stretching cylinders have occurred in processes of extrusion in metal, plastic, and food products, as well as in the cooling system (Wang and Ng, 2011). In many engineering and industrial applications, the cooling of a solid surface is a primary tool for minimizing the boundary layer (Majeed et al., 2016). Because of these practical and realistic implications, the problem of cooling solid on moving surfaces has become a topic of concern for scientists and engineers.

Aside from that, study into these issues is going on in processes such as polymer and rubber sheet extraction, hot rolling, wire drawing, paper manufacture, melt-spinning, and glass fibre production (Zaimi et al., 2013). The cooling rate affects the final product's quality (Bachok et al., 2012b). Meanwhile, the study on the flow and transmission of heat over a shrinking cylinder has attracted the interest of researchers only recently due to its application in industries such as manufacturing high-performance materials for aerospace coating.

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Many thermal applications could benefit from fluids with higher thermal conductivities. Motivated by the benefits gained from nanofluid applications, this study focuses on the problem of boundary layer flow, heat, and mass transfer in a nanofluid over a linearly, exponentially, and nonlinearly stretching or shrinking surface, as well as a cylinder surface with focusing on Tiwari-Das model. This research hopefully helps to understand the thermal transmission processes of the various surface materials and thus enhances the quality of the final products. As a result, the following research questions can be raised:

The following issues have been raised in this study:

1. What parameters contribute to the existence of dual solutions?
2. Which parameters contribute to broadening the range of possible solutions?
3. How does the presence of nanoparticles volume fraction give impact on the flow and heat transfer characteristics at the surface?
4. How would the changes in physical parameters (suction, slip, chemical reaction, magnetic, Soret and Dufour, viscous dissipation and heat generation parameters) affect the skin friction, local Nusselt number, and local Sherwood number?
5. Which type of nanoparticles performs better?
6. Which of the solutions obtained is a stable solution?

1.14 Objectives

This thesis aims to extend the problem of boundary layer flow, heat and mass transfer in a nanofluid towards various surfaces using Tiwari and Das model. The stability analysis has been performed for some of the problems studied. The objectives of this present study are to:

1. construct mathematical formulations using similarity transformation technique and create an algorithm for the various nonlinear nanofluid flow problems,
2. apply the bvp4c solver in MATLAB program to numerically solve the mathematical models and run validation tests for the present study, which compare it with the numerical findings in the literature,
3. examine the effects of various parameters on the nanofluid's flow, heat, and mass transfer characteristics, and
4. perform the stability analysis on dual solutions for some of the problems (in Chapter 4 and Chapter 7).

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There are five problems that have been considered:

1. Boundary layer flow over a cylinder in the presence of suction effect.
2. Axisymmetric stagnation point flow over a vertical plate in the presence of slip effect.
3. Stagnation point flow past a stretching or shrinking vertical surface in a nanofluid with chemical reaction effect.
4. Stagnation point flow over an exponentially stretching or shrinking sheet in the presence of magnetohydrodynamics with Soret and Dufour numbers.
5. Stagnation point flow over a nonlinear stretching or shrinking cylinder in the presence of magnetohydrodynamics with viscous dissipation and heat generation effects.

1.15 Scopes of Study

This study uses the Tiwari and Das model (Tiwari and Das, 2007) to investigate the problem of steady two dimensional and three dimensional, incompressible flow of boundary layer and stagnation point, and transfer of heat and mass over a stretching or shrinking surface in a nanofluids. Copper (Cu), alumina (Al_2O_3), and titania (TiO_2) are the three types of nanoparticles that were taken into consideration, with water serving as the base fluid. The Prandtl number taken in this study is Pr= 6.2 (water-base fluid).

1.16 Outline of Thesis

This thesis consists of nine chapters starting with Chapter 1, the introduction, which elaborates on the research background, problem statement, objective and scope and significance of the study. This chapter will give the basic knowledge of the content of this thesis with several terms and definitions. The literature review in Chapter 2 captures the flow of the progressing and the growth of the research among researchers from the same field. This chapter is important as a starter key to the problems studied and to gain motivation for the problems that have been considered.

Chapter 3 depicts the derivation of the mathematical formulation for the problem in Chapter 4 together with detailed description of the numerical phase for addressing mathematical formulations. The main steps is to reduce the governing equations in partial differential equations (PDEs) to ordinary differential equations (ODEs) using the similarity transformation technique. The simplified ODEs were then numerically solved with MATLAB's bvp4c programme.

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Next, from Chapter 4 until Chapter 8, the five main objectives of this study will be discussed. The objectives of our study include the mathematical formulations of the flow of boundary layer and heat exchange over an exponential, linear and nonlinear stretching or shrinking surface in nanofluid with suction, slip, chemical reaction, Soret and Dufour, and viscous dissipation and heat generation or absorption effects. The parameters studied are nanoparticle volume fraction, suction, chemical reaction, curvature, mixed convection, buoyancy ratio, stretching or shrinking, magnetic, heat generation, and radiation, with Soret, Dufour, and Eckert numbers. Finally, Chapter 9 summarises all of the research done and highlights several ideas for further investigation.

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