RAYLEIGH-BÉNARD CONVECTION IN ROTATING NANOFLUIDS LAYER OF POROUS AND NONPOROUS WITH FEEDBACK CONTROL

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By

IZZATI KHALIDAH BINTI KHALID

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December 2018

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Rayleigh–Bénard convection is the heat transfer process due to buoyancy effect involved that occurred in a horizontal plane of nanofluids layer heated from below. The model for nanofluids includes the mechanisms of Brownian motion and thermophoresis. The onset of Rayleigh–Bénard convection in a horizontal rotating nanofluids layer and in a horizontal nanofluids layer saturated in a rotating porous medium with feedback control, internal heat source, magnetic field, double–diffusive coefficients, porosity, anisotropic, viscosity variation and thermal conductivity variation parameters are investigated theoretically. The confining lower and upper boundary conditions of the nanofluids layer are assumed to be free–free, rigid–free and rigid–rigid. A linear stability analysis of Rayleigh–Bénard convection is used, then the eigenvalue is obtained numerically using the Galerkin method and solved using Maple software. The impact of the feedback control, rotation, internal heat source, magnetic field, double–diffusive coefficients, porosity, anisotropic, viscosity variation and thermal conductivity variation parameters on the onset of convection in nanofluids system are analyzed and presented graphically. It is found that the impact of increasing the effects of feedback control, rotation, magnetic field, Dufour, porosity, anisotropic and thermal conductivity variation parameters help to delay the onset of convection in the system, meanwhile elevating the effects of internal heat source, Soret and viscosity variation parameters hasten the instability of the system. Further, the lower and upper boundary conditions in the present investigation are obviously found to be more stable in rigid–rigid boundaries compared to free–free and rigid–free boundaries.

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

OLAKAN RAYLEIGH–BÉNARD DALAM LAPISAN BERPUTAR BENDALIR NANO BERLIANG DAN TIDAK BERLIANG DENGAN KAWALAN SUAP BALIK

Oleh

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Olakan Rayleigh–Bénard merupakan suatu proses pemindahan haba yang disebabkan oleh daya apungan yang berlaku dalam lapisan mengufuk bendalir nano yang dipanaskan dari bawah. Model bagi bendalir nano mengandungi mekanisma gerakan Brown dan thermophoresis. Permulaan olakan Rayleigh–Bénard dalam lapisan mengufuk bagi putaran bendalir nano dan dalam lapisan mengufuk bendalir nano dalam putaran medium berliang dengan parameter kawalan suap balik, sumber penjanaan haba, medan magnet, pekali resapan ganda dua, keliangan, anisotropik, variasi kelikatan dan variasi kekonduksian terma dikaji secara teori. Syarat sempadan bawah dan atas lapisan bendalir nano diandaikan bebas–bebas, tegar–bebas dan tegar–tegar. Analisis kestabilan linear bagi olakan Rayleigh–Bénard digunakan, kemudian nilai eigen diperoleh secara berangka menggunakan kaedah Galerkin dan diselesai menggunakan perisian Maple. Kesan parameter strategi kawalan suap balik, putaran, sumber penjanaan haba, medan magnet, pekali resapan ganda dua, keliangan, anisotropik, variasi kelikatan dan variasi kekonduksian terma ke atas permulaan olakan dalam sistem bendalir nano dianalisa terhadap pelbagai parameter dan dipaparkan secara grafik. Didapati apabila kesan parameter strategi kawalan suap balik, putaran, medan magnet, Dufour, keliangan, anisotropik dan variasi terma kekonduksian ditingkatkan, ia dapat membantu melengahkan permulaan olakan dalam sistem, manakala peningkatan kesan sumber penjanaan haba, Soret dan variasi kelikatan parameter mempercepatkan ketakstabilan dalam sistem. Tambahan lagi, syarat sempadan bawah dan atas bagi kajian ini jelas mendapati sempadan tegar-tegar adalah lebih stabil berbanding sempadan bebas-bebas dan tegar–bebas.

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I certify that a Thesis Examination Committee has met on 12 December 2018 to conduct the final examination of Izzati Khalidah Khalid on her thesis entitled "Rayleigh-Benard Convection in Rotating Nanofluids Layer of Porous and Nonporous Medium with Feedback Control" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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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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a	**Wavenumber**
a_c	**Critical wavenumber**
c	Specific heat
c_f	Specific heat of the fluids
c_p	Specific heat of the particles
C^*	**Solute concentration**
C_l^*	**Solute concentration at the lower wall**
C_u^*	**Solute concentration at the upper wall**
D	**Differential operator**
Da	**Darcy number**
D_B	Brownian diffusion coefficient
D_{CT}	**Diffusivity of Soret type**
Df	**Dufour parameter**
D_S	**Solutal diffusivity**
D_T	Thermophoretic diffusion coefficient
D_{TC}	**Diffusivity of Dufour type**
$e(t)$	**Error of deviation from the measurement**
g	**Gravitational acceleration**
h	Electrical conductivity of fluids
H	**Magnetic Chandrasekhar number**
H^*	Vertical uniform magnetic field
K	**Feedback control parameter**
K_D	**Differential gain**
K_L	**Integral gain**
K_P	**Proportional gain**
K	**Permeability of the porous medium**
K_H	**Permeability in the horizontal i and j directions**
K_V	**Permeability in the vertical k direction**
L	Thickness of the nanofluids layer
Le	**Lewis number**
Ln	Nanofluids Lewis number
N_A	Modified diffusivity ratio
N_B	Modified particle density increment
p^*	**Pressure**
Pr	**Prandtl number**
Pr_d	**Darcy–Prandtl number**
Pm	**Magnetic Prandtl number**
$q(t)$	**Determination of a control**
	Internal heat source
r	**Calibration of the control**

Ra	Thermal Rayleigh number
Ra_c	Critical thermal Rayleigh number
Rd	Thermal Darcy–Rayleigh number
Rd_c	Critical thermal Darcy–Rayleigh number
Rd^{osc}	Oscillatory thermal Darcy–Rayleigh number
Rd_c^{osc}	Oscillatory critical thermal Darcy–Rayleigh number
Rm	Basic–density Rayleigh number
Rm_d	Basic–density Darcy–Rayleigh number
Rn	Nanoparticles concentration Rayleigh number
Rn_d	Nanoparticles concentration Darcy–Rayleigh number
Rs	Solutal Rayleigh number
Sr	Soret parameter
t^*	Time
Ta	Taylor number
Ta_d	Darcy–Taylor number
Ta_v	Taylor-Vadasz number
T^*	Temperature
T_u^*	Temperature at the upper wall
T_l^*	Temperature at the lower wall
u	Nanofluids velocity
u_a	Anisotropic modified velocity vector
u_D	Nanofluids Darcy velocity
Va	Vadász number
n	Kinematic viscosity of nanofluids
(u v w)	Velocity components
(x y z)	Cartesian coordinates

Greek Symbols

a_f	Thermal diffusivity of the fluids
a_m	Thermal diffusivity of the porous medium
a_C	Solutal volumetric coefficient
a_T	Thermal volumetric coefficient
g_a	Acceleration coefficient
h	Resistivity of the fluids
k	Thermal conductivity of the fluids
k_n	Thermal conductivity of the nanofluids
k_p	Thermal conductivity of the particles
k_s	Thermal conductivity of the solid material forming the matrix of the porous medium
k_v	Thermal diffusivity of the porous medium (anisotropy)
k	Thermal conductivity variation
k_m	Thermal conductivity of the porous medium saturated by nanofluids

k_{mH}	**Thermal conductivity in the horizontal i and j directions**
k_{mV}	**Thermal conductivity in the vertical k direction**
l	**Relaxation parameter**
l_m	**Stress relaxation time**
m	Viscosity of the fluids
m_e	Magnetic permeability of the fluids
m_m	Viscosity of the porous medium saturated by nanofluids
m	**Viscosity variation**
m	**Effective viscosity**
	Current density
$^{*}_{z}$	**z–component of current density**
^{2}	**Laplacian operator**
$^{2}_{H}$	**Horizontal Laplacian operator**
W^{*}	**Uniform angular velocity**
f^{*}	**Volumetric fraction of nanoparticles**
f_u^{*}	**Volumetric fraction of nanoparticles at the upper wall**
f_l^{*}	**Volumetric fraction of nanoparticles at the lower wall**
y	**Vorticity due to rotation**
y_z^{*}	**z–component of vorticity due to rotation**
r	**Density**
r_p	**Nanoparticles mass density**
r_f	**Fluids density**
$(r\,c)_m$	Heat capacity of fluids in porous medium
s	**Heat capacity ratio**
e	**Porosity of the porous medium**
x	**Mechanical anisotropy parameter**
z	**Thermal anisotropy parameter**

Superscript

*	**Dimensional variable**
0	**Perturbation variable**

Subscript

b	**Basic state**
f	**Fluids**
m	**Porous medium**
p	**Particles**

CHAPTER 1

INTRODUCTION

1.1 Research Background

The elementary property of heat transfer consists of the temperature and flow of heat. The temperature defines as the amount of thermal energy supplied into the system, while the flow of heat depicts as the migration of thermal energy from one place to another place. The second law of thermodynamics stated that the heat transfer initially arises from heated area to cooler area. Consequently, heat transfer mechanism is the navigation of thermal energy due to the temperature difference, and the motion of heat transfer will occur from a higher temperature to a lower temperature objects until the objects and the surrounding reach thermal equilibrium. Once the temperature difference between the objects and surroundings are in equilibrium, heat transfer mechanism cannot be stopped, it can only be postponed.

Heat transfer mechanism can be divided into three, which are conduction, radiation and convection. In conduction, the heat transfer mechanism occurs through the stationary medium (motionless solid or fluids) when there exist a temperature difference. As for the radiation mechanism, the surfaces of the material mediums transmit the energy in the mode of electromagnetic waves. According to Incropera and Dewitt (1996), convection refers to heat transfer mechanism that occurs between a solid and a moving fluid when there exist a temperature difference between a solid and a fluid as shown in Figure 1.1.

Generally, the fundamental objective of this research is to examine the stability of the nanofluids layer on Rayleigh–Benard convection subjected to infinitesimal disturbances. The infinitesimal thermal perturbation will be introduced on a particular flow, and the problem is linearized through the use of the classical linear stability analysis. Then, the eigenvalue problem of the perturbed state will be obtained from

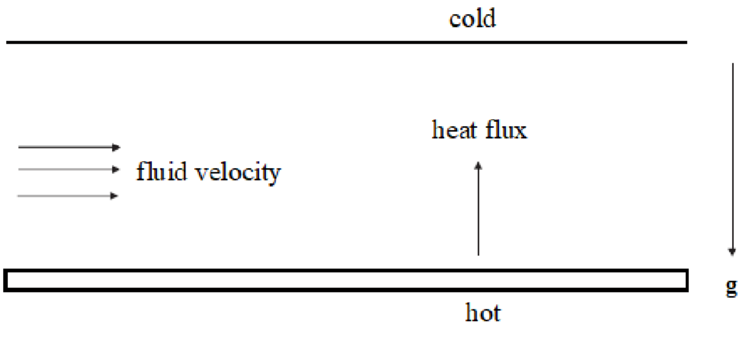

Figure 1.1: Heat transfer between two different material

a normal mode technique, solved numerically using the Galerkin technique and computed using the Maple software.

1.2 Convection and Applications of Convection

The classification of convection can be divided into two types of convections, the natural (or free) convection and the forced convection depending on how the fluids motion are initiated. The mechanism of natural convection, in which the fluids motion are induced by density differences in fluids occurring due to temperature differences. At the bottom boundary layer, the heated fluids received heat become less **dense and rise. At the upper boundary layer, the surrounding, more dense cooler** fluids move down, sink and subsequently heated, causing a circular motion and the process continues. Therefore, the convective flows in fluids layer can be driven by **buoyancy (Bénard convection) force due to temperature difference. Examples of natural convection, we have:**

1. **The initiation process of boiling water occurs when the heat is transferred from the burner into the pot by conduction, thus heating the water at the bottom layer of the pot. Subsequently, this hot, less dense water rises and starts bubbling, thereby transferring heat from the hot water at the bottom to the cooler water at the top by convection. At the same time, the cooler, more dense water at the top moves down and sink to the bottom, become heated and the process repeat.**
2. **Hot air balloon consists of a bag contains heated air. A burner heats the air trapped inside the balloon, making it less dense than the air outside and so the air moves upward causing the balloon to rise. Once the pilot wants to go down, he let off some of the hot air and at the same time, cool air takes it place, driving the balloon to drop down.**
3. **Oceanic circulation is critically important in the movement of heat over the planet. Environmental scientists found that along with patterns of air movement in the atmosphere, the movement of water through the oceans helps to determine weather and climate conditions in different regions around the world. Gyres, upwelling and thermohaline circulations are the main patterns of oceanic circulation. Basically, ocean circulation moves the cooler water from the poles to the equator, where the water is warmed before the gyre sends it back toward the poles.**
4. **A star has a convection zone, the outer–most layer of the interior of the star where energy is moved by convection. The convection in the sun and other stars involves the upward motion of hotter gas and downward motion of cooler gas, and is the process which the sun uses to transport heat close to surface (Mulan, 1991).**

The mechanism of forced convection, in which fluids motion are induced by an external source such as fan, pump or suction devices used to facilitate convection. Forced convection can be found in everyday life, including air conditioning and central heating and in various types of machineries. Forced convection is frequently encountered by engineers in designing or inspecting heat exchangers, pipe flow and so on. Examples of forced convection, we have:

1. Generating forced convection is as simple as turning on a fan. The heated air from the furnace is pushed through the house by the fan blower situated in the ventilation system. After it has travelled through the vents by being pushed through by fans, the treated air is forced out through floor or ceiling vents into the house.
2. Heat exchangers like radiators are employed to transfer thermal energy in the aim of heating and cooling from one medium to another. Commonly, radiators are designed to operate in buildings, automobiles as well as electronics devices. The radiator put the warm air out at the top and draws in cooler air at the bottom and the process continues.

1.3 Nanofluids and Applications of Nanofluids

Nanofluids term are proposed by Choi (1995) and relatively new engineered fluids consist of nano–sized particles (1–100 nm) suspended within the base fluids, reported by Masuda et al. (1993) as shown in Figure 1.2. These particles, typically a metal or metal oxide, enhance conduction and convection coefficients, allowing the greater amount of heat transfer released from the coolant. Serrano et al. (2009) provided an excellent illustration of nanometer in corresponding from millimeter to micrometer as can be seen in Figure 1.3.

Nanofluids are potentially heat transfer fluids with enhanced thermophysical properties and can be employed in various devices for excellent achievement, especially in energy and heat transfer performances (Mahdi et al., 2015). Their particles are small, low weight and less chances of sedimentation, therefore they possess the following advantages (Choi, 1995 Das et al., 2006):

1. High specific surface area therefore more heat transfer surfaces occured between fluids and particles.
2. High dispersion stability with predominant Brownian motion of particles.
3. Reduced pumping power as compared to pure liquids to achieve equivalent heat transfer intensification.
4. Reduced particles clogging as compared to conventional slurries, thus promoting system miniaturization.
5. Adjustable properties, including thermal conductivity and surface wettability, by varying particles concentrations to suit different applications.

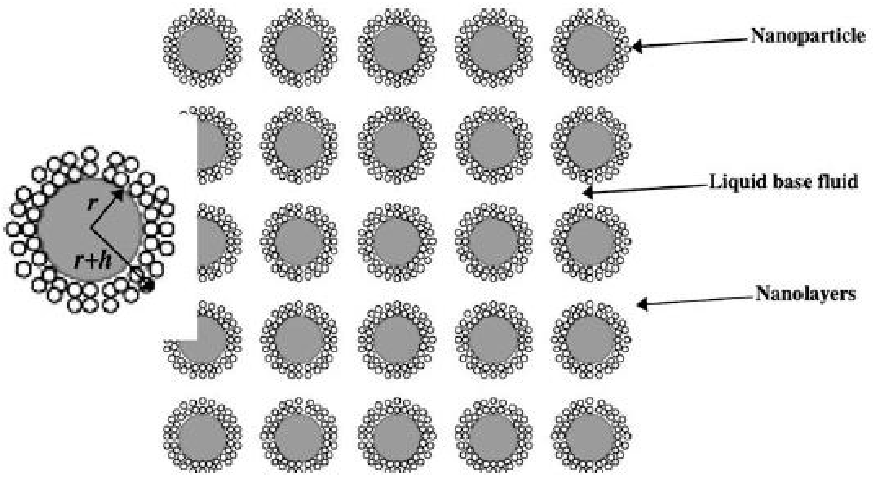

Figure 1.2: Schematic cross section of nanofluids structure
(Source: Yu and Choi, 2003)

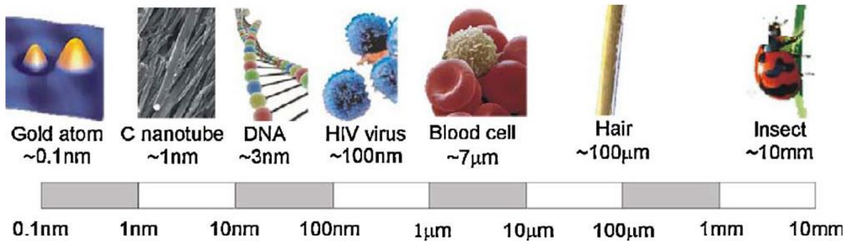

Figure 1.3: Length scale and some examples related
(Source: Serrano et al., 2009)

Nanofluids are the innovated formation of heat transfer fluids offered various inducing new possibilities for the heat transfer enhancement and have superior properties contrary to pure liquids. The large surface area of nanoparticles clearly improvises the performance of heat transfer and reinforces the steadiness of the suspensions. Successful utilization of nanofluids will support the latest tendency toward miniaturization of the components by empowering the design of lighter and smaller heat exchanger systems. Special properties of nanofluids offer the possibility of applying nanofluids in numerous applications of engineering systems, from the advanced nuclear system to the drug delivery system (Buongiorno et al., 2008 Kim et al., 2009; Kleinstreuer et al., 2008). However, the development of nanofluids is still hindered by several factors such as the lack of agreement between results, lack of theoretical understanding about the mechanisms and poor characterization of suspensions. Therefore, necessary studies are needed before extensive application can be found for nanofluids.

Buongiorno (2006) model identified the Brownian motion and thermophoresis mechanisms on the thermophysical properties of the nanofluids and act as the primary mechanisms for the characteristic of convective enhancement in nanofluids. Suspended nanoparticles in various base fluids can significantly alter the flow and heat transfer characteristics of the nanofluids. The heat transfer enhancement in natural convection is more pronounced at higher volumetric fraction of nanoparticles and the enhancement reduces by decreasing the volumetric fraction of nanoparticles. The definition of Brownian motion and thermophoresis mechanisms defined as below:

1. Brownian motion is the random movement of particles suspended in a fluid (a liquid or a gas) resulting from their collision with the fast moving atoms or molecules in the gas or liquid as reported by Jang and Choi (2004) and Singh (2008). The more amount of suspended particles in a fluid, the higher rate of collision between the atoms or molecules. Therefore, Brownian motion can increase the thermal conductivity of the nanofluids.

2. Thermophoresis is a mechanism observed in mixtures of moving particles where the different particles types exhibit different responses to the force of a temperature gradient.

The potentials of nanofluids in heat transfer applications have attracted much attention especially in the industry sector about a decade ago. There are some review papers, which present overviews of various aspects of nanofluids, including preparation and characterization, techniques for the measurements of thermal conductivity, theory and model, thermophysical properties, and convective heat transfer (Trisaksri and Wongwises, 2007 Ma and Liu, 2007 Arruebo et al., 2007 Wang and Mujumdar, 2007 Wang and Mujumdar, 2008 Li et al., 2009 Kakac and Pramuanjaroenkij, 2009; Yu et al., 2010). Saidur et al. (2011) explained the applications of nanofluids in industrial, commercial, residential and transportation sectors written as below:

1. Nanofluids have high thermal conductivity and act as heat transfer intensification. Wong and de Leon (2010) reported that the application of nanofluids is crucial in industrial cooling due to their impact in great energy preservations and emissions reductions. Kulkarni et al. (2008) used nanofluids of ethylene or propylene glycol mixed with water in different proportions as heat transfer fluids in heating system of buildings in cold regions. The outcomes showed that by applying heat exchangers with nanofluids decrease the volumetric and mass flow rates, preserving an overall pumping power.

2. Demirbas (2006) reported that the development of thermal energy storage in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on conservation of the waste heat and solar energy in industry and buildings. Wu et al. (2010) classified the Al_2O_3–H_2O nanofluids as a new phase change material for the thermal energy storage of cooling systems. The addition of Al_2O_3 nanoparticles remarkably reduced the supercooling degree of water, advanced the beginning freezing time and reduced the total freezing time.

3. Various nanofluids can be employed in conventional heat exchangers used in buildings in order to reduce volumetric flow, the mass flow rate and pumping power savings. Nanofluids also require smaller heating systems in order to be able to deliver the same amount of thermal energy, thus reducing the size and the initial cost of equipment. This will reduce the release of pollutants to the environment due to a reduction in power consumption, and the waste produced at the end of the heat transfer system life cycle. In cooling systems, Yu et al. (2007) reported that nanofluids can be used in place of chilled water, which is commonly used in coils of air conditioning ducts.

4. Over the last few decades, Vonarbourg et al. (2006) developed colloidal drug delivery systems to improve the efficiency and the specificity of drug action. The small size, customized surface improved solubility, and multifunctionality of nanoparticles opens many doors and creates new biomedical applications. Singh and Lillard (2009) reported that the novel properties of nanoparticles offered the ability to interact with complex cellular functions in new ways. Mahapatra et al. (2008) briefly discussed the antibacterial activity research of CuO nanoparticles against four bacterial strains. The size of nanoparticles was less than that of the pore size in the bacteria, and thus, they had a unique property of crossing the cell membrane without any hindrance. It could be hypothesized that these nanoparticles formed stable complexes with vital enzymes inside cells which hampered cellular functioning resulting in their death.

1.4 Rayleigh–Bénard Convection

Rayleigh–Benard convection is a type of natural convection, occurring in infinite horizontal planes of fluids layer heated from below and cooled from above. Bénard (1900) performed the first experiment where he melted a layer of wax about 1mm deep in a metal dish heated from below. Once the base layer was hot enough to melt all the wax, at first observation there was no–motion of the liquid wax. But as the base was heated above some critical temperature, he observed the appearance of hexagonal cells when the thermal instability of convection developed on the surface of the wax, and analyzed the presence of convection cells. Figure 1.4 showed a convection cell known as Bénard cell, a hexagonal pattern obtained by Bénard (1900).

Consider a fluid layer maintained at a constant temperature, confined between two infinite horizontal planes. Initially, the fluid layer is motionless. Then, the fluid layer is heated from below where the lower boundary is at a higher temperature than the upper boundary and is said to have an adverse temperature difference because the fluid at the bottom will be lighter than the fluid at the top. This top–heavy arrangement is unstable and by buoyancy force, the fluid moves where the initial movement is the upwelling of warmer fluid from the heated layer below as shown in Figure 1.5.

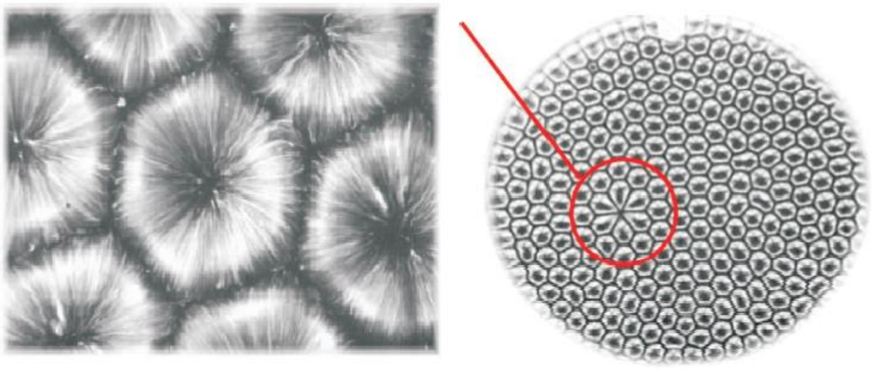

Figure 1.4: The pattern of Bénard cell
(Source: Chandrasekhar, 1961)

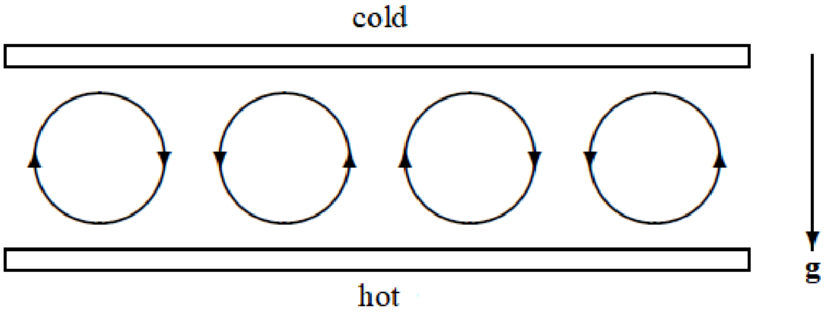

Figure 1.5: Mechanism of convection due to buoyancy force (Bénard convection)

This movement of fluid by convection due to buoyancy force is called Bénard convection. Once the temperature gradient is below a certain value, the natural tendency of the fluid to move, because of buoyancy force, will be inhibited by its own viscosity and thermal diffusivity. Thus the thermal instability will manifest itself only when the adverse temperature difference exceeds a certain critical value. According to Wilson (1993b), the thermal Rayleigh number is governed by

$$Ra \quad \frac{r_f a_T g L^3 DT^*}{m a_f} \qquad (1.1)$$

where r_f is the fluids density, a_T thermal volumetric coefficient, g is the gravitational force, L is the depth of the fluids layer, $DT^* \quad (T_l^* - T_u^*)$ is the temperature difference across the fluids layer, m is the viscosity and a_f is the thermal diffusivity.

1.5 Double–Diffusive Convection

The study on double–diffusive convection began progressively with the article of The salt fountain and thermohaline convection by Stern (1960). The opposing

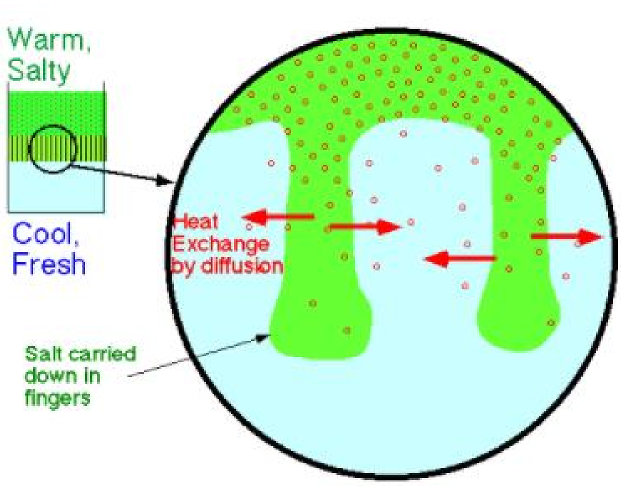

Figure 1.6: Mechanism of salt fingers in a double–diffusive convection (Source: Turner, 1973)

stratifications of two components species drives a convection if their diffusiveness are differed. Stommel et al. (1956) reported that there is a significant potential energy available in the decrease of the salinity with depth found in much of the tropical and subtropical ocean. They investigated that the flow of the salt fountain would be driven in a thermally conducting pipe. It was Stern (1960) who found out that the two orders of magnitude difference in heat and salt diffusiveness allowed the ocean to form its own pipes, which later known as “salt fingers”. Stern also identified the potential for the oscillatory instability when cold, fresh water overlies warm, salty water. In fluid dynamics, the double–diffusive convection is a form of convection driven by two different density gradients, with different rates of diffusion (Mojtabi and Charrier–Mojtabi, 2000). Convection in fluids is driven by density variation within them, and this density variation may be caused by gradients in the composition of the fluids or by differences in temperature (through thermal expansion). Thermal and compositional gradients can often diffuse with time, reducing their ability to drive the convection, and requiring that gradients in other regions of the flow exist in order for convection to continue. Therefore, the compositional gradients (thermo–diffusion) and thermal diffusion are known as the Dufour diffusion and Soret diffusion.

Figure 1.6 is an example of double–diffusive convection called salt fingers by Turner (1973). In this investigation, he used a flourescein salt, which makes the water “heavy on top” in the salt concentration, but the stratification is kept gravitationally stable by the warm on top temperature gradient. The key to the instability is the fact that heat diffuses much more rapidly than salt (hence the term double–diffusion). A downward moving finger of warm saline water (see diagram) cools off via molecular diffusion of heat, and therefore, becomes more dense. This provides the downward buoyancy force that drives the finger. Similarly, an upward moving finger gains heat from the surrounding fingers, becomes lighter, and rises. The net effect is a vertical exchange of water containing the salt, and hence a downwards salt flux. The heat flux is also downward, but is much smaller since most of the heat diffuses out sideways to adjacent fingers. The combined heat and salt fluxes yield a density flux that is downwards. Hence the top layer of water actually becomes less dense over time, and the lower layer becomes more dense. In terms of eddy diffusivities, the effective salt and heat diffusivities are positive (i.e., down gradient), but the density diffusivity is negative, an upgradient flux.

Much of this work was initiated with an application to the ocean in mind, and because heat and salt (or some other dissolved substance) are then important, the process has been called thermohaline (or thermosolutal) convection. Related effects have now been observed in other contexts, to be described below, and the name double–diffusive convection has been used to encompass this wider range of phenomena. The minimum requirements for the occurrence of double–diffusive convection, in the sense implied here, are the following

1. The fluids must contain two or more components having different molecular diffusivities. It is the differential diffusion that produces the density differences required to drive the motion.

2. The components must make opposing contributions to the vertical density gradient.

1.6 Porous Medium

Porous medium is a solid (often called frame or matrix) permeated by an interconnected network of pores (voids) filled with a fluid (liquid or gas). Usually both the solid matrix and the pore network (also known as the pore space) are assumed to be continuous, so as to form two interpenetrating continua such as in a sponge. The porosity e of a porous medium is defined as the fraction of the total volume of the medium that is occupied by void space. There are numerous types of porous media and almost limitless applications of and uses for porous media. Many natural substances such as rocks, soils, biological tissues (e.g. bones), and man made materials such as cements, foams and ceramics can be considered as porous media. Some of the well known porous materials can be seen in the Figures 1.7 and 1.8. Straughan (2008) reported that a poroelastic medium is characterized by its porosity, permeability as well as the properties of its constituents (solid matrix and fluid).

Permeability symbolized as K in fluid mechanics is a measure on the ability of a porous material to transmit fluids. The concept of permeability is important in determining the flow characteristics of hydrocarbons in oil and gas reservoirs, and of groundwater in aquifers. Kaviany (1995) studied that for a rock to be considered as an exploitable hydrocarbon reservoir without stimulation, its permeability must be greater than approximately 100 mD (depending upon the nature of the

Figure 1.7: Lava from Mount Etna, Sicily
(Source: Straughan, 2008)

Figure 1.8: Wood is a very good example of a porous medium which exhibits a strong anisotropy
(Source: Straughan, 2008)

hydrocarbon–gas reservoirs with lower permeabilities are still exploitable because of the lower viscosity of gas with respect to oil).

Bejan and Lage (1991) reported that in analyzing transport phenomena of a porous medium in a pore space region comprising of at least two homogeneous material constituents with at least one of the constituents remaining fixed or slightly **deformable and the other constituent is moving. In a natural porous medium the distribution of pores with respect to shape and size is irregular with pore scale is in the microscopic scale. But in typical experiments, the quantities of interest are measured over areas that cross many pores, and such space averaged (macroscopic)**

quantities change in a regular manner with respect to space and time, and hence are amenable to theoretical treatment (Nield and Bejan, 2006).

Porous materials with high porosity (for example, foametals) can be applied in numerous practical applications such as fluid filters, heat exchangers and chemical reactors, thus, attracts interest in various technological problems. Generally, they are man–made and major used for the design of heat transfer devices. Hill and Straughan (2009) reported that the use of higher order Darcy–Brinkman equation is more appropriate in order to model the fluids flow with highly porous materials. In general, anisotropy is a consequence of orientation or asymmetric geometry of porous matrix or fibers and is, in fact, employed in numerous systems in industry and nature. Furthermore, anisotropy can also be a characteristic of artificial porous materials such as pelleting used in chemical engineering process, fiber material used in insulating purpose and packed beds used for the storage of heat energy.

Nanofluids in porous media incorporates an emerging idea; the review from the literature points out to at least two possible applications. Mahdi et al. (2015) reported that there are two superiorities of applying porous media in nanofluids layer system. First, its dissipation area is greater than the conventional fins that enhance the heat transfer. Second is the irregular motion of the fluids flow around the individual beads which mix the fluids more effectively. Nanofluids have very high thermal conductivities. Therefore, it would be the best convection heat transfer by using two applications together: porous media and nanofluids.

1.7 Galerkin Method

One of the best known approximate methods was developed by the Russian engineer Galerkin (1915). According to Fletcher (1984), Galerkin method used to solve problems in structural mechanics, dynamics, fluid flow, hydrodynamic stability, magnetohydrodynamics, heat and mass transfer, acoustics, microwave theory, neutron transport, etc. Problems governed by partial differential equations, ordinary differential equations and integral equations have been investigated via a Galerkin formulation. Steady, unsteady and eigenvalue problems have been proved to be equally amenable to a Galerkin treatment. Finlayson (1972) reported that in this method, the weighting functions are chosen to be the trial functions, $w_i \quad T_i$. The trial functions must be chosen as members of a complete set of functions. A set of functions w_i is complete if any function of a given class can be expanded in terms of the set, $f \qquad a_i w_i$. Then the series of equation is inherently capable of representing the exact solution, provided enough the terms are used. A continuous function is zero if it is orthogonal to every member of a complete set. Thus the Galerkin method forces the residual to be zero by making it orthogonal to each member of a complete set of functions (in the limit as $N \qquad$). The Galerkin method is highly developed for eigenvalue problems and widely advocated by numerous papers.

1.8 Applications in Industry

Many fluids flows in engineering and industrial applications are driven by buoyant convection and subsequently modulated by feedback control, rotation, internal heat source, magnetic field and so on. One of the classical convection systems is the Rayleigh–Benard setup: a fluid in a horizontally confined container heated from below and cooled from above. The knowledge about this system is relevant for the problem in a limitless range of industrial applications and through a superior understanding of Rayleigh–Benard convection in nanofluids with feedback control, rotation, internal heat source, magnetic field and many more including the porous medium, one can provide profitable outcomes to the industry such as:

1. The concept of control strategy systems in convective heat transfer in fluids is constantly changing in order to meet and keep pace with modern day application requirement. Practically, these types of systems are very useful to improve significant capabilities and reduces costs. Autopilot control systems play a vital role in controlling the speed of automobile to a desirable speed limit or to keep the aircraft to autopilot so that the pilot should not continue to operate the controls to maintain the desired heading and altitude. In autopilot mode, the pilot is free to perform other tasks and helps to reduce crew members and operating cost.

2. The effect of magnetic field on double–diffusive convection finds importance on the role of engineering and industrial applications. These applications include design of chemical processing equipment, formation and dispersion of fog, distributions of temperature and moisture over agricultural fields and groves of fruit trees and damage of crops due to freezing and pollution to the environment, etc.

3. The rotating turbulence is an example of an interesting variation of Rayleigh–Bénard convection is the case where the sample is rotated about the vertical axis. The turbulent rotating convection on anisotropic effects with experiment and numerical simulation is provided by the industry where the setup (rotating table, laser, cameras, computers, LED light, etc.) is required in the engineering turbulence pipe flows studies.

4. In industrial applications, internal heat sources are used very often in affecting the thermal indoor climate. Typical heat sources are machines, appliances and equipment, and all kinds of processes taking place in the room. The internal heat source transfers the energy to room air by convection and normally is sensible heat.

5. Design and optimization of industry products where modelling the flows of liquids, heat as well as moisture transfer away in a porous media through the hygiene product is crucial to the development of consumer products, such as diapers and wipes (Suresh, 2016). Well design diapers containing the layer of a porous medium (fibers) that is particularly effective without breaking the bank. As for the wipes, they are designed to be durable enough for heavy duty

cleaning tasks. The fabric is saturated with cleansing solution designed to be mild yet effective.

6. According to Ghenai et al. (2003), the use of double–diffusive convection is important in the process of solidification of a metal analog system of ammonium chloride with water, $NH_4Cl–H_2O$ in a differentially heated cavity. Casting is the common metal solidification which used the melting and resolidification of a metal within a mold to produce a desired product. During the solidification process, the metal is shrinking, and it is important to feed this shrinking to ensure the castings are free of voids and defects.

Accordingly, it would be favorable to have the appropriate recognition knowledge of the Rayleigh–Bénard convection with various effects discussed above since their advantages can provide valuable practical implementation to the industry, and their beneficial outcomes can improve the technological innovation.

1.9 Problem Statement

uite recently, the paramount way of achieving a great performance on convective thermal instability in nanofluids for various engineering applications and industrial processes have increased rapidly. Heat transfer problems in nanofluids for industry are usually of a very complex in nature, frequently involving different mechanisms. The major challenges in heat transfer industry are to maintain the stability of the system, increase efficiency of mechanical equipment, energy conservation, reduce the costs and outcome uncertainties. Therefore, modelling the most sophisticated methods and formulations is considered in order to solve the onset of convection problems where the outcome results consistently not significant, representative and scientifically accurate. Due to these issues, suitable numerical methods with appropriate governing equations are highly required.

The area of active control in convective processes is no less important from a technological point of view. The ideas behind the methodology can be implemented into real life, especially in industrial applications of the heat energy control systems through the use of feedback controller performance assessment. Heat energy control system is constructed to measure and regulate the flow of hot and cold fluids as a fundamental study of the control system in order to behave in a desired manner. Some of the significant achievements of control systems in industry area are the ability to enhance the quality of the product, minimize the products waste and to protect the environment. In some processes, it may be desirable to suppress chaotic or turbulence motions and maintain a steady, time–independent flow in order to minimize unpredictable flow, remove temperature oscillations which may exceed safe operational conditions and reduce drag.

Scrutinizing the effect of feedback control in nanofluids system can help to improve

the industrial problem regarding convection. As far as I concern, feedback control has been investigated by many authors in few types of fluids layer system such as micropolar fluids and fluids saturated in a porous medium, but less research on feedback control in nanofluids layer system. Thus, this study is intended to be comprehensible with some knowledge as a reference in the subject area of nanofluids study **to researchers. Variational types of effects also have been considered in the problem of feedback control for the onset of Rayleigh–B**enard convection in nanofluids layer system, the considered effects are rotation, magnetic field, internal heat source, **porosity of the porous medium, anisotropic parameters, thermal conductivity variation and viscosity variation parameters, respectively. Finally, students or researchers** that are interested in a control system in nanofluids engineering will find this thesis **useful as it will help to explain the basic of control system theory.**

1.10 Objectives and Scopes of Study

The objectives of this present study are to analyse the mathematical modelling for each problem below:

1. **Rayleigh–B**enard convection in rotating nanofluids layer with feedback control subjected to double–diffusive coefficients. In this problem, we investigate **the effects of feedback control K, rotation (Taylor number Ta), Soret parameter Sr, Dufour parameter D f** and nanofluids parameters in the system. These **two types of interdiffusion, Soret and Dufour parameters play an important** role within nanofluids layer system. Then, to explore the performance involving double–diffusive coefficients with feedback control **K and rotation in the respective system.**

2. **Rayleigh–B**enard convection in rotating nanofluids layer with feedback control subjected to the magnetic field. In this problem, we analyze the sensitiveness **main effects of feedback control K, Taylor number Ta, magnetic Chandrasekhar number H** and nanofluids parameters for two types of nanofluids in**volved in this problem, that are alumina–water Al_2O_3–H_2O and copper–water Cu–H_2**O nanofluids. Then, to compare and discuss the behaviour of these two **types of alumina–water Al_2O_3–H_2O and copper–water Cu–H_2**O nanofluids in **details.**

3. **Rayleigh–B**enard convection in nanofluids layer saturated in a rotating **anisotropic porous medium with feedback control and internal heat source. In this problem, we use the Darcy s law on the Oberbeck–Boussinesq approximation for Darcy model of a porous medium to investigate the effects of feedback control K, rotation, internal heat source , anisotropic parameters (mechanical anisotropy parameter x and thermal anisotropy parameter z), porosity e and** nanofluids parameters involved such as: **Rn_d N_A N_B and Ln in the respective system.**

4. **Rayleigh–B**enard convection in Darcy–Brinkman nanofluids layer saturated in **a rotating anisotropic porous medium with feedback control and internal heat**

source. In this problem, we consider the Brinkman model of a porous medium to study the effects of feedback control K, rotation with internal heat source , Darcy number Da, porosity e, anisotropic parameters (mechanical anisotropy parameter x and thermal anisotropy parameter z) and nanofluids parameters in this respective system.

5. Stationary and oscillatory mode of Rayleigh–Bénard convection in Maxwell nanofluids layer saturated in a rotating porous medium with feedback control subjected to thermal conductivity variation and viscosity variation, respectively. In this problem, we use a modified Darcy–Maxwell nanofluids model incorporates the Brownian motion and thermophoresis mechanism. We also consider the modified Darcy model for a porous medium saturated with Maxwell nanofluids subjected to the effects of Vadász number Va, relaxation parameter l, feedback control K, rotation, viscosity variation m and thermal conductivity variation k as the main parameters where the respective results will be examined.

The scope of study is limited to the Rayleigh–Benard convection in nanofluids with porous and nonporous. It has not escaped our notice that the major scope of this study is to mainly focus upon the effects of feedback control strategy and rotation on the convective instability in nanofluids layer and nanofluids layer saturated in a porous medium, where several other parameters are considered in their respective problems.

In this thesis, the mathematical models are extended from the previous researchers, and each of these explanations will be listed in the respective chapter. It is worth mentioning that the sources of this study are from well–known journals and published papers. For each considered problem, the systems governed by the partial differential equations (PDE) are nondimensionalized, perturbed and changed into a system of ordinary differential equations (ODE). The resulting equations then are solved numerically by Maple software. However, to ensure our obtained results are in an equivalent agreement correspondence to previously published results, each of the results from these problems has to undergo a comparison test, and the results should be aligned in the similar value with the previously published results. Once we found out that our respective results are in a good agreement, we are confident to perform further examinations in order to obtain the results in each problem.

1.11 Outline of Thesis

This thesis covers nine chapters, including introduction and conclusion. Chapter 1 is the preliminary chapter consisting of the introduction of this study, which involves the definition, applications and methods that are used for this research as well as the problem statement, the objectives and the outline of the thesis. Chapter 1 focused on how this topic has been exposed and finally become one of the topics that are important to be studied.

Chapter 2 reviews the pioneering studies performed by many researchers on the convective instability experimentally and numerically. We also highlighted the investigators who studied the Rayleigh–Benard convection in nanofluids layer with double–diffusive convection, rotation, feedback control, internal heat source, magnetic field, thermal conductivity and viscosity variation effects followed by the investigation in a porous medium with anisotropic parameters. Furthermore, the methodology and contribution from their research is highlighted.

Chapter 3 explains the methodology for five following problems for five different models of the research problem with lower–upper bounding surfaces of free–free, rigid–free and rigid–rigid. The mathematical formulation includes the linear stability analysis upon normal mode technique, Galerkin technique and Maple software. The governing equations of nanofluids model as formulated by Buongiorno (2006) associated with Brownian motion and thermophoresis mechanism. An explanation on the use of controller has been discussed throughout this chapter as well as the effect of rotation.

The first problem of this study, namely the Rayleigh–Bénard convection in rotating nanofluids layer with feedback control subjected to double–diffusive coefficients is discussed in details in Chapter 4. Chapter 4 starts with the introduction, accompanied by mathematical formulation then, proceeds with the results and discussion, and ends with the conclusion. The effects of feedback control K, rotation, Soret Sr together with Dufour D f parameters, solutal Rayleigh number Rs and nanofluids parameters are illustrated graphically and discussed in details.

Discussion in Chapter 5 focused on feedback control K, rotation together with magnetic Chandrasekhar number H combination effects on the Rayleigh–Bénard convection in nanofluids layer. We consider two types of nanofluids in this problem, alumina–water Al_2O_3–H_2O and copper–water Cu–H_2O nanofluids. In the interest of understanding the applications of feedback control K, rotation and magnetic Chandrasekhar number H on these two types of nanofluids, the simulation is performed and briefly discussed throughout this chapter.

Investigation is continued in Chapter 6 for Rayleigh–Benard convection in nanofluids layer saturated in a rotating anisotropic porous medium with feedback control and internal heat source. Linear stability analysis of nanofluids in the Rayleigh–Bénard problem in a porous medium is studied based on the Darcy model. The obtained results for feedback control K, rotation, internal heat source , porosity e, anisotropic parameters (mechanical anisotropy parameter x and thermal anisotropy parameter z) and nanofluids parameters are discussed briefly and presented graphically.

The effects of rotation due to the Coriolis force measured by Taylor–Vadasz number Ta_V and feedback control K on the Rayleigh–Bénard convection in an anisotropic porous medium saturated by Darcy–Brinkman nanofluids layer subjected to internal heat source is carried out in Chapter 7. In this chapter, the Brinkman model for nanofluids saturated in a porous medium has been used for linear stability analysis upon normal mode technique. The Galerkin technique and Maple software have been used to solve the eigenvalue problem and the obtained results for feedback control K, rotation, internal heat source , Darcy number Da, porosity e, anisotropic parameters (mechanical anisotropy parameter x and thermal anisotropy parameter z) and nanofluids parameters are discussed and presented graphically.

Chapter 8 discussed on stationary and oscillatory mode of Rayleigh–Bénard convection in nanofluids layer saturated in a rotating porous medium with feedback control subjected to viscosity variation and thermal conductivity variation. In this chapter, linear stability analysis of Maxwell nanofluids on the Rayleigh–Bénard problem in a porous medium is studied upon Darcy–Maxwell model. The important effects of feedback control K, rotation, Vadász number Va, relaxation parameter l , viscosity variation m, thermal conductivity variation k, porosity e and nanofluids parameters have been presented graphically and discussed.

Lastly, Chapter 9 contains the summary of the Rayleigh–Bénard convection in rotating nanofluids layer with feedback control. In this study, we focused on the stationary mode of convection of the respective problems from Chapter 4 until Chapter 7, meanwhile for Chapter 8, we include both the stationary and oscillatory mode of convection. At the same time, we can conclude these problems can be extended into oscillatory cases and nonlinear cases, with different types of fluids and models, where further and tremendous analyses of computational methodology are required to solve these problems.

The following section reviews the literature in the aforementioned areas.

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