NUMERICAL SIMULATION FOR THIN-FILM FLOW OF NEWTONIAN AND CASSON HYBRID NANOFLUID WITH HEAT TRANSFER

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DEDICATION

بسم الله الرحمن الرحيم

Special dedication to

my beloved parents,
Kamis Muda and Rohani Hasan
who always picked me up on time and encouraged me to go on every adventure
especially this one

my loving siblings, nieces and nephews,
“that happiness comes when you are ready to face the test of your life"

my respectful supervisors,
Assoc. Prof. Dr. Sharidan Shafie, Dr. Lim Yeou Jiann, Dr. Md Faisal Md Basir,
Dr. Taufiq Khairi Ahmad Khairuddin,
“everything that happens is about our attitude to deal with the problem"

my supportive colleagues,
Dr. Qushairi, Dr. Raihan
“seize the opportunity to seize your success"

my close friends,
Ain, Harith, Hana, Syiham, Fatin (Yong), Athirah, Fazlina, Salwa, Mariaam, Amalina,
Mariah, Aisyah, Fatini,
“What a reason to say you can’t succeed? You can do it!"

my friends and seniors,
Thank you for everything.
Without you all my success would not have been possible.

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ABSTRACT

Nanofluid is one of the technologies used to improve heat transfer system. A class of nanofluid called hybrid nanofluid has been introduced recently. Hybrid nanofluid can upgrade thermal properties and consequently exhibit good heat transfer performance compared to nanofluid and conventional fluid. Besides that, the hybrid nanofluid has also manifested exquisite properties such as better chemical and mechanical inertness, greater thermal and electrical conductivity, and lower cost. In view of this, the problem of boundary layer flow of hybrid nanofluid embedded by the thin-film for viscous and Casson fluid past an unsteady porous stretching sheet is investigated in this thesis. Thin-film flow on a stretching sheet has a significant effect on heat transfer analysis. Such applications are used in many industrial operations including wire and fiber coating, metal and polymer extrusion, transpiration cooling, and optical industry such as production of smart contact lenses. This study begins with the derivation of the governing equation for the thin-film fluid flows and heat transfer based on the conservation law of mass, momentum, and energy. The modified Tiwari and Das model is applied to describe the properties of the hybrid nanofluid. Then, the developed nonlinear governing partial differential equations that are subjected to the appropriate boundary conditions are transformed into the nonlinear ordinary differential equations (ODEs) using the similarity transformation technique. The resulting nonlinear systems of the ODEs are then solved using the Keller box method. The unknown constant, thin-film thickness is obtained by the homotopy analysis method. The numerical results of surface shear stress and heat transfer coefficient as well as the velocity and temperature distributions for the pertinent parameters which are unsteadiness, nanoparticles volume fraction, Casson parameter, and intensity of suction and injection parameters are displayed graphically and in tabular forms. For both fluids, it is found that the thickness of thin-film is reduced due to increasing values of unsteadiness, nanoparticles volume fraction, Casson parameter, and intensity of injection. Numerical results depict that the presence of hybrid nanoparticles in both fluids not only enhanced the temperature distribution but it also reduced the velocity distribution, shear stress, and heat transfer coefficient. A similar pattern is revealed at the increment of Casson parameter. The unsteadiness parameter tends to upgrade the velocity and temperature distributions as well as the local skin friction. Incrementation of the velocity, temperature and shear stress in all fluids have been noticed along with the enhancement of injection parameter. Interestingly, suction fluid has changed the thickness of the thin-film that tends to be dense and helps to escalate heat transfer performance of the hybrid nanofluid.

ABSTRAK

Bendalir nano ialah salah satu teknologi yang digunakan untuk menambah baik sistem pemindahan haba. Satu kelas cecair nano yang dipanggil cecair nano hibrid telah diperkenalkan baru-baru ini. Bendalir nano hibrid boleh meningkatkan sifat terma dan seterusnya mempamerkan prestasi pemindahan haba yang baik berbanding cecair nano dan cecair konvensional. Selain itu, cecair nano hibrid juga menunjukkan ciri-ciri yang lebih baik seperti lengai kimia dan mekanikal yang lebih baik, kekonduksian haba dan elektrik yang lebih besar, dan kos yang lebih rendah. Memandangkan perkara ini, masalah aliran lapisan sempadan cecair nano hibrid yang disertakan oleh filem nipis untuk cecair likat dan Casson melepasi helaian regangan berliang yang tidak stabil telah disiasat dalam tesis ini. Aliran filem nipis pada lembaran regangan mempunyai kesan yang ketara pada analisis pemindahan haba. Aplikasi ini banyak digunakan dalam operasi di industri termasuk lapisan dawai dan serat, penyemperitan logam dan polimer, penyejukan transpirasi, dan industri optik seperti penghasilan kanta sentuh pintar. Kajian ini dimulakan dengan terbitan persamaan menakluk untuk aliran bendalir filem nipis dan pemindahan haba berdasarkan undang-undang pemuliharaan jisim, momentum dan tenaga. Model Tiwari dan Das yang diubah suai digunakan untuk menerangkan sifat cecair nano hibrid. Kemudian, persamaan pembezaan separa yang tak linear yang dikembangkan tertakluk kepada syarat sempadan yang sesuai diubah menjadi persamaan pembezaan biasa tak linear (ODEs) dengan menggunakan teknik penjelmaan keserupaan. Sistem tak linear ODEs yang terhasil kemudiannya diselesaikan dengan menggunakan kaedah kotak Keller. Pemalar yang tidak diketahui, ketebalan filem nipis diperoleh dengan kaedah analisis homotopi. Keputusan berangka tegasan ricih dan pekali pemindahan haba serta taburan halaju dan suhu untuk parameter yang berkaitan iaitu ketidakstabilan, pecahan isipadu nanozarah, parameter Casson, dan keamatan parameter sedutan dan suntikan telah dipaparkan dalam bentuk grafik dan jadual. Bagi kedua-dua cecair, didapati ketebalan filem nipis berkurangan disebabkan oleh peningkatan nilai ketidakstabilan, pecahan isipadu nanozarah, parameter Casson, dan keamatan suntikan. Keputusan berangka menggambarkan bahawa kehadiran nanopartikel hibrid dalam kedua-dua cecair bukan sahaja meningkatkan taburan suhu tetapi ia juga mengurangkan taburan halaju, tegasan ricih, dan pekali pemindahan haba. Corak serupa didedahkan pada peningkatan parameter Casson. Parameter ketidakstabilan mempunyai kecenderungan untuk menaik taraf taburan halaju dan suhu serta geseran kulit setempat. Penambahan halaju, suhu dan tegasan ricih dalam semua cecair telah diperhatikan bersama-sama dengan peningkatan parameter suntikan. Menariknya, cecair sedutan telah mengubah ketebalan filem nipis yang cenderung tebal dan membantu meningkatkan pemindahan haba cecair nano hibrid.

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LIST OF ABBREVIATIONS

PDEs	-	Partial Differential Equations
ODEs	-	Ordinary Differential Equations
HAM	-	Homotopy Analysis Method
MHD	-	Magnetohydrodynamics
FDM	-	Finite Difference Method
FEM	-	Finite Element Method
BEM	-	Boundary Element Method
MWCNT	-	Multi-Wall Carbon Nanotubes
SWCNT	-	Single-Wall Carbon Nanotubes
CMC	-	Carboxymethyl Cellulose
RK4	-	Fourth-Order Runge-Kutta
OHAM	-	Optimal Homotopy Analysis Method
IOP	-	Intraocular Pressure

LIST OF SYMBOLS

Roman Letter

Pr	-	Prandtl number
a	-	Acceleration of the element (ms^{-2})
t	-	Time (s)
k	-	Thermal conductivity $\left(Wm^{-1}K^{-1}\right)$
$h(t)$	-	Uniform thickness of a thin-film
x	-	$x-$ axis coordinate
y	-	$y-$ axis coordinate
S	-	Dimensionless unsteadiness parameter
u, υ	-	Velocity components along $x-$ axis and $y-$ axis
T	-	Temperature (K)
C_ρ	-	Specific heat at constant pressure $\left(Jkg^{-1}K^{-1}\right)$
T_w	-	Surface temperature of the fluid (K)
T_0	-	Initial temperature of the fluid (K)
T_{ref}	-	Reference temperature of the fluid (K)
α and b	-	Positive constants
f	-	Velocity profile
U_w	-	Stretched velocity
V_w	-	Velocity for suction/injection
M	-	Magnetic interaction parameter
$A_i(i = 1, ..., 6)$	-	Thermophysical properties of hybrid nanofluid
k_I	-	Iteration index
k_i	-	Δx^i
h_j	-	Δy^j
H	-	Thickness of liquid film

L	-	Length of substrate
C_f	-	Local skin friction
Nu_x	-	Nusselt number
q_w	-	Heat transfer rate $\left(\mathrm{Wm}^{-2}\right)$
Re	-	Reynold number
w	-	Dimensionless suction/injection parameter
p	-	Point
$\frac{d}{dt}$	-	Material time derivative
$\mathbf{I}$	-	Identity tensor
i, j	-	Cartesian unit vector in the x and y -directions
p	-	Pressure (Pa)
$\mathbf{T}$	-	Cauchy stress tensor
$\mathbf{V}$	-	Velocity vector field
V	-	Magnitude of velocity
V_0	-	Volume
u, v, w	-	Velocity in x, y and z -directions
U_∞	-	Free stream velocity
q	-	Embedding parameter
Al_2O_3	-	Aluminium oxide or alumina
Fe_2O_3	-	Ferric oxide
Si_3N_4	-	Silicon nitride
SiC	-	Silicon carbide
CuO	-	Copper oxide
ZrO_2	-	Zirconia
SiO_2	-	Silicon oxide
TiO_2	-	Titanium oxide
Ag	-	Silver
Cu	-	Copper
Zn	-	Zinc

Al	-	Aluminium
Si	-	Silicon
Fe	-	Ferum
Mg	-	Magnesium
GO	-	Graphene Oxide
Cr	-	Chromium
AlN	-	Aluminium nitride
Mn	-	Maganese

Greek Letter

σ	-	Electrical conductivity $(\Omega m)^{-1}$
β	-	Casson parameter
ξ	-	Thin-film thickness
δ	-	Small prescribed value
ϕ	-	Volume fraction of nanoparticles
ψ	-	Physical stream function
η	-	Similarity variable
θ	-	Dimensionless temperature
ν	-	Kinematic viscosity $\left(\mathrm{m^2s^{-1}}\right)$
ρ	-	Density $\left(\mathrm{kgm^{-3}}\right)$
μ	-	Effective dynamic viscosity $\left(\mathrm{kgm^{-1}s^{-1}}\right)$
ϵ	-	Stop criteria
λ	-	Dimensionless thin-film thickness
∇	-	Vector operator
δ_h	-	Boundary layer thickness
δ_t	-	Thermal boundary layer thickness
τ	-	Anisotropic viscouss stress
τ_{ij}	-	Shear stress

Γ	-	Thin-film thickness dependent on q
$\hbar_f$ and $\hbar_\theta$	-	non-zero auxiliary parameters
H_f and H_θ	-	non-zero auxiliary functions
N_f	-	Nonlinear operator
σ	-	Sum of multiple terms
τ_w	-	Wall shear stress (Pa)

Subscript/Superscript

ref	-	Reference
bf	-	Base fluid
hnf	-	Hybrid nanofluid
s_1	-	Alumina nanoparticles
s_2	-	Copper nanoparticles
$'$	-	Differentiation with respect to η

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter gives an account of the background of the problem. Then, the statement of the problem and the objective of this research are be highlighted. Some limitations and scopes of the research are also be explained in detail. Finally, the significance of this study and thesis organization of this research are be presented.

1.2 Research Background

Recently, technological developments have pushed researchers to perform diverse studies to fulfill consumers' needs. One of such inquiries is the study of heat transfer as it can develop mechanical items or apparatuses that work marvellously for manufacturing operations and industrial engineering these days. Heat transfer is a significant aspect of the synthetic industry, oil and gas, atomic energy, electrical energy, and so on. Heat transfer is the passage of heat across the device border due to the difference in temperature between the system and the environment. The heat transfer in the system can also be accomplished at multiple places inside the system because of temperature differences.

Thermal energy is exchanged via heat conduction, the microscopic interchange of energy between neighboring objects. Energy transfer occurs in solids, liquids, and gases [1]. The heat transfer occurs in three ways of mechanisms which are conduction, convection, and radiation [2]. Heat transfer in conduction is due to molecular interaction, molecules not being displaced, and the motion of free electrons. An example of conduction heat transfer is when two bodies at different temperatures are kept in contact. Secondly, radiation is absorbed or released by the matter within the system as electromagnetic radiation that crosses the system's boundary. The sun's heat going to Earth is one of the most important examples of radiation in heat transfer. The third type of heat transfer is convection, which occurs when the fluid components travel to cooler areas of the system or fluid displacement. For instance, water heating from the vessel is a form of heat transfer in the convection mechanism. Convection of heat transfer can be classified into three: free convection, forced convection, and mixed convection. Buoyancy forces cause the fluid motion for free convection. The fluid flow is driven by the density differences that happened because of the temperature variation between the surface and the fluid. For instance, heat flow from a heated metal plate to the ambient atmosphere. On the other hand, fluid that is forced to flow over a solid surface by external agencies is termed as forced convection. Nuclear reactors and air conditioning apparatus are examples of forced convection heat transfer. Whereas, mixed convection occurs when free and forced convection occur together. There are various types of fluid which are responsible for the motion of convection flow.

1.2.1 Fluids

Fluid can be divided into two types namely Newtonian and non-Newtonian [3]. Newton's Law of viscosity defines the behavior of the Newtonian fluid as follows

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

where τ demonstrates the shear stress exerted by the fluid, μ is the dynamic viscosity of the fluid, and $\frac{\partial u}{\partial y}$ represents the velocity gradient or rate of strain. The Newtonian fluid is named for after Sir Isaac Newton, who first researched the association between the intensity of shear strain and shear stress for these fluids in the differential form [4]. Levenspiel [5] reported that the fact of stress rate could characterize the Newtonian and non-Newtonian fluids. Isaac Newton stated that shear stress in a Newtonian fluid is proportional to the time rate of strain such as velocity gradient. The shear stress of non-Newtonian fluid is not proportional to the gradient of velocity [6]. At a wide range of temperatures and pressures, the vast majority of natural fluids (liquids and gases) such as water, organic solvents, fats, air, wind, oxygen, and rare gases are Newtonian.

Whereas, perfume, paint, blood, ketchup, pillows, toothpaste, and starch suspensions are examples of non-Newtonian fluid.

Casson fluid has drawn the attention of researchers due to its unique properties among non-Newtonian fluids. Casson fluid was first proposed by Casson [7] for predicting the flow behavior of pigment-oil suspensions. According to Husannan *et al.* [8], Casson is a form of viscoplastic fluid. The Casson fluid model is a shear-thinning liquid with an infinite viscosity at zero rate of shear, yield stress below which no flow occurs, and a zero viscosity at an infinite rate of shear [9]. It indicates that when the shear stress is less than the yield stress applied to a fluid, it acts like a solid: however, when the shear stress is more than the yield stress applied, the fluid begins to flow. Jelly, tomato sauce, honey, soup, concentrated fruit juice, and human red blood cells are examples of Casson fluid. Human red blood cells can form aggregates or rouleaux, which are chainlike structures. Furthermore, Casson's shear stress shear rate relation explains the characteristics of numerous polymers over a large range of shear rates [10].

In this study, the effect of nanoparticles in Newtonian and Casson fluids is given attention. Heat transfer of nanofluid exhibits superior thermophysical attributes than the conventional base fluid in terms of thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficient. The reason for this is that traditional heat transfer fluids have low thermal conductivity when compared to solids. As a result, scientists have attempted to create fluids that use uniformed dispersion and stable suspension of solid nanoparticles to improve the low thermal conductivity of these traditional heat transfer fluids.

1.2.2 Nanoparticles

The existence of nanoparticles in the fluid also influences the heat transfer of the fluid. The mixture of solid nanoparticles with a base liquid is known as nanofluid which was introduced by Choi [11]. There are several groups of nanoparticles as listed below [12]

i. **Chemically stable metals**: gold (Au), copper (Cu),

ii. **Metal oxide**: alumina (Al_2O_3), silica (SiO_2), zirconia (ZrO_2), titania (TiO_2),

iii. **Metal carbides**: silicon carbide (SiC),

iv. **Metal nitrides**: aluminium nitride (AlN), silicon nitride (Si_3N_4),

v. **Carbon (in the various form)**: diamond, graphite, carbon nanotubes (CNTs), fullerene.

The mixes of nanoparticles termed "hybrid nanofluids" have gained a response from various industries that are interested to explore it more deeply due to its extensive technical, industrial, and scientific applications such as for transportation, microfluidics, medical manufacturing and so on. The perfect combination of various nanoparticles properties has demonstrated an outstanding heat transfer coefficient enhancement with a low-pressure decrease limit [13–16]. According to Maskeen *et al.* [14], the mix of stabilized nanofluids leads to an increase in the rate of thermal conductivity with a minor amount of nanoparticles concentrations in the fluid. Moreover, the proper hybridization of the improved thermal conductivity of the nanocomposites is believed to enlarge the heat transfer of fluid flow as well as counteract the disadvantage of increased viscosity [17]. Normally, stable hybrid nanomaterials can be classified into three classes as shown in Table 1.1 [18–20].

Yazid *et al.* [21] found that the host fluid with the hybrid nanoparticles has greater heat flux in the fluid. The numerical study of convection flow embedded with hybrid nanoparticles in a nanofluid has been explored by Izadi *et al.* [22]. As stated by Ravisankar and Chand [23], the important properties that affect the heat transfer coefficients of the hybrid nanoparticles are thermal conductivity, viscosity, density, and heat capacity of the nanoparticles. Figure 1.1 depicts the thermal conductivity of some nanoparticles which is applied in choosing the hybrid nanofluids [24].

Figure 1.1 displays that the thermal conductivity of pure metal is higher than the metal oxide. In comparison to other metal oxides, the presence of nanoparticles Al_2O_3 in a fluid improved the Nusselt number coefficient, which measures the heat transfer rate of the fluid, as compared to other metal oxides [25]. This is because the thermal

Table 1.1 Group of stable hybrid nanoparticles

Nanomaterials	Hybrid nanoparticles
Metal	i. Alumina (Al_2O_3) + nickel (Ni), ii. Magnesium (Mg) + carbon nanotube (CNTs), iii. Magnesium (Mg) + iron (Fe), iv. Alumina (Al_2O_3) + chromium (Cr), v. Alumina (Al_2O_3) + copper (Cu).
Ceramic	i. Alumina (Al_2O_3) + titanium oxide (TiO_2), ii. Silica (Si) + alumina (Al_2O_3), iii. Carbon nanotubes (CNTs) + ferric oxide (Fe_2O_3), iv. Silica (Si) + nickel (Ni), v. Alumina (Al_2O_3) + silicon carbide (SiC).
Polymer	i. Polymer + carbon nanotubes (CNTs), ii. Thermoplastic + layered silicates polymer, iii. Polymer + hydroxide, iv. Polyester + titanium oxide (TiO_2).

conductivity of Al_2O_3 is higher compared to the other metal oxides. Besides that, Al_2O_3 also exhibits several excellent properties like powerful stability and chemical inertness [26, 27]. Furthermore, as stated in Mikkola [25], the heat capacity of the Cu nanoparticle is higher compared to the Ag nanoparticle. Physically, heat capacity is the amount of heat needed to increase the temperature of a substance by $1°C$. The fluid takes a long time to gain heat and to cool. Therefore, incorporating Cu and Al_2O_3 in a fluid can significantly improve the thermal properties of the fluid. Several researchers have investigated the heat transfer of metal nanomaterials Al_2O_3 - Cu by conducting experimental and theoretical studies because the hybrid nanoparticles can enhance the thermal conductivity and result in an increase of the convective heat transfer [20,26–35].

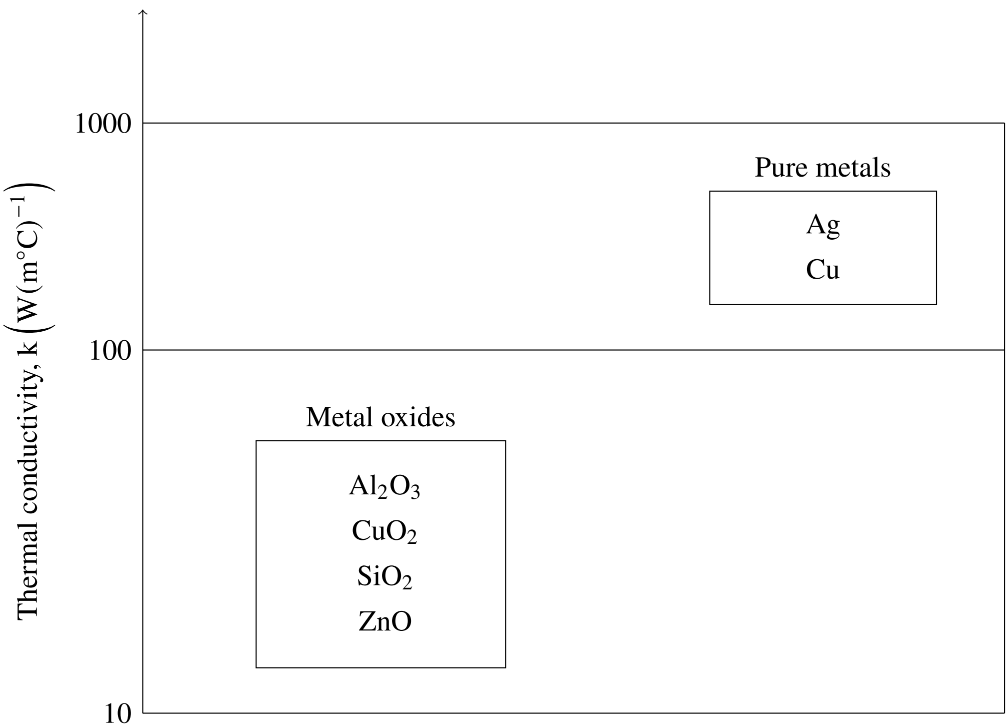

Figure 1.1 Thermal conductivity for metal oxides and pure metals

1.2.3 Thin-Film Flow

Thin-film flows are ubiquitous in engineering, geophysics, biology, and elsewhere, and are often the basis for simplified fluid dynamical models. The investigation on laminar thin-film flow across moving vertical, horizontal or slanted flat plates is now focusing on developing a number of specialists since it has a massive potential to be utilized as a mechanical instrument in many designing applications. The principle utilization of such thin-film fluid entails several processes of draining, coating, wetting, biological and solar cells [36–44]. Thin-film is defined as a layered material of thickness ranging from fractions of a nanometer to several micrometers. It is produced through a process called thin-film decomposition which is a process of applying thin-film onto a surface that is to be coated [45]. Based on the theory of thin-film flow indicated by O' Brien and Schwartz [46], a common thin-film stream comprises a field of fluid mostly limited by a strong substrate with a free surface where the fluid is presented to another fluid as seen in Figure 1.2. The thickness H in one direction, is much smaller than the characteristics length scale L in the other direction. The stream flows transcendentally towards one of the more extended measures as a result of extrinsic factors such as gravity, surface pressure inclinations, and a pivoting substrate.

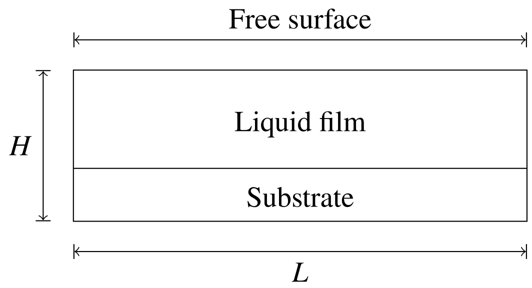

Figure 1.2 Thin-film flow

The first problem of the hydrodynamics of the thin liquid film over a stretching sheet has been explored by Wang [47] without considering the heat transfer. Wang [47] studied the issue of thin-film flow in the Newtonian fluid. The study done by Wang [47] was inspired by the research activities that had been done by Sakiadis [48], Crane [49] and Carragher and Crane [50] who studied the theoretical technique to solve the heat transfer flow along with the stretching sheet. The study found that the rare exact similarity solution of the unsteady Navier-Stokes equation and an investigation on integration for that equation is needed. Therefore, Andersson *et al.* [51] started an analysis to explore the nature of the hydrodynamic heat transfer problem solved by Wang [47]. Andersson *et al.* [51] extended Wang [47]'s analysis and introduced the similarity transformation for the thermal equation. The temperature on the thin-film flow enlarges from the elastic sheet towards the free surface.

Then, Wang [52] explored the flow problem with heat transfer. The homotopy analysis method (HAM) was applied to attain the solution for the investigated parameters which are unsteadiness and Prandtl number towards velocity and temperature profiles. As a result, different values of parameters tend to vary in the thickness of the thin-film. Shear stress between the wall of thin-film and fluid flow was enlarged but decreased in thin-film thickness due to the increase in the unsteadiness parameter that points out the stretching rate of the plane. The enhancement of the Prandtl number declines the heat transfer of the thin-film flow. Then, Xu *et al.* [53] extended the work of Wang [52] by considering the presence of nanofluid. The model developed by Tiwari and Das [54] was considered in this study.

Recently, Aziz *et al.* [55] reported that the increment of nanoparticles volume fraction in the nanofluid enhanced the heat transfer rate in a thin-film flow across an unsteady stretching sheet. Giri *et al.* [56] studied the magnetohydrodynamics (MHD) nanofluid across a stretching sheet and the authors claimed that the increase of the magnetic parameter reduces the velocity profile while elevating the temperature of the nanofluid over similar geometry as Wang [52]. In addition, Mahian *et al.* [57] and Turkyilmazoglu [58] cross-examined the nanofluid flow in the thin-film due to a moving substrate and heat transfer which accounted for seven different types of nanoparticles. The study by Turkyilmazoglu [58] summarized that the rate of heat transfer is dependent on the thermal conductivities of the nanoparticles. Besides that, Pal *et al.* [59] investigated the effect of the porous medium in a thin-film nanofluid flow and found that the particles of nanofluid move slowly due to the porous medium of the stretching sheet. Lu *et al.* [60] studied the thin-film flow of single and multi-walled carbon nanotubes. They observed that the dimensionless temperature increases as the concentration of the nanoparticles in the thin-film increase. Furthermore, the existence of the hybrid nanoparticles in the thin-film flow increases the heat transfer rate compared to the single nanofluid as reported by Sulochana and Aparna [61].

Andersson *et al.* [62] initiated to explore the power-law fluid in a thin-film flow. The research by Megahed [63], Vijaya *et al.* [64], Abd El-Aziz and Afify [65], Mahmoud and Magehad [66], Khan *et al.* [67], Ray Atul *et al.* [68] and Rehman *et al.* [69] also contributed to the development of non-Newtonian thin-film flow. Recently, the Casson fluid in thin-film has attracted the interest of many researchers and engineers. Vijaya *et al.* [64] and Khan *et al.* [67] cross-examined the MHD Casson fluid in a liquid film but Vijaya *et al.* [64] also considered viscous dissipation and internal heating. An excellent performance between the analytical method and numerical method for solving the Casson fluid film has been reported by Rehman *et al.* [69] together with slip, suction, and injection effects in uniformed film thickness when the sheet is stretched. Ray *et al.* [68] added the nanoparticles to the magneto-bioconvection of Casson fluid in a thin-film over a similar geometry. Ray *et al.* [68] found that increasing bioconvection

Péclet number substantially elevates the temperatures in the regime, thermal boundary layer thickness, nanoparticle concentration values and nanoparticle species boundary layer thickness.

Motivated by the work done by Devi and Devi [30–32], Wang [52], Xu *et al.* [53], Sulochana and Aparna [61] and Rehman *et al.* [70], the behavior of the boundary layer flow and heat transfer in the thin-film of hybrid nanofluid and Casson hybrid nanofluid due to the stretching sheet are considered in this study. The horizontal sheet is assumed to be encapsulated in the suction and injection effects. The effect of the nanoparticle's volume fraction is the additional feature of the current study. To better comprehend the physics of the thin-film flow, the nonlinear ordinary differential equations (ODEs) are attained by transforming nonlinear partial differential equations (PDEs) as governing equations when implementing the similarity transformations technique. Then, the nonlinear and dimensionless ODEs are solved numerically by exploiting an implicit finite difference method namely the Keller box method.

1.3 Problem Statement

Thin-film flow modeling and analysis have increased significantly nowadays due to their application in industrial manufacturing. The existence of the fluids either Newtonian or non-Newtonian can complete the thin-film model. It is well known that conventional heat transfer fluids are unable to meet the maximum heat transfer rate since they have low conductivity in heat transfer. Therefore, to overcome this limitation, a perfect combination of nanoscale solid particles has been proposed to change the thermophysical properties of the fluid and intensify rate of the heat transfer. The hybrid nanofluid enhances the heat transfer rate without significantly increasing the viscosity of the fluid as compared to nanofluid and fluid [30–32, 61, 71]. The existence of the hybrid nanoparticles in the thin-film flow could possibly pose an essential influence on the fluid fields and heat transfer. Besides that, the flow problem becomes even more complicated if the effects of suction and injection of the sheet are taken into consideration. This alters the fluid flow behavior and the fluid's physical quantities. Furthermore, the flow problem becomes more advanced and interesting if the non-Newtonian type of fluid is considered. The complex rheological behavior of the non-Newtonian fluid may dominantly affect the distribution of the velocity and temperature of the thin-film hybrid nanofluid flow. Therefore, together with this study, the following questions have been explored:

i. How to mathematically model the unsteady thin-film flow for Newtonian and non-Newtonian hybrid nanofluids over the stretching sheet?

ii. How does the presence of hybrid nanofluid alter the features of the thin-film flow and heat transfer in different types of fluids?

iii. How does the presence of suction or injection impact the velocity and temperature profiles as well as local skin friction and Nusselt number of the hybrid nanofluid in the thin-film?

1.4 Objectives of Study

An unsteady incompressible boundary layer flow and heat transfer in Newtonian and Casson hybrid nanofluids thin-film are numerically studied and analyzed. The flow over a porous stretching sheet is investigated. The main objectives of this research are:

i. To derive the mathematical models of the problems which consist of continuity, momentum, and energy equations.

ii. To carry out mathematical formulation and simplification.

iii. To solve the governing equations together with boundary conditions of the thin-film flow by using the HAM and Keller box method.

iv. To develop a computational algorithm for solving the problem.

v. To obtain the numerical results of velocity and temperature distributions as well as skin friction and Nusselt number for each of the problems.

vi. To analyze the results obtained graphically and tabulated for different physical conditions namely, thin-film thickness, unsteadiness, the intensity of suction and injection, nanoparticle volume fraction, and Casson parameter.

1.5 Scopes of Study

The boundary layer flow and heat transfer on Newtonian and Casson hybrid nanofluids passing through a thin-film is investigated in this study. The suction and injection effects are considered at the boundary layer of the horizontal sheet. The Cu and Al_2O_3 spherical nanoparticles are selected for each issue based on prior study by Devi and Devi [30–32], Waini *et al.* [33–35] and Sulochana and Aparna [61]. The spherical particles have small particles with a high surface area. The smaller particles have a low sedimentation rate and higher energy levels. Based on an experimental study by Suresh *et al.* [26], thermal conductivity for the spherical Cu and Al_2O_3 shows an excellent correlation with the theoretical model (Hamilton and Crosser [72] model) when the authors set $n = 3$ (empirical shape factor for spherical).

The present study also considered ethylene glycol plus water as the base fluid for the Newtonian model as proposed by Sandeep [73] and CMC plus water as the base fluid for the Casson fluid as recommended by Rawi *et al.* [74] and Maleki *at al.* [75]. Ethylene glycol plus water is the Newtonian fluid since the viscosity of the ethylene glycol plus water is constant when the shear rate is increased [76]. Ethylene glycol is primarily used as an antifreeze ingredient in cooling systems. Depending on whether the system is used for heating or cooling, the ethylene glycol either absorbs energy from the source or distributes it to the sink.

CMC is not an ion exchanger but a water-soluble polymer. It is a cellulose derivative in which carboxymethyl groups are covalently linked to some of the hydroxyl groups of the glucopyranose monomers that comprise the cellulose backbone. It is insoluble in organic liquids (those containing volatile organic compounds such as petroleum distillates) and combines with the heavy metal salts to generate insoluble films in water, making it transparent, reasonably tough, and resistant to organic materials. It produces a film due to its polymeric composition and is used to improve the moisturizing agent. The experimental studies found that CMC plus water exhibits the shear-thinning fluid at the low concentrations of the solution [77–79]. The following problems are discussed in Chapter 4 and Chapter 5 of this thesis:

i. Boundary layer flow and heat transfer in a hybrid nanofluid thin-film over an unsteady porous stretching sheet.

ii. Boundary layer flow and heat transfer in a Casson hybrid nanofluid thin-film over an unsteady porous stretching sheet.

The governing PDEs are initially transformed into a set of nonlinear ODEs by using an appropriate similarity transformation as given in the published paper [52]. The unknown thin-film thickness is approximated by HAM with the help of open-source code BVPh 2.0 by Shi-Jun Liao [80]. Then, the nonlinear and dimensionless ODEs are solved by exploiting an implicit finite difference method, namely the Keller box method. HAM was first developed by Shi-Jun Liao in 1992 [81]. It is one of the most successful and efficient methods for solving nonlinear equations. The HAM is a general semi-analytic method for attaining series solutions of various types of nonlinear equations [82]. The Keller box method which implements the finite difference method (FDM) is extremely powerful in obtaining the estimated results for a nonlinear differential system. The FDM is more versatile for the clarification that underlies approximations control the convergence rate, among various other mathematical strategies. The details of this method can be found in the manuscript of Cebeci and Bradshaw [83]. Numerical solutions for temperature and velocity profiles as well as the surface shear stress in terms of local skin friction coefficient and heat transfer rate characterized by the Nusselt number are obtained by solving the governing ODEs of each proposed problem. Figure 1.3 illustrates the research framework of this study.

1.6 Significances of Study

Numerical simulation is a computational technique used nowadays among educational, engineering, and scientific. In the real world, most of the flow problems are formed as PDEs or ODEs. As stated in the book Computational Methods in Engineering by Venkateshan and Swaminathan [84], numerical methods for ODEs can also be extended to the solution of PDEs. Example of numerical methods includes the finite difference method (FDM), finite element method (FEM), boundary element

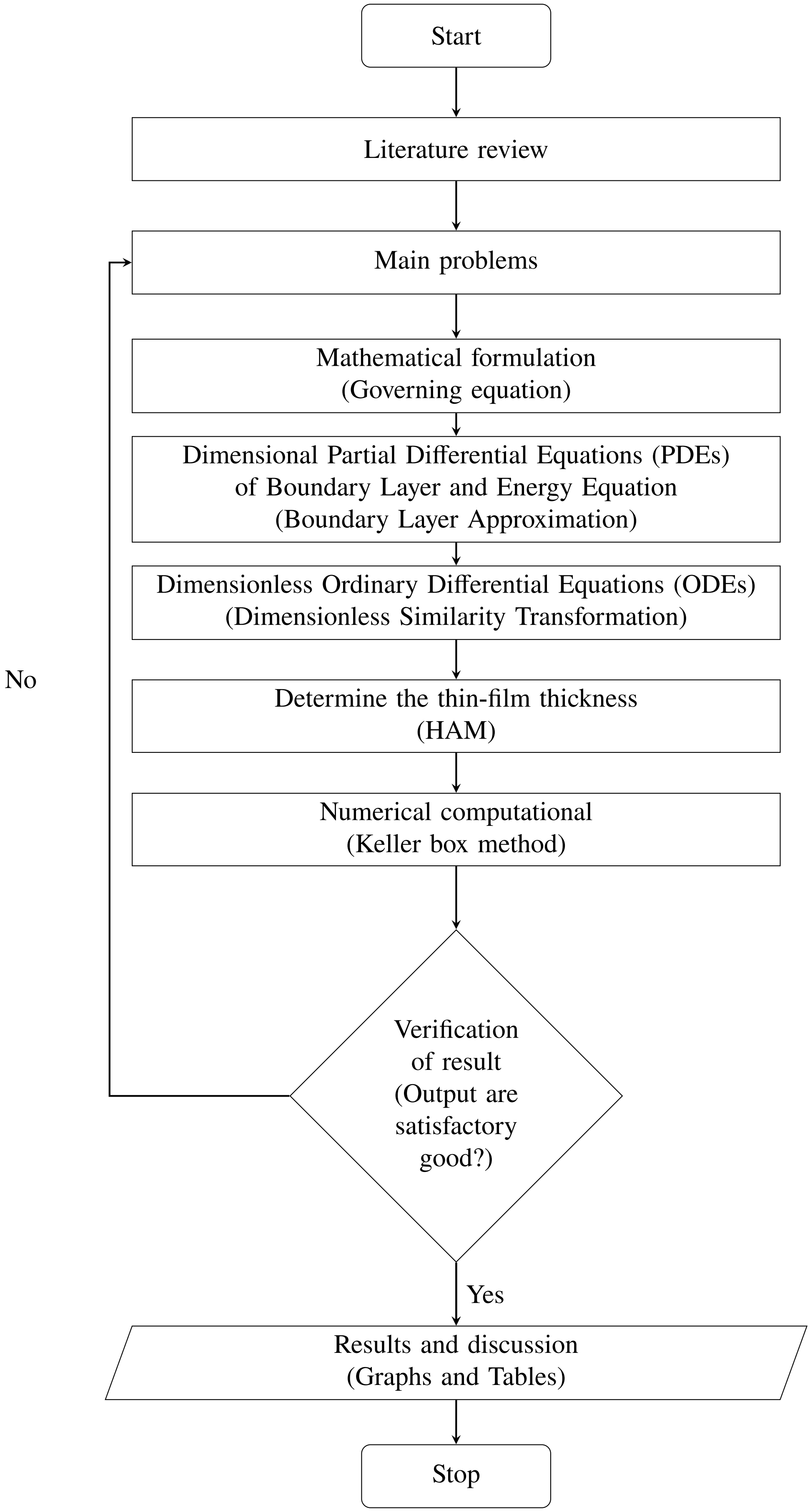

Figure 1.3 Research framework

method (BEM), and many more which are commonly used for attaining the solution of PDEs and ODEs numerically [84].

Numerical techniques can have a significant impact on solving mathematical problems. Mostly, the researcher code the coding in mathematical software like MATLAB, MAPLE, and C++ programming to run or produce the outputs as the results of the mathematical models. Patankar [85] states that computational investigation can reduce cost and gain complete output information. The cost of a computer run is very much lower than a corresponding experimental investigation. A computational result gives detailed and complete information to the researchers. For example, the output from the computational coding can provide accurate and convergence values for all pertinent parameters that are used in the study of fluid flow such as velocity, pressure, temperature, and concentration parameters [85].

The existence of the nanoparticles in the fluid can improve the change rate of the heat and working fluid properties due to their special features [86]. According to Choi [11] who proposed that metallic or non-metallic particles that have a high thermal conductivity in a fluid can tend to uplift the superior of heat transfer. The incorporation of nanoparticles and fluid can reduce the boiling performance and increase degradation. Most importantly, it smooths out the surface of nucleate sites, hence there is a considerable deterioration of the heat transfer coefficient [87, 88]. The increase of heat transfer aids the industries to produce better products in various areas such as industrial cooling applications, nuclear reactors, automotive applications (nanofluid coolant, nanofluids in fuel, brake, and other vehicular nanofluids), electronic applications (cooling of microchips, microreactors) and biomedical applications (nano-drug delivery, cancer therapeutics, cryopreservation, nano cryosurgery, sensing, and imaging) [89, 90].

Gould *et al.* [91] reports that thin-film is commonly used in the optical and electrical sectors. All coating processes need a smooth glossy finish that meets the best appearance and maximum performance requirements, such as low friction, clarity, and strength. The rate of heat transfer within the thin liquid film directly affects the coating process's performance and the component's chemical characteristics. In many industrial applications, the thin-film medium also plays a leading role, including solar thin-film, thin-film batteries, and thin-film photovoltaic cells [92]. Microfabrication is another interesting method of materials science, in which thin-films are an important concept and guiding principle [93].

The study of boundary layer flow and heat transfer in thin-film flow numerically is important as it can benefit our daily life, especially in the production of products. The results and analysis from this research could build a better understanding of the behavior of Newtonian and Casson hybrid nanofluids through a thin-film. Also able to enhance the knowledge of the thin-film flow and heat transfer characteristics through the variation of the governing physical parameters. Besides that, the computational algorithm incorporated with new scientific study information can guide scholars, implementations for manufacturing, and education in solving the computational fluid dynamics for the future.

1.7 Thesis Organization

This thesis comprises six chapters. Chapter 1 explains the important elements for starting a new research which include research background, problem statement, objectives, scope, and significance of the research. A systematic overview of the literature review related to current problems in this research is presented in Chapter 2.

Chapter 3 focuses on the basic governing equations for the boundary layer which consists of continuity, momentum, and energy equations. The boundary layer approximation is applied to reduce the complexity of the governing equation. The mathematical formulation and the similarity transformation employed for reducing the governing equation using dimensionless variables are discussed. After that, the main elements of the solution methods employed in this study which are HAM and the Keller box method are discussed in detail.

Chapter 4 reports on the hybrid nanofluids' thin-film flow and heat transfer on an unsteady stretching sheet with the suction and injection effects. The problem is solved by using the semi-analytical method, HAM and numerical method, Keller box method. The effects of particle concentration, unsteadiness as well as suction and injection parameters are shown graphically and implications are discussed.

Then, the heat transfer for Casson hybrid nanofluid is explored in Chapter 5. The HAM and Keller box methods are also applied in this chapter. The flow to solve the proposed problems starts with the introduction, mathematical formulation, followed by the numerical procedures, and continued with the results and discussion in the form of graphs and tables. At the end of each problem, the obtained results which include the thin-film thickness, velocity, and temperature distributions, as well as skin friction and heat transfer coefficients are summarized and presented in the form of a table. Finally, the summary of this study is conferred in Chapter 6 as well as the suggestions and recommendations for future work. All the references that support this study's supportive explanation are listed.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Nur Ilyana Kamis**, Lim Yeou Jiann, Taufiq Khairi Ahmad Khairuddin, Sharidan Shafie, Md Faisal Md Basir, Forced convection boundary layer flow in a thin nanofluid film on a stretching sheet under the effects of suction and injection, Journal of Applied Science and Engineering 2021. 25(3):429-435. https://doi.org/10.6180/jase.20220625(3).0009, **(Q3, I.F: 0.28)**.

2. **Nur Ilyana Kamis**, Lim Yeou Jiann, Taufiq Khairi Ahmad Khairuddin, Sharidan Shafie, Md Faisal Md Basir, MHD boundary layer flow of hybrid nanofluid in a thin-film over an unsteady stretching permeable sheet, Journal of Nanofluids 2022. 11(1):84-98. **(Q2, I.F: 2.0)**.

Non-indexed Journal

1. **Nur Ilyana Kamis**, Md Faisal Md Basir, Nurul Aini Jaafar, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Kohilavani Naganthran. Heat transfer and boundary layer flow through a thin-film of hybrid nanoparticles embedded in kerosene base fluid past an unsteady stretching sheet, Open Journal of Science and Technology 2020. 3(4):322-334. https://doi.org/10.31580/ojst.v3i4.1678.

2. **Nur Ilyana Kamis**, Lim Yeou Jiann, Taufiq Khairi Ahmad Khairuddin, Md Faisal Md Basir, Heat transfer of thin-film Casson hybrid nanofluid flow across an unsteady stretching sheet, Annals of Mathematical Modeling 2021. 1(13):22-31. http://dx.doi.org/10.33292/amm.v13i1.100.

Indexed Conference Proceedings

1. **Nur Ilyana Kamis**, Md Faisal Md Basir, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Lim Yeou Jiann, Suction Effect on An Unsteady Casson Hybrid Nanofluid Film Past A Stretching Sheet with Heat Transfer Analysis, IOP Conference Series: Materials Science and Engineering, 2021.1078, 012019. https://doi:10.1088/1757-899X/1078/1/012019. **(Indexed by Scopus)**.

Book Chapter

1. **Nur Ilyana Kamis**, Lim Yeou Jiann, Md Faisal Md Basir, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Casson Hybrid Nanofluid in a Thin Film Flow, *Geometric Modelling and Simulation on Heat Transfer Problems*, Penerbit UTM Press, 2022.

National Conferences

1. **Nur Ilyana Kamis**, Md Faisal Md Basir, Nurul Aini Jaafar, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Kohilavani Naganthran. *Heat transfer and boundary layer flow through a thin-film of hybrid nanoparticles embedded in kerosene base fluid past an unsteady stretching sheet*, 4th Asian International Multidisciplinary Conference **(AIMC 2020)** Universiti Teknologi Malaysia (UTM), 17-19 April 2020.

2. **Nur Ilyana Kamis**, Md Faisal Md Basir, Nurul Aini Jaafar, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Kohilavani Naganthran. *Heat Transfer Analysis of Casson Fluid Restricted by Thin-Film with Hybrid Nanoparticle in A Porous medium Pass an Unsteady Stretching Sheet*, International Conference on Research and Practices in Science, Technology and Social Sciences 2020 **(I-CReST 2020)** Universiti Teknologi MARA (UiTM), Cawangan Selangor, Kampus Dengkil, Dengkil Selangor, 4 July 2020.

3. **Nur Ilyana Kamis**, Md Faisal Md Basir, Nurul Aini Jaafar, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Kohilavani Naganthran. *Dual solutions for an unsteady thin second-grade film flow with heat transfer analysis over a permeable stretching sheet*, International E-Conference on Green and Renewable Energy 2020 **(Green2020)** Universiti Putra Malaysia (UPM) Kampus Bintulu, Sarawak, 18-19 August 2020.

4. **Nur Ilyana Kamis**, Md Faisal Md Basir, Nurul Aini Jaafar, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Kohilavani Naganthran. *Heat transfer analysis of Eyring-Powell fluid model in a thin-film pass an unsteady stretching sheet*, 6th Malaysia-Japan Joint International Conference 2020 **(MJIIC 2020)** in conjunction with 5th International Conference on Advanced Technology and Applied Sciences 2020 **(ICaTAS 2020)**, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia Campus Kuala Lumpur (UTMKL), 7-9 October 2020.

5. **Nur Ilyana Kamis**, Md Faisal Md Basir, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin. *Forced Convection Boundary Layer Flow In A Thin Nanofluid Film On A Stretching Sheet Under The Effects Of Suction And Injection*, The 6th International Online Conference on Science, Technology and Interdisciplinary Research **(IC-STAR)**

2020, Universiti Teknologi Malaysia Campus Kuala Lumpur (UTMKL), 8-9 December 2020.

6. **Nur Ilyana Kamis**, Md Faisal Md Basir, Sharidan Shafie, Taufiq Khairi Ahmad Khairuddin, Lim Yeou Jiann. *Suction Effect on An Unsteady Casson Hybrid Nanofluid Film Past A Stretching Sheet with Heat Transfer Analysis*, 2nd International Postgraduate Conference on Mechanical Engineering **(IPCME)**, Universiti Malaysia Pahang (UMP), 19-20 January 2021.

Competitions

1. **Postgraduate Students Faculty of Science Poster Competition under Research Month@Fs 2020**. Organized by Faculty of Science, Universiti Teknologi Malaysia (UTMJB) on 24th August 2020.
2. **Research Canvas Competition 2020**. Organized by UTM Library and Springer Nature from 23rd August to 13th September 2020.
3. **Research Canvas Competition 2021**. Organized by UTM Library and Springer Nature from 4th July to 29th August 2021.

Awards

1. **Best Oral Presenter** for International Conference on Research and Practices in Science, Technology and Social Sciences 2020 (I-CReST 2020). Project: *Heat Transfer Analysis of Casson Fluid Restricted by Thin-Film with Hybrid Nanoparticle in a Porous Medium past an Unsteady Stretching Sheet*.
2. **Best Paper Award** for 2nd International Postgraduate Conference on Mechanical Engineering (IPCME). Project: *Suction Effect on an Unsteady Casson Hybrid Nanofluid Film past a Stretching Sheet with Heat Transfer Analysis*.
3. **Finalist** for Postgraduate Students Faculty of Science Poster Competition under Research Month@Fs 2020. Project: *Effect of Suction on the Hybrid Casson Fluid Flow in a Thin-Film past an Unsteady Stretching Sheet*.