PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

UNIVERSITY YAHIA FARES DE MEDEA

Faculty of Technology

Department of Process Engineering and Environment



Final thesis for the Master's Degree

Field**: Process engineering**

Specialty: **Materials Process Engineering**

Digital study of thermal and mass transfer converted with nanofluid between two vertical plates

Presented by:

- Bouguessa Salah Eddine
- Benouared Abdel Hakim

Framed by:

Dr.Alouaui Redha

Pr.Bouaziz.M.N

Promotion June/2022

Acknowledgment

At the end of this modest work, we wish to express our deep and heartfelt thanks:

First of all, we thank ALLAH for giving us the strength and patience to carry out this work.

To our parents who have always encouraged and supported us throughout our studies.

To our promoter Dr. Alouaui Redha and our Co-promoter PR. Bouaziz. M. N, each one for his availability and assistance

Valuable that he offered us for modeling this work.

To all teachers of the Environmental Process Engineering department.

Dedication

I dedicate this modest work to

My dear Mother, *who has always been present for me, in the most difficult moments and who constantly watches over me with her prayers, for her great sacrifices and all the love that brings me.*

My dear father*, for all his advice and for all the confidence he has placed in me and for his dedication to my happiness.*

To my dearest sister: *Meriem.*

To my dear brothers: *Rabeh, Hocine, Miloud, Zakaria Yahia, Mohamed, Djamel.*

To my cousins: *Besma, Abdel Kader.*

To my nephews: *Katre el nada and Anes.*

To all my friends and especially Mohamed, Hakimo, Aymen, Raouf and Sofiane , Houssem, Yassine , Islam.

Salah Eddine

Dedication

I dedicate this modest work to

My dear Mother, *who has always been present for me, in the most difficult moments and who constantly watches over me with her prayers, for her great sacrifices and all the love that brings me.*

My dear father*, for all his advice and for all the confidence he has placed in me and for his dedication to my happiness.*

To my dearest sister: *Yassmine.*

To my dear brothers: *Nazim.*

To all my friends and especially Mohamed, SALA, Aymen, Raouf .

Abd el hakim

Summary

Figure List **9**

List of tables 10

List of abbreviations **11**

Abstract **14**

General introduction 1

Chapter I : General information on mass and heat transfer **3**

I.1. Introduction 3

I.2. Diffusion mass transfer 4

I.3. Fick's law of diffusion 5

I.4. Convective mass transfer 7

I.5. Similarity between heat and mass transfer 8

I.6. Modes of mass transfer 8

I.6.1. Mass transfer by diffusion (molecular or eddy diffusion) : 9

I.6.2. Mass transfer by convection 9

I.6.3. Mass transfer by change of phase 9

I.7. Conclusion: 10

Chapter II : Overview of heat transfer **11**

II.1. Introduction 11

II.2. Heat 11

II.3. Definition of heat transfer 12

II.4. Importance of heat transfer 12

II.5. Differences between thermodynamics and heat transfer 13

II.6. Modes of heat transfer 14

II.6.1. Conduction 15

II.6.2. Convection 15

II.6.3. Radiation 16

II.7. Combined modes of heat transfer 17

II.8. Heat Transfer by Convection 18

II.9. The basic laws of heat transfer and their application 20

II.10. Overview on convection 21

II.10.1. Introduction 21
II.10.2. Mechanism of convection.....22
II.10.3. Methods used in convection studies.....23
II.10.4. Forced and free convection.....24
II.10.5. Natural convection 25
II.10.6. Methods of analysis 27
II.11. Overview on dimensional analysis 30
II.11.1. Introduction 30
II.11.2. Uses of Dimensional Analysis:.....30
II.11.3. Dimentions 30
II.11.4. Methods of dimensional analysis.....31
II.11.5. Advantages and limitation of dimensional analysis.....33
II.11.6. Dimensionless numbers and their physical significance 34
II.12. Conclusion: 39
Chapter III : General information on Nanofluid and Biosurfactant and MHD 40
III.1. Nanofluid.....40
III.2. Nanoparticles and carrier fluids 40
III.3. Thermo-physical properties : 41
III.3.1. Specific heat.....42
III.3.2. Volumetric mass.....42
III.3.3. Heat conductivity.....42
III.3.4. Dynamic viscosity: 42
III.4. Studies on nanofluids 44
III.5. Techniques de fabrication.....44
III.6. Preparation of nanofluids:.....44
III.7. Effects on the thermo-physical properties of nanofluids :.....45
III.7.1. Effect of particle volume concentration:.....45
III.7.2. Effect of temperature: 45
III.7.3. Effect of the type of the nanoparticle.....45
III.8. Domains of application of nanofluids : 46
III.8.1. Cooling of thermal systems :.....46
III.8.2. Cooling of electronic systems : 47
III.8.3. Cooling of military systems : 47

III.8.4. Cooling of space systems :.....47
III.8.5. Cooling of nuclear systems :.....47
III.8.6. Biomedicine:.....47
III.8.7. Other applications :.....48
III.9. Surfactants.....48
III.9.1. Natural surfactants.....49
III.9.2. Biosurfactants.....49
III.9.3. Classification of biosurfactants.....49
III.9.4. Parameters influencing the production of biosurfactants.....50
III.9.5. Production of biosurfactants.....50
III.9.6. Physicochemical characterization of biosurfactants.....51
III.9.7. Use of biosurfactants.....51
III.9.8. Applications of biosurfactants in industry.....51
III.9.9. Benefits of Biosurfactants.....52
III.9.10. Disadvantages of biosurfactants:.....53
III.10. MHD.....53
III.10.1. Introduction.....53
III.11. Definition of magnetohydrodynamics.....53
III.12. Mathematical model.....55
III.12.1. Loi de la force de Lorentz :.....55
III.12.2. Maxwell's equations :.....55
III.12.3. The Navier-Stokes equation:.....56
III.12.4. Ohm's law:.....56
III.12.5. Magnetohydrodynamic approximation:.....57
III.12.6. The magnetic induction equation:.....58
III.13. Conclusion :.....59
Chapter IV : Results and discussion.....60
IV.1. Introduction.....60
IV.2. Mathematical formulation.....62
IV.3. Results and discussion.....67
IV.3.1. Effect of the magnetic parameter *M* and the material parameter *K*.....71
IV.3.2. Effect of the suction/injection parameter f_w and the material parameter K.....74
IV.3.3. Effect of the Prandtl number Pr and the material parameter K.....78

[Summary]

Conclusion.....82

Bibliographic – Reference.....

Figure List

Figure I-1 : Diffusion of gases 4
Figure I-2 : Mass transfer by diffusion in binary gas mixture....5
Figure I-3: Concentration profile....6
Figure I-4: Species concentration boundary layer development on flat plate 7
Figure II-1: Modes of heat transfer combined modes on heat transfer....17
Figure II-2 : Combined modes of heat transfer....17
Figure II-3 : Cooling of hot plate by flowing fluid 20
Figure II-4: Velocity and temperature variation of a point in fluid over a surface 22
Figure II-5 : Free convection boundary layer near a vertical surface 24
Figure II-6 : Forced on an element in the boundary layer 27
Figure III-1 : Effect of particle types on thermal conductivity 46
Figure III-2 : Schematic representation of a surfactant monomer 48
Figure III-3: Induced current in a conductive fluid in the presence of a magnetic field (59)....54
Figure III-4 : Effect of magnetic field on conductive fluid flow and hand law (59)....54
Figure III-5 : The tow key's physical effects occurring in MHD (59) 55
Figure IV-1 : Physical model and coordinate system 70
Figure IV-2 : Velocity profiles $f'(\eta)$ for comparison with results of Alam and al. [2009]....70
Figure IV-3 : Velocity profiles $f'(\eta)$ for different values of *M*....71
Figure IV-4 : Microrotation profiles $h(\eta)$for different values of *M*....72
Figure IV-5 : Temperature profiles $\theta(\eta)$ for different values of *M*. 73
Figure IV-6 : Concentration profiles $\phi(\eta)$ for different values of *M*. 74
Figure IV-7 : Velocity profiles $f'(\eta)$ for different values of f_w. 75
Figure IV-8 : Microrotation profiles $h(\eta)$ for different values of f_w. 76
Figure IV-9 : Temperature profiles $\theta(\eta)$ for different values of f_w....77
Figure IV-10 : Concentration profiles $\phi(\eta)$ for different values of f_w....78
Figure IV-11 : Velocity profiles $f'(\eta)$ for different values of *Pr*. 79
Figure IV-12 : Microrotation profiles $h(\eta)$ for different values of *Pr*. 80
Figure IV-13 : Temperature profiles $\theta(\eta)$ for different values of *Pr*....81
Figure IV-14 : Concentration profiles $\phi(\eta)$ for different values of *Pr*....81

List of tables

Tableau II-1: Diffrence between thermodynamics and heat transfer modes of heat transfer.....14

Tableau III-1: Thermophysical properties of deferential materials.....43

Tableau IV-1 : Values of $\frac{1}{2}C_f\,Re_x^{1/2}$, $M_w Re_x$, $Nu_x\,Re_x^{-1/2}$ and $Sh_x\,Re_x^{-1/2}$ for selected values of ,M and K with Gr_x = 2.0, Pr = 0.71, f_w=1.0, Ec =0.1, Sc =0.3 67

Tableau IV-2 : Values of $\frac{1}{2}C_f\,Re_x^{1/2}$, $M_w Re_x$, $Nu_x\,Re_x^{-1/2}$ and $Sh_x\,Re_x^{-1/2}$ for selected values of , f_w and K with Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec =0.1, Sc =0.3 69

Tableau IV-3 : Values of $\frac{1}{2}C_f\,Re_x^{1/2}$, $M_w Re_x$, $Nu_x\,Re_x^{-1/2}$ and $Sh_x\,Re_x^{-1/2}$ for selected values of , Pr and K with Gr_x = 2.0, Pr = 0.71, M= 1.0, f_w= 1.0, Ec =0.1, Sc =0.3 69

List of abbreviations

Nomenclature:

B_0 : Uniform magnetic field.

C_f : Skin friction coefficient.

c_p : Specific heat at constant pressure.

D : Mass diffusivity.

D_B : Brownian diffusion coefficient.

D_T : Thermophoretic diffusion coefficient.

Ec : Eckert number.

f : Dimensionless stream function.

f_w : Suction/injection parameter of dimensionless wall suction.

g : Acceleration due to gravity.

h : Dimensionless angular velocity.

Ha_x : Local Hartmann number.

Gm_x : Local concentration Grashof number.

Gr_x : Local temperature Grashof number.

j : Microinertia density.

K : Material parameter.

Ln : Nanofluid Lewis number.

M : Magnetic parameter.

N : Angular velocity or component of microrotation.

Nb : Brownian motion parameter.

Nu_x : Local Nusselt number.

Pr : Prandtl number.

[List of abbreviations]

q_w : Surface heat flux.

q'_w : Surface mass flux.

Re_x : Referential local Reynolds number.

S : Dimensionless stream function.

Sh_x : Local Sherwood number.

Sc : Schmidt number.

T : Temperature.

t_w : Surface shear stress.

v_w : Suction velocity or injection velocity.

U : Velocity of the plate.

u, v : Velocity components in the *x* and *y* directions.

Greek symbols:

α_{nf} : Thermal diffusivity.

β : Thermal expansion coefficient.

ϕ : Nanoparticule volume fraction.

ϕ_w : Nanoparticule volume fraction at the vertical plate.

ϕ_∞ : Ambient nanoparticule volume fraction attained as y tends to infinity.

γ : Spin gradient viscosity.

η : Similarity space variable.

μ : Dynamic viscosity.

ν : Kinematic viscosity.

σ : Electrical conductivity of the fluid.

θ : Dimensionless temperature.

ρ : Fluid density.

[List of abbreviations]

$(\rho c)_f$ **:** Heat capacity of the fluid.

$(\rho c)_p$ **:** Effective heat capacity of the nanoparticule materiel.

ψ **:** Stream function.

κ **:** Vortex viscosity.

λ_g **:** Thermal conductivity of fluid.

Abbreviation:

MHD*:* Magnetohydrodynamique

Subscripts:

w **:** evaluated on the wall.

∞ **:** evaluated at the outer edge of the boundary layer.

الملخص:

يبحث هذا العمل بشكل أساسي في تأثير المجال المغناطيسي على نقل الحرارة في تدفق الطبقة الحدودية الصفيحية الثابتة من الموائع النانوية الدقيقة على صفيحة عمودية متحركة ونفاذة تخضع لمجال مغناطيسي.

يتم تحويل المعادلات التفاضلية الحاكمة إلى المعادلات التفاضلية العادية التي يتم حلها عدديًا.

تُجرى دراسة بارامترية للبارامترات الفيزيائية لإظهار تأثيرها على مختلف الملامح.

تظهر النتائج أن التحديد الدقيق للجسيمات النانوية المعلقة ووجود المجال المغناطيسي بشكل عام، يصبحان مهمين في نقل الحرارة وبالتالي لا ينبغي إهمالهما عند الحساب.

الكلمات المفتاحية : موائع نانوية، هيدروديناميكية مغناطيسية، طبقة حدودية، لوحة متحركة، خافض للتوتر السطحي الحيوي

Abstract

This work investigates mainly the magnetic field effect on the heat transfer in steady laminar boundary layer flow of micropolar nanofluids over a moving vertical and permeable plate subjected to a magnetic field.

The governing differential equations are transformed into the ordinary differential equations which are solved numerically.

A parametric study of physical parameters is conducted to display their influence on the various profiles.

The results show that microrotation of the suspended nanoparticles and the presence of the magnetic field in general, become important on heat transfer and should therefore not be neglected when calculating

Key Words: Nanofluids, magnetohydrodynamic, boundary layer, moving plate, Biosurfactant

Résumé :

Ce travail étudie principalement l'effet du champ magnétique sur le transfert de chaleur dans un écoulement laminaire régulier en couche limite de nanofluides micropolaires sur une plaque verticale mobile et perméable soumise à un champ magnétique.

Les équations différentielles gouvernantes sont transformées en équations différentielles ordinaires qui sont résolues numériquement.

Une étude paramétrique des paramètres physiques est menée pour montrer leur influence sur les différents profils.

Les résultats montrent que la microrotation des nanoparticules en suspension et la présence du champ magnétique en général, deviennent importantes sur le transfert de chaleur et ne doivent donc pas être négligées lors des calculs.

Mots clés : Nanofluides, magnétohydrodynamique, couche limite, plaque mobile, Biosurfactant

General introduction

General introduction

During the past years, there has been a significant growth in the use of micropolar nanofluids, the need to improve heat transfer fluids has led to the development of nanofluids. These engineered particles dispersed in a base fluid have numerous applications such as in micro electromechanical systems (MEMS), nano electromechanical systems (NEMS), biomedical engineering (imaging and ablation), nuclear reactors, extraction of geothermal power, etc. of G.C. Bourantas and al. (1)

These kinds of the fluids have been modelled firstly by Eringen (2) adding a supplementary equation representing the local angular momentum which operates also in the classical momentum equation.

The use of biosurfactants to act both as reducing agents and stabilizers in the synthesis of nanoparticles has been reported by Priyadarshini and al (3) . Kasture and al. (4) and Kumar C. G. and al. (5) , heat transfer by mixed convection in micropolar nanofuides has been discussed by Rehman and al. (6)

A Ishak and al. (7) analyses a micropolar fluid with MHD flow near a stagnation point. Thermal radiation and chemical reaction effects for the same type of fluid has been considered by Das (8) .The first cited effect is also treated numerically by Mahmoud (9) considering a stretching surface with variable thermal conductivity. A numerical model is developed to examine the combined effects of Soret and Dufour on mixed convection magnetohydrodynamic heat and mass transfer in micropolar fluid-saturated Darcian porous medium in the presence of thermal radiation, non-uniform heat source/sink and Ohmic dissipation is presented by Pal and Chatterjee (10) .Seddeek and al. (11) derived an analytical solution for a magneto-micropolar fluid past a moving plate. Radiation, suction and blowing are the mechanisms incorporated. The steady laminar magnetohydrodynamic (MHD) boundary-layer flow past a wedge with constant surface heat flux immersed in an incompressible micropolar fluid in the presence of a variable magnetic field is investigated by Ishak and al. (12) .Mahmoud and Waheed (13) examined an interaction between a MHD micropolar fluid and a moving surface with radiation. In the area of high temperature differences, Abd-El Aziz (14) studied the above effects on a moving semi-infinite plate with mixed convection flow of a micropolar fluid. The problem of the flow and heat transfer on a cylinder with a suction-case is discussed by Elbarbary and Elgazery (15) Unsteady MHD

natural convection is studied by Chamkha (16) for a heated porous plate with combined effects.

Efforts to improve the heat exchangers in many industrial sectors (automotive, electronics ...) require the intensification of heat transfer by convection. Improvements called "passive", in exchange surfaces are a path already widely explored and reach their limits. New optimization pathways should be studied. One of them is to use new media able to increase heat transfer: the case of nanofluids. (17)

Nanofluid research has the fastest growth rate in science citation index (SCI) publications. These fluids are engineerly manufactured fluids by suspension of ultrafine size (10^{-9}–10^{-11} m) particles in the simple fluid. Choi (18) named these fluids as nanofluids due to the addition of nano-size particles. He concluded that the pumping cost of a heat exchanger system can be reduced several times, because these particles have a higher thermal conductivity than that of base fluids.

In this context, Reddy and al. (19) presented analysis of the boundary layer for the mixed convection for the flow of a non-Newtonian nanofluid past in vertical cylinder. Solutions of the set of non-similarity equations are obtained using the finite difference method with implicit Keller box method of disposal.

The purpose assigned to this study is the understanding and exploration of structure dynamic and thermal fields and the quantification of heat transfer between the surface of the movable plate and the micropolar nanofluids in addition to their stability by using biosurfactants.

Chapter I

General information on mass and heat transfer

I.1.Introduction

Mass transfer can take place by molecular diffusion and convection. The molecular diffusion ,is mass transfer at microscopic level due to a concentration difference, from the region of high concentration to the region of low concentration. The diffusion may also take place due to pressure differences (pressure diffusion) or temperature differences (thermal diffusion). However, these forms of diffusion will not be discussed here. The molecular diffusion is analogous to heat conduction, while the mass transfer in a flowing fluid, termed as convective mass transfer, is analogous to convective heat transfer (20)

Mass transfer is different from the flow of fluid. Mass transfer is the flow of molecules from one body to another when these bodies are in contact or within a system consisting of two components when the distribution of materials is not uniform. When a copper plate is placed on a steel plate, some molecules from either side will diffuse into the other side. When salt is placed in a glass and water poured over it, after sufficient time the salt molecules will diffuse into the water body. A more common example is drying of clothes or the evaporation of water spilled on the floor when water molecules diffuse into the air surrounding it. Usually mass transfer takes place from a location where the particular component is proportionately high to a location where the component is proportionately low. Mass transfer may also take place due to potentials other than concentration difference. (21)

The terms mass convection or convective mass transfer describes the process of mass transfer between a surface and a moving fluid. Just like heat convection, mass convection can be free or forced, laminar or turbulent and internal or external. (20)

Consider the system, shown in Fig, where two gases B and C, at the same temperature and pressure, are initially separated by a thin partition. When the partition is removed, the two gases diffuse through each other. During diffusion, the molecules of gas B move from the zone of high concentration of component B to the zone of lower concentration of the component. From left to right across the plane where the partition was present. A higher concentration means more molecules per unit volume. Similarly the molecules of the gas C move from right to left. Fig also shows the concentration profile of constituent B at a certain instant shortly after the removal of the partition. In this example, the concentration gradient is

the cause of the diffusion. It is to note that the diffusion basically happens because of the random motion of the molecules. (20)

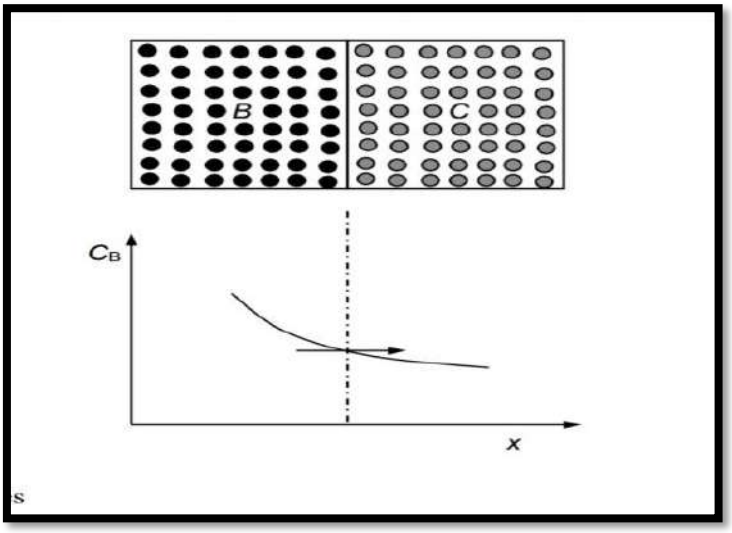


Figure I-1 : Diffusion of gases

I.2.Diffusion mass transfer

Diffusion mass transfer occurs without macroscopic mass motion or mixing. A lump of sugar dropped into a cup of tea will dissolve by diffusion even if left unstirred. But it will take a long time for the sugar to reach all of the volume in the cup. However it will diffuse into the volume by and by. Consider a chamber in which two different gases at the same pressure and temperature are kept separated by a thin barrier. When the barrier is removed, the gases will begin to diffuse into each other's volume. After some time a steady condition of uniform mixture would be reached. This type of diffusion can occur in solids also. The rate in solids will be extremely slow. Diffusion in these situations occurs at the molecular level and the governing equations are similar to those in heat conduction where energy transfer occurs at the molecular level. (21)

The basic law governing mass transfer at the molecular diffusion level is known as Fick's law. This is similar to the Fourier heat conduction law. (21)

In Mass transfer, molar quantities are more convenient to use as compared to mass units, because mass transfer is due to the movement of molecules as discrete quantities. Hence it is convenient to use number of moles, or molar concentration instead of density etc. (21)

I.3. Fick's law of diffusion

In order to understand the "mass diffusion" (a transport process originating from molecular activity), consider a chamber in which two different gas species A and B, at the same temperature and pressure are initially separated by a partition. The left compartment has a high concentration (more molecules per unit volume) of gas A (open circles) whereas the right compartment is rich in gas B (dark circles). When the partition wall is removed a driving potential comes into existence which tends to equalize the concentration difference. Mass transfer by diffusion will be in the direction of decreasing concentration and subsequently there will be a net transport of species A to the right and of species B to the left. After a sufficiently long period, equilibrium conditions prevail, uniform concentrations of species A and B are achieved and then the mass diffusion ceases. (22)

It has been observed through experiments that molecular diffusion is governed by Fick's law which is expressed as. (22)

$$N_A = \frac{m_A}{A} = -D_{AB}\frac{dC_A}{dx} \qquad \textbf{(I-1)}$$

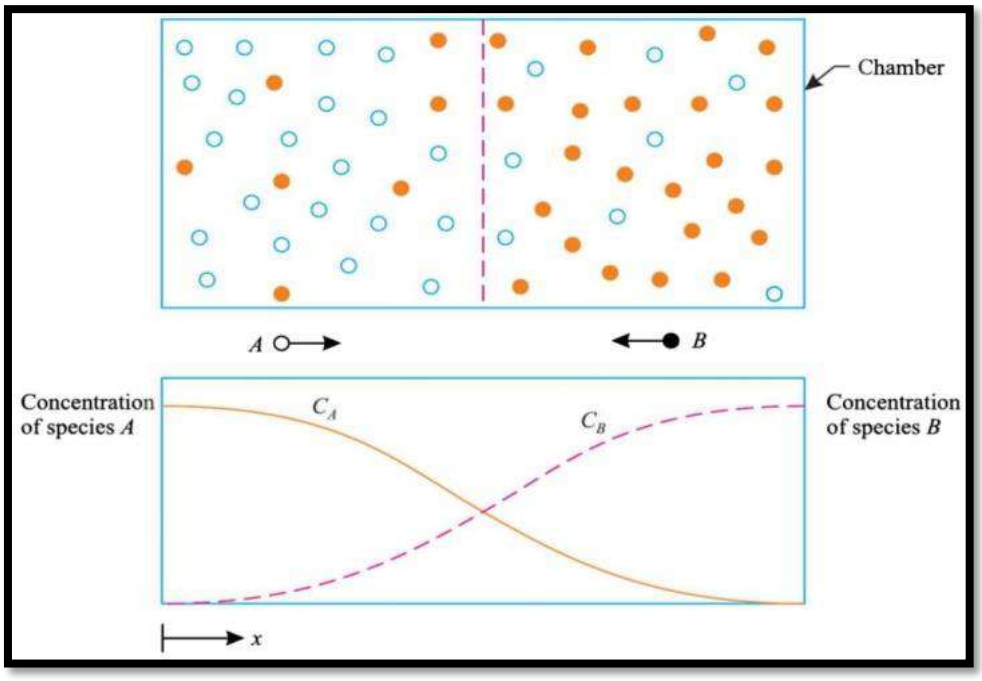


Figure I-2 : Mass transfer by diffusion in binary gas mixture

In (I-1)- The sign indicates that diffusion takes place in the direction opposite to that of increasing concentration (22)

The diffusion rate for species B is given by (22)

$$N_B = \frac{m_B}{A} = -D_{BA}\frac{dC_B}{dx} \qquad \textbf{(I-2)}$$

It may be noted that "diffusion coefficient D (D_{AB} or D_{BA} in this case) is dependent upon the temperature, pressure and nature of the components of the system (22)

The Fick's law, which describes the transport of mass due to concentration gradient, is analogous to the Fourier's law of heat conduction, which gives transport of heat due to the temperature gradient. (23)

$$\mathbf{\frac{Q}{A} = -k\frac{dt}{dx}}$$

And to the Newton's law of viscosity for the transport of momentum across fluid layers due to the velocity gradient. (23)

$$\tau = \mu\frac{du}{dy}$$

By comparison of the above equations, we find that the Fourier equation describes the transport of heat energy due to temperature gradient, the shear equation describes the trans port of momentum due to velocity gradient while the Fick's law describes the mass trans port

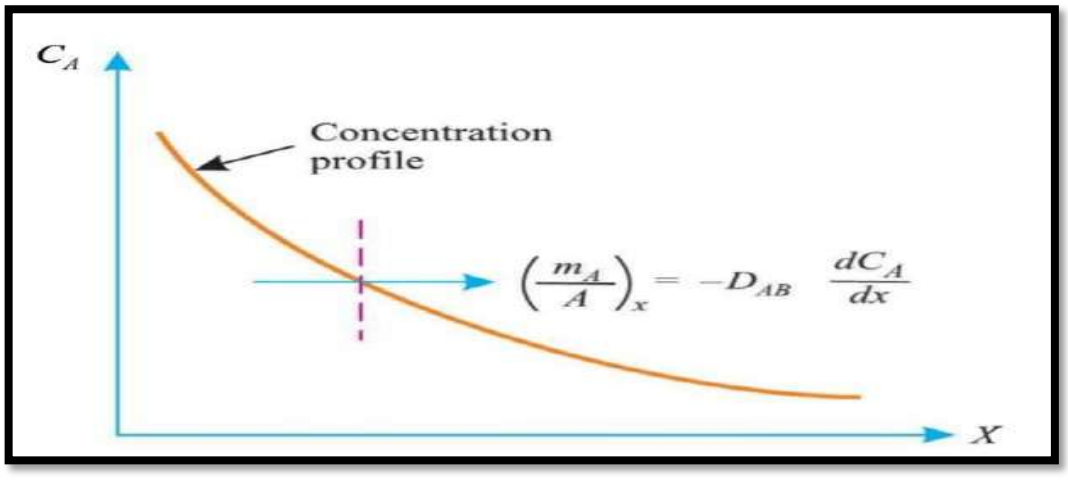


Figure I-3: Concentration profile

due to concentration gradient. (22)

I.4.Convective mass transfer

When a medium deficient in a component flows over a medium having an abundance of the component, then the component will diffuse into the flowing medium. Diffusion in the

Opposite direction will occur if the mass concentration levels of the component are interchanged. (24)

In this case a boundary layer develops and at the interface mass transfer occurs by molecular diffusion (In heat flow at the interface, heat transfer is by conduction). (24)-5

Velocity boundary layer is used to determine wall friction. Thermal boundary layer is used to determine convective heat transfer. Similarly concentration boundary layer is used to determine convective mass transfer.The Fig. shows the flow of a mixture of components *A* and *B* with a specified constant concentration over a surface rich in component *A*. A concentration boundary layer develops. (24)

The concentration gradient varies from the surface to the free stream. At the surface the mass transfer is by diffusion. Convective mass transfer coefficient *hm* is defined by the equation, where *hm* has a unit of m/s. (24)

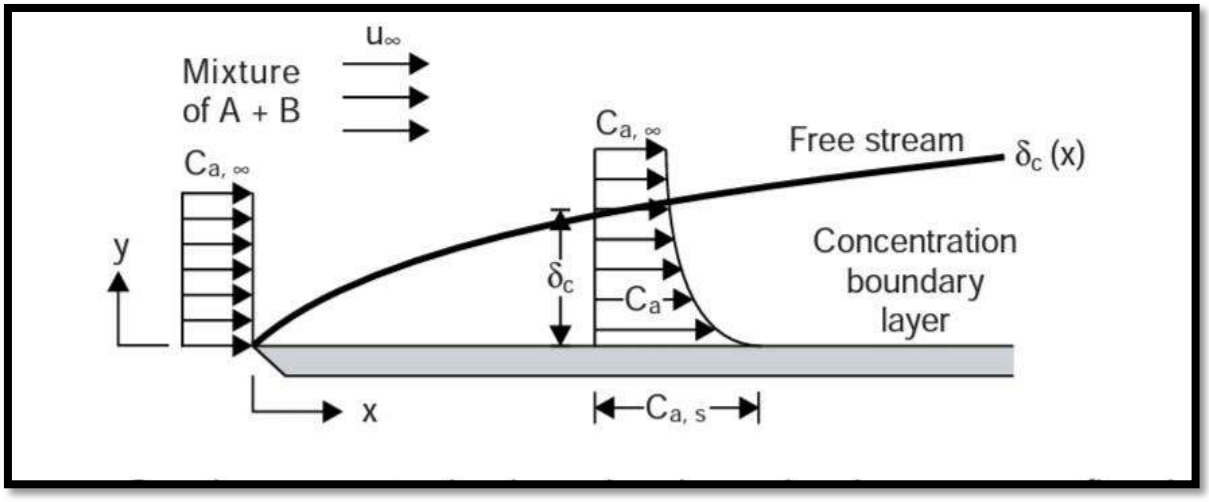


Figure I-4: Species concentration boundary layer development on flat plate

Mass transfer by convection involves the transportation of material between a boundary sur face and a moving fluid or between two immiscible moving fluids. It is expressed as: (25)

$$\frac{m_A}{A} = h_m(\Delta C_A) \quad \textbf{(I-3)}$$

I.5.Similarity between heat and mass transfer

It is possible from similarity between the heat convection equation and mass convection equation to obtain value of *hm*. (called as Lewis number) (26)

$$\frac{h}{h_m} = \rho C_P / Le^{2/3} \quad \textbf{(I-4)}$$

where

$$Le = \frac{\alpha}{D} \quad \textbf{(I-5)}$$

Many of the correlation in heat transfer can be applied to mass transfer under similar condition, by replacing Nusselt number by Sherwood number and Prandtl number by Schmidt number. (26)

I.6.Modes of mass transfer

The mechanism of mass transfer depends greatly on the dynamics of the system in which it occurs. Like those of heat transfer, there are different modes of mass transfer, which are: (27)

- Mass transfer by diffusion.
- Mass transfer by convection.
- Mass transfer by change of phase.

Mass transfer by diffusion (molecular or eddy diffusion):

I.6.1.Mass transfer by diffusion (molecular or eddy diffusion) :

. The transport of water on a microscopic level as a result of diffusion from a region of high concentration to a region of low concentration in a system/mixture of liquids or gases is called molecular diffusion. It occurs when a substance diffuses through a layer of stagnant fluid and may be due to concentration, temperature or pressure gradients. In a gaseous mixture, molecular diffusion occurs due to random motion of the molecules. (27)

When one of the diffusing fluids is in turbulent motion, the eddy diffusion takes place. Mass transfer is more rapid by eddy diffusion than by molecular diffusion. An example of an eddying diffusion process is dissipation of smoke from a smoke stack. Turbulence causes mixing and transfer of smoke to the ambient air. (27)

I.6.2. Mass transfer by convection

Mass transfer by convection involves transfer between a moving fluid and a surface, or between two relatively immiscible moving fluids. The convective mass transfer depends on the transport properties and on the dynamic (laminar or turbulent) characteristics of the flowing fluid. Example: The evaporation of ether (27)

I.6.3.Mass transfer by change of phase

Mass transfer occurs whenever a change from one phase to another takes place. The mass transfer in such a case occurs due to simultaneous action of convection and diffusion. Somes exemples are : (27)

- Hot gases escaping from the chimney rise by convection and then diffuse into the air above the chimney.
- Mixing of water vapor with air during evaporation of water from the lake surface (partly by convection and partly by diffusion).
- Boiling of water in open air there is first transfer of mass from liquid to vapor state and then vapor mass from the liquid interface is transferred to the open air by convection as well as by diffusion.

I.7.Conclusion:

Heat transfer describes the exchange of thermal energy between physical systems, as a function of temperature, by dissipating heat. This chapter has allowed us to review the generalities of heat transfer and the different parameters involved in this phenomenon, in order to proceed and facilitate the interpretation and discussion of the results.

Chapter II

Heat Transfer and Convection

II.1. Introduction

The present standard of living is made possible by the energy available in the form of heat from various sources like fuels. The process by which this energy is converted for everyday use is studied under thermodynamics, leaving out the rate at which the energy is transferred. In all applications, the rate at which energy is transferred as heat, plays an important role. The designs of all equipments involving heat transfer require the estimate of the rate of heat transfer. There is no need to list the various equipments where heat transfer rate influences their operation. (28)

The driving potential or the force which causes the transfer of energy as heat is the difference in temperature between systems. Other such transport processes are the Transfer of Momentum, mass and electrical energy. In addition to the temperature difference, physical parameters like geometry, material properties like conductivity, flow parameters like flow velocity also influence the rate of heat transfer. (28)

The aim of this text is to introduce the various rate equations and methods of determination of the rate of heat transfer across system boundaries under different situations (28)

The heat flow with temperature difference is one example of irreversible flow. In studies of processes that involve flow of heat or mass, the rate of flow is an important parameter. Heat can be transferred in three different ways: by conduction, convection and radiation. In most of the engineering applications, it is a combination of the two or three modes.

II.2. Heat

Thermodynamically, heat is a form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference. (29)

According to the modern or dynamical theory of heat: "Heat is a form of energy. The molecules of a substance are in parallel motion. The mean kinetic energy per molecule of the substance is proportional to its absolute temperature". (30)

A molecule may consist of one or two or many atoms depending upon the nature of the gas. The force of attraction between the molecules of a perfect gas is negligible. The atoms in a molecule vibrate with respect to one another, consequently a molecule has vibrational energy'. The whole molecule may rotate. About one or more axes, so it can have 'rotational energy. A molecule has translational energy' due to its motion. Thus kinetic energy of a molecule is the sum of its translational, rotational and vibrational energies. Summarily heat energy given to a substance is used in increasing its internal energy. Increase in internal energy causes increase in kinetic energy or potential energy or increase in both the energies. Due to increase in kinetic energy of a molecule, its translational, vibrational or rotational energy may increase. (30)

II.3. Definition of heat transfer

The study of heat transfer is directed to the estimation of rate of flow of energy as heat through the boundary of a system both under steady and transient conditions, and the determination of temperature field under steady and transient conditions, which also will provide the information about the gradient and time rate of change of temperature at various locations and time. T (x, y, z, τ) and $dT/dx, dT/dy, dT/dz, dT/d\tau$ etc. These two are interrelated, one being dependent on the other. However explicit solutions may be generally required for one or the other.(28)

II.4.Importance of heat transfer

Heat transfer may be defined as:

The transmission of energy from one region to another as a result of temperature gradient**.** (30)

The study of heat transfer is carried out for the follows purposes (30)

- To estimate the rate of flow of energy as heat through the boundary of a system under study (both under steady and transient conditions).
- To determine the temperature field under steady and transient conditions.

In almost every branch of engineering, heat transfer (and mass transfer) problems are encountered which cannot be solved by thermodynamic reasoning alone but require an

analysis based on heat transfer principles. The areas covered under the discipline of heat transfer are: (30)

- Design of thermal and nuclear power plants including heat engines, steam generators, condensers and other heat exchange equipments, catalytic converters, heat shields for space vehicles, furnaces, electronic equipments etc.
- Internal combustion engines.
- Refrigeration and air conditioning units.
- Design of cooling systems for electric motors, generators and transformers.
- Heating and cooling of fluids etc. in chemical operations.
- Construction of dams and structures; minimization of building-heat losses using improved insulation techniques.
- Thermal control of space vehicles.
- Heat treatment of metals.
- Dispersion of atmospheric pollutants

II.5.Differences between thermodynamics and heat transfer

The fundamental differences between thermodynamics and heat transfer are given below:

To understand the difference between thermodynamics and heat transfer, let us consider the cooling of a hot steel bar which is placed in a water bath.

Thermodynamics may be used to predict the final equilibrium temperature of the steel bar-water combination; however, it will not help us to find out how long it takes to reach this equilibrium condition or what the temperature of the bar will be after a certain length of time before the equilibrium condition is attained. Heat transfer on the other hand, may be used to predict the temperatures of both the bar and the water as a function of time. Heat transfer theory combines thermodynamics and rate equations together (to quantify the rate at which heat transfer occurs in terms of the degree of non-equilibrium). (31)

Tableau II-1: Difference between thermodynamics and heat transfer modes of heat transfer

Thermodynamics	Heat transfer
• It deals with the equilibrium states of matter, and precludes the existence of temperature gradient • When a system change from one equilibrium state to determine the quantity of work and heat interaction. It describes how much heat is to be exchanged during a process but does not hint how the same could be achieved	• It is inherently a non- equilibrium process (since a temperature gradient must exist for exchange of heat to place) • It helps to predict the distribution of temperature and to determine the rate at which energy is transferred across a surface of interest due to temperature gradient at the surface, and difference of temperature between different surfaces

II.6.Modes of heat transfer

Heat transfer which is defined as the transmission of energy from one region to another as a result of temperature gradient takes place by the following three modes (31)

- Conduction.
- Convection.
- Radiation.

Heat transmission, in majority of real situations, occurs as a result of combinations of these modes of heat transfer. Example: The water in a boiler shell receives its heat from the fire-bed by conducted, convected and radiated heat from the fire to the shell, conducted heat through the shell and conducted and convected heat from the inner shell wall, to the water. Heat always flows in the direction of lower temperature.

The above three models are similar in that a temperature differential must exist and the heat exchange is in the direction of decreasing temperature; each method, however, has different controlling laws.

II.6.1.Conduction

"Conduction" is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance. (31)

In solids, the heat is conducted by the following two mechanisms: (31)

- ✓ By lattice vibration (the faster moving molecules or atoms in the hottest part of a body transfer heat by impacts some of their energy to adjacent molecules).
- ✓ By transport of free electrons (Free electrons provide an energy flux in the direction of decreasing temperature - For metals, especially good electrical conductors, the electronic mechanism is responsible for the major portion of the heat flux except at low temperature).

In case of gases, the mechanism of heat conduction is simple. The kinetic energy of a molecule is a function of temperature. These molecules are in a continuous random motion exchanging energy and momentum. When a molecule from the high temperature region collides with a molecule from the low temperature region, it loses energy by collisions. (31)

In liquids, the mechanism of heat is nearer to that of gases. However, the molecules are more closely spaced and intermolecular forces come into play. (31)

II.6.2.Convection

"Convection" is the transfer of heat within a fluid by mixing of one portion of the fluid with another. (31)

- ✓ Convection is possible only in a fluid medium and is directly linked with the transport of medium itself.
- ✓ Convection constitutes the macroform of the heat transfer since macroscopic particles of a fluid moving in space cause the heat exchange
- ✓ The effectiveness of heat transefer by convection depends largely upon the mixing motion of the fluid.

This mode of heat transfer is met with in situations where energy is transferred as heat to a flowing fluid at any surface over which flow occurs. This mode is basically location in a

very thin fluid layer at the surface and then mixing caused by the flow. The heat flow depends on the properties of fluid and is independent of the properties of the material of the surface. However, the shape of the surface will influence the flow and hence the heat transfer. (31)

Free or natural convection**.** Free or natural convection occurs when the fluid circulates by virtue of the natural differences in densities of hot and cold fluids; the denser portions of the fluid move downward because of the greater force of gravity, as compared with the force on the less dense. (31)

Forced convection**.** When the work is done to blow or pump the fluid, it is said to be forced convection (31)

II.6.3.Radiation

"Radiation**"** is the transfer of heat through space or matter by means other than conduction or convection. (31)

Radiation heat is thought of as electromagnetic waves or quanta (as convenient) an emanation of the same nature as light and radio waves. All bodies radiate hear, so a transfer of heat by radiation occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits. Radiant energy (being electromagnetic radiation) requires no medium for propagation and will pass through vacuum. (31)

- The properties of radiant heat in general, are similar to those of light. Some of the properties are:
- It does not require the presence of a material medium for its transmission.
- Radiant heat can be reflected from the surfaces and obeys the ordinary laws of reflection.
- It travels with velocity of light.
- Like light, it shows interferences, diffraction and polarisation etc.
- It follows the law of inverse square

The wavelength of heat radiations is longer than that of light waves, hence they are invisible to the eye. (31)

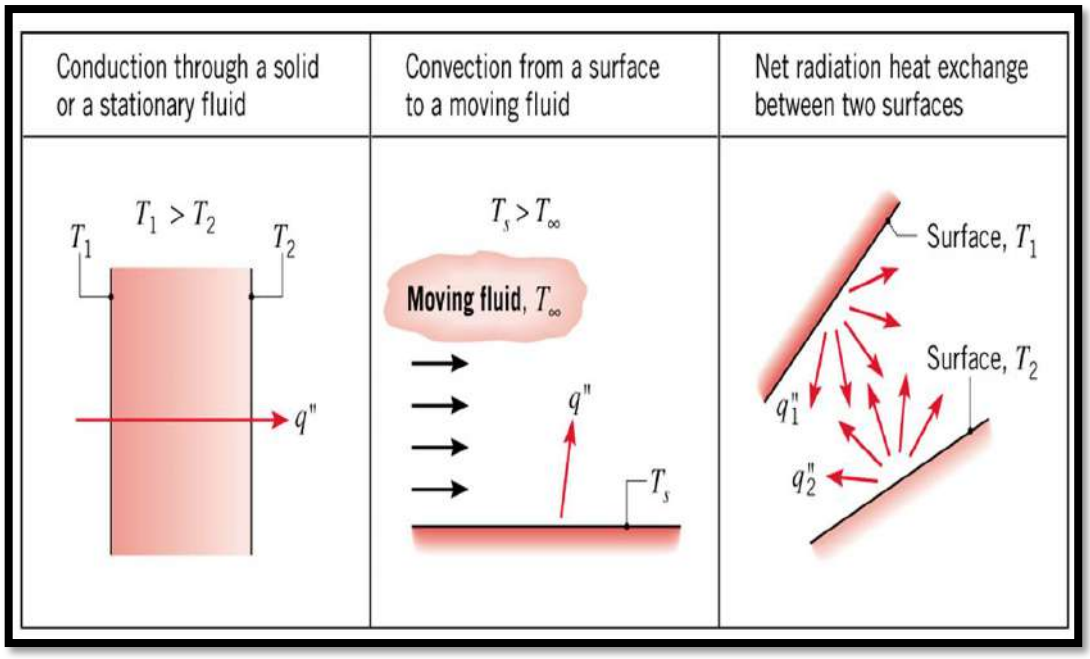


Figure II-1: Modes of heat transfer combined modes on heat transfer

II.7.Combined modes of heat transfer

Previous sections treated each mode of heat transfer separately. But in practice all the three modes of heat transfer can occur simultaneously. Additionally heat generation within the solid may also be involved. Most of the time conduction and convection modes occur simultaneously when heat from a hot fluid is transferred to a cold fluid through an intervening barrier. Consider the following example. A wall receives heat by convection and radiation on one side. After conduction to the next surface heat is transferred to the surroundings by convection and radiation. This situation is shown in Fig (32)

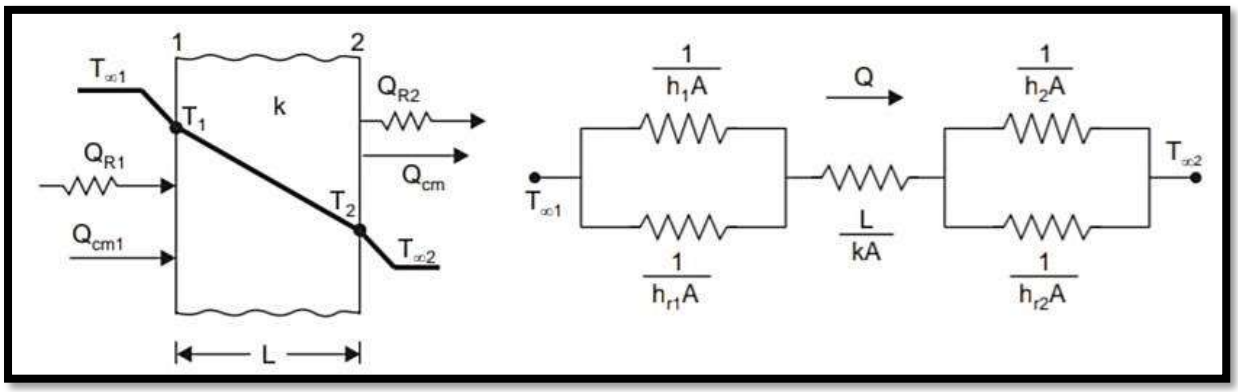


Figure II-2 : Combined modes of heat transfer

The heat flow is given by equation (II-1) (32)

$$\frac{Q}{A} = \frac{T_\infty - T_\infty}{\frac{1}{hr1 + h_1} + \frac{1}{hr2 + h_2} + \frac{L}{k}} \quad \textbf{(II-1)}$$

where *hr*1 and *hr*2 are radiation coefficients and *h*1 and *h*2 are convection coefficients (32)

II.8.Heat Transfer by Convection

The term is applied to transport of heat as a volume of liquid or gas moves from a region of one temperature to that of another temperature. Thus, the transport of heat is linked with the movement of the medium itself. The convection can be observed in liquids if we carry out a simple experiment. Consider a pot with water which is placed over a burner. The water at the bottom of the pot is heated and becomes less dense than before due to its thermal expansion. Thus, the water at the bottom, which is less dense than the cold water in the upper portion, rises upwards. It transfers its heat by mixing as it rises. The movement of the water, referred to as the convection currents, can be observed by putting a few crystals of potassium permanganate in the bottom of the pot. Density differences and the gravitational force of the earth act to produce a force known as buoyancy force, which drives the flow. When the flow is due to the density differences only, it is called natural or free convection. Density differences may also be caused by the composition gradients. For example, water vapor rises mainly due to the lower density of water vapor present in the moist air. (33)

Convection is termed as forced if the fluid is forced to flow over a surface or in a duct by external means such as a fan, pump or blower, that is, the forced convection implies mechanically induced flow. (33)

Heat transfer processes involving change of phase of a fluid (boiling of liquids or condensation of vapors) are also considered to be convection because of the motion of fluid that is set up due to the rising vapor bubbles during boiling or the falling liquid droplets during the condensation. The heat transfer by convection is always accompanied by conduction. The combined process of heat transfer by convection and conduction is referred

to as convective heat transfer. The heat transfer, between a solid surface and a fluid, is expressed by Newton's law of cooling as (33)

$$q = hA\Delta t \quad \textbf{(II-2)}$$

Where Δt is the temperature difference between the fluid and the surface, A is the area of the surface transferring heat and h is known as heat transfer coefficient or film coefficient

(33)

In general, the value of the heat transfer coefficient h depends on the fluid-flow conditions, the thermophysical properties of the fluid and the type of flow passage. Order of magnitude of convective heat transfer coefficients

Consider a heated plate at temperature t_w as shown in Fig, which is exposed to a fluid flowing parallel to the plate surface at velocity U_∞ and is at a temperature t_∞. The velocity of the fluid at the plate surface will be zero because of the viscous effect. Since the velocity of the fluid at the wall is zero, we can imagine that there exists a thin film of the fluid quite close to the wall, which is practically stationary. In most of the cases, the temperature gradient is confined to this thin layer where at a greater distance from the wall, only a small temperature difference exists because of the mixing of the fluid. The heat is, thus, transferred across the film by conduction. This heat is then carried away by fluid motion. (33)

Assuming that the temperature variation in the fluid film is linear, the flow of heat across the film can be expressed by Fourier's law as (33)

$$q = k_f A \frac{(t_w - t_\infty)}{\delta_f} \quad \textbf{(II-3)}$$

Where δ_f the thickness of the fluid film and kf is is the thermal conductivity of the fluid

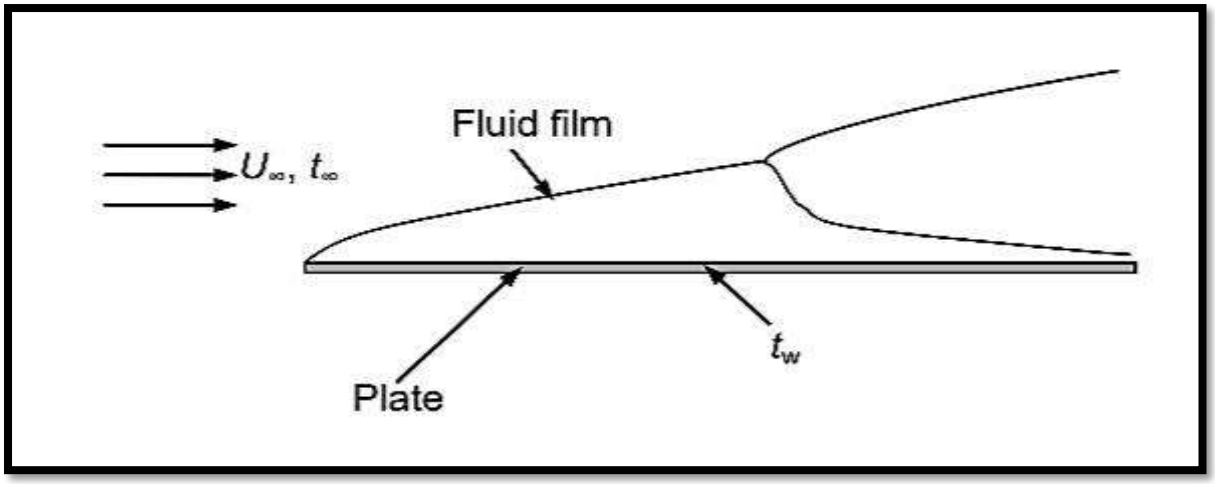


Figure II-3 : Cooling of hot plate by flowing fluid

II.9.The basic laws of heat transfer and their application

The basic laws governing heat transfer and their application are as below: (28)

- **First law of thermodynamics postulating the energy conservation principle:**

This law provides the relation between the heat flow, energy stored and energy generated in a given system. The relationship for a closed system is: The net heat flow across the system boundary + heat generated inside the system = change in the internal energy, of the system. This will also apply for an open system with slight modifications. The change in internal energy in a given volume is equal to the product of volume density and specific heat ρcV and dT where the group ρcV is called the heat capacity of the system. The basic analysis in heat transfer always has to start with one of these relations. (28)

- **The second law of thermodynamics :**

The second law of thermodynamics establishing the direction of energy transport as heat. The law postulates that the flow of energy as heat through a system boundary will always be in the direction of lower temperature or along the negative temperature gradient. (28)

- Newton's laws of motion used in the determination of fluid flow parameters.
- Law of conservation of mass, used in the determination of flow parameters.
- The rate equations as applicable to the particular mode of heat transfer.

II.10.Overview on convection

II.10.1.Introduction

The basic mechanism of convection was not discussed so far. it is attempted to explain the basic mechanism of convection. In industrial processes involving heat transfer, convection plays a very important role. When heat is to be transferred from one fluid to another through a barrier convection is involved on both sides of the barrier. In most cases the main resistance to heat flow is by convection. (34)

The process of heat transfer between a surface and a fluid flowing in contact with it is called convection. If the flow is caused by an external device like a pump or blower, it is termed as forced convection. If the flow is caused by the buoyant forces generated by heating or cooling of the fluid the process is called as natural or free convection. (34)

In the previous chapters the heat flux by convection was determined using equation (34)

$$q = h(T_s - T_\infty) \quad \textbf{(II-4)}$$

q is the heat flux in W/m2, Ts is the surface temperature and T_∞ s the fluid temperature of the free stream, the unit being °C or K. Hence the unit of convective heat transfer coefficient h is W/m2 K or W/m2 °C both being identically the same. (34)

Convective heat transfer coefficient is influenced by fluid properties like density, viscosity and other thermal properties like specific heat, conductivity the flow velocity and the surface geometry. As the properties vary with temperature and location the value of convective heat transfer coefficient will vary from point to point. This leads to the situation that analytically derived equations are applicable only to a limited extent. Practical correlations obtained through experiments are discussed in the next chapters. Property table for various fluids available in hand books is necessary for obtaining numerical value for convective heat transfer coefficient. (34)

II.10.2.Mechanism of convection

In conduction, energy is transferred as heat either due to free electron flux or lattice vibration. There is no movement of mass in the direction of energy flow. In convection, energy flow occurs at the surface purely by conduction. But in the next layers both conduction and diffusion-mass movement in the molecular level or macroscopic level occurs. Due to the mass movement the rate the rate of energy transfer is higher. Higher the rate of mass movement, higher will be the heat flow rate. The velocity variation and the temperature variation at a point in the flow of a fluid over a surface is shown in Fig. (34)

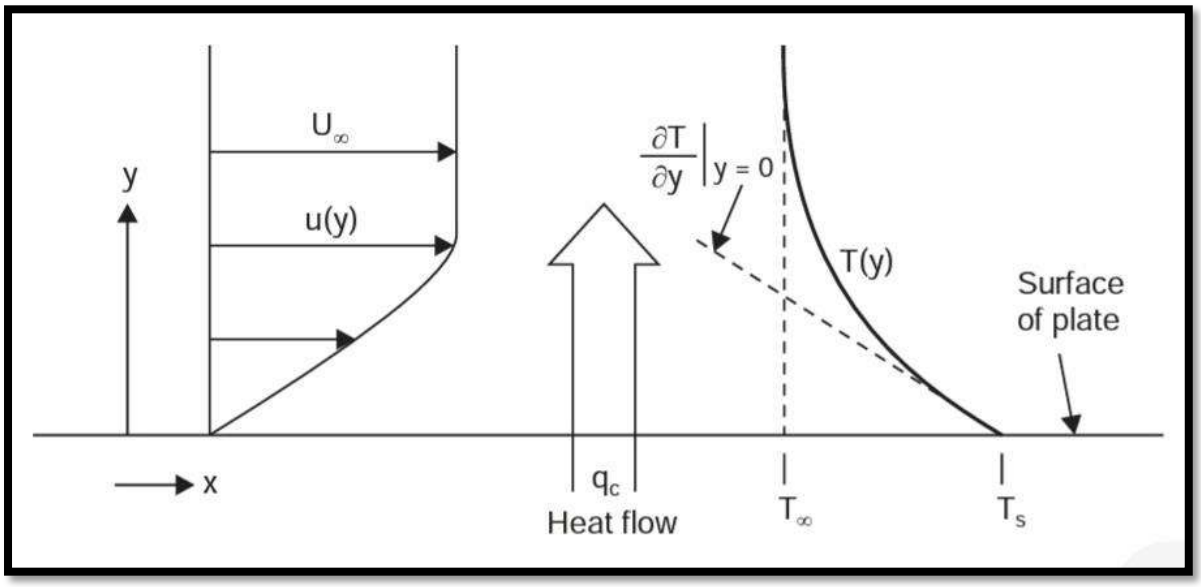


Figure II-4: Velocity and temperature variation of a point in fluid over a surface

The fluid coming in contact with the surface receives heat by conduction. This is passed on by diffusion and mass movement to the fluid in the free stream. (34)

Considering conduction at the surface layer the heat flux is given by the equation (34)

$$q = -k\frac{\partial T}{\partial y} \qquad \textbf{(II-5)}$$

Where k is the thermal conductivity of the fluid. Combining equations (II-4) and ((II-5)we obtain equation.((II-6) for Convection coefficient. (34)

$$\frac{q = -k\frac{\partial T}{\partial y}}{(T_s - T_\infty)} \quad \textbf{(II-6)}$$

As the values of thermal conductivity of the fluid and the temperatures of the surface and the fluid, Ts and T∞ are known, the value of convection coefficient can be determined if the temperature gradient at the surface is known. The model postulated is used to solve for temperature as a function of y so that the temperature gradient can be calculated. The gradient is influenced by the fluid stream and the surface. Boundary layer theory is applied for the determination of the gradient. (34)

II.10.3.Methods used in convection studies

The important methods of analysis used in convection studies are: (35)

1) Analytical method which can again be subdivied as
   - Formulating and solving the differential equation, also known as exact method
   - Formulating and solving integral equations using assumed profiles for velocity and temperature–(approximate analysis)
   - Numerical finite element method
2) Dimensional analysis
3) Analogical methods which apply solutions from one transport phenomenon to another
4) Empirical correlations developed from experimental results guided by the results of analytical methods and dimensional analysis

II.10.4.Forced and free convection

When heat transfer occurs between a fluid and a surface, if the flow is caused by a fan, blower or pump or a forcing jet, the process is called forced convection. The boundary layer development is similar to the descriptions in the previous section. When the temperature of a surface immersed in a stagnant fluid is higher than that of the fluid, the layers near the surface get heated and the density decreases in these layers. (35)

The surrounding denser fluid exerts buoyant forces causing fluid to flow upwards near the surface. This process is called free convection flow and heating is limited to a layer, as shown in Fig. The heat transfer rate will be lower as the velocities and temperature gradients are lower. If the surface temperature is lower, the flow will be in the downward direction. (35)

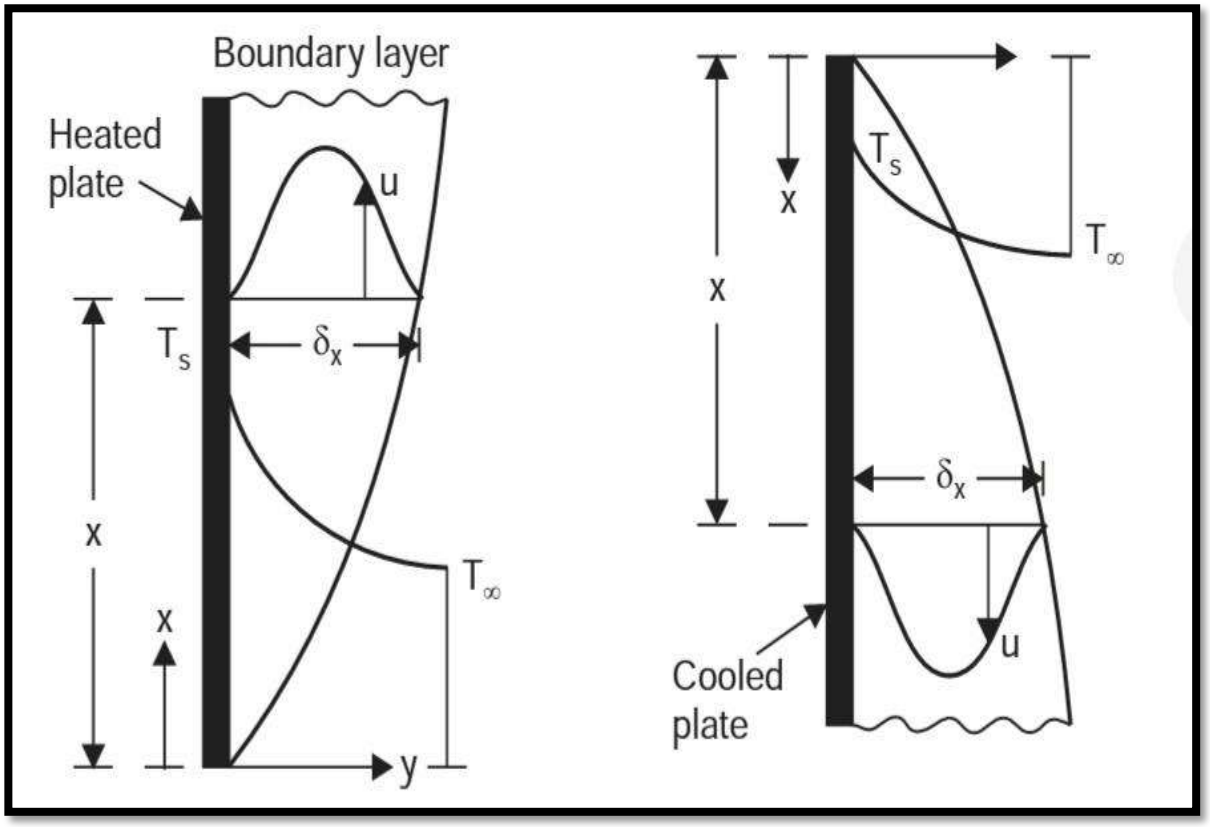


Figure II-5 : Free convection boundary layer near a vertical surface

II.10.5.Natural convection

II.10.5.1.Introduction

When a surface is maintained in still fluid at a temperature higher or lower than that of the fluid, a layer of fluid adjacent to the surface gets heated up or cooled. A density difference is created between this layer and the still fluid surrounding it. The density difference introduces a buoyant force causing flow of the fluid near the surface. Heat transfer under such conditions is known as natural or free convection. Usually a thin layer of flowing fluid forms over the surface. The fluid beyond this layer is essentially still, and is at a constant temperature of T_∞. (36)

The flow velocities encountered in free convection is lower compared to flow velocities in forced convection. Consequently the value of convection coefficient is lower, generally by one order of magnitude. Hence for a given rate of heat transfer larger area will be required. As there is no need for additional devices to force the fluid, this mode is used for heat transfer in simple devices as well as for devices which have to be left unattended for long periods. (36)

The heat transfer rate is calculated using the general convection equation given below: (36)

$$Q = h\,A(T_w - T_\infty) \qquad \textbf{(II-7)}$$

T_∞ $->$ fluid temperature at distances well removed from the surface (here the stagnant fluid temperature).

II.10.5.2.Characteristic parameters in free convection

It has been observed that during heat transfer from a heated surface to the surrounding fluid, the fluid adjacent to the surface gets heated, this results in thermal expansion of the fluid and reduction its density (compared to the fluid away from the surface). Subsequently a buoyancy force acts on the fluid causing it to flow up the surface, and in the neighbourhood of the plate, hydrodynamic and thermal boundary layers are set up. Since here the flow velocity is developed due to difference of temperatures, the two boundary layers are of the same order irrespective of Prandtl number. (37)

A property that comes into play in free or natural convection is the coefficient of thermal expansion of the fluid defined by (37)

$$\beta = \frac{1}{\vartheta}\left(\frac{\partial \vartheta}{\partial T}\right) = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right) \qquad \textbf{II-8)}$$

For an ideal gas

$$\vartheta = \frac{RT}{\rho}\left(\frac{\partial \vartheta}{\partial T}\right) = \frac{R}{\rho}$$

And hence

$$\beta = \frac{1}{T}$$

Since in free convection heat transfer coefficients are low and Reynalds number is not an inde pendent parameter, a new dimensionless grouping plays the major role (in free convection) which incorporates the coefficient of thermal expansion B in the expression. This dimensionless grouping is called the Grashoff number, expressed as (37)

$$GR = \frac{L^3 g \beta \Delta t}{\vartheta^2} \qquad \textbf{II-9)}$$

The role of Grashoff number is the same in free convection as that of Reynolds number in forced convection.

The critical Grashoff number for the flow of air over a flat plate has been observed to be 4×10^8 (approximately).

In general

$$Nu = f(\mathrm{Gr}, \mathrm{Pr}) = \mathrm{C}\ (\mathrm{Gr})^{\mathrm{a}}(\mathrm{Pr})^{\mathrm{b}} \qquad \textbf{II-10)}$$

In several cases, the above relation simplifies to the from

$$Nu = C(Gr, Pr)^m \qquad \textbf{II-11)}$$

The product is also a criterion of laminar or turbulent character of the flow as determined by its values Thus.

For laminar flow

$$10^4 < GrPr < 10^4$$

For turbulent flow

$$GrPr > 10^9$$

The values of **Gr** and **Pr** are evaluated at the mean film temperature

$$\left(t_f = \frac{t_w - t_\infty}{2}\right)$$

II.10.6.Methods of analysis

Derivation of continuity and momentum equations. Consider the element in the boundary layer of size *dx dy* as shown in Fig.

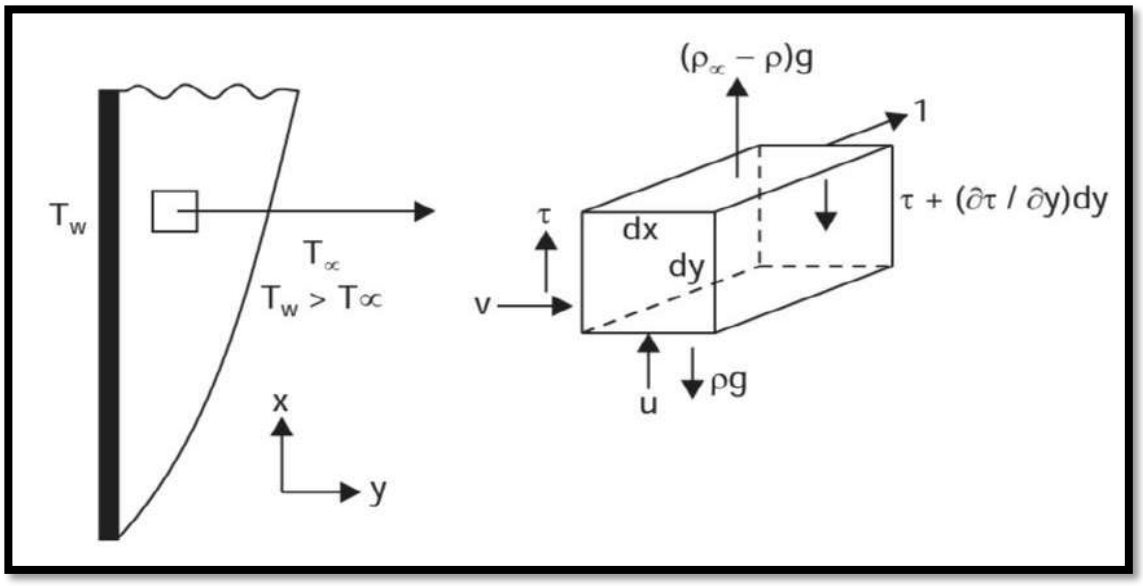


Figure II-6 : Forced on an element in the boundary layer

The continuity equation is found identical to that in forced convection: (38)

$$\frac{\partial u}{\partial x}+\frac{\partial U}{\partial y}=0 \qquad \textbf{(II-12)}$$

In the momentum equation, an additional force term is involved namely the buoyant force term given by: $g\,\beta\,(T-T_\infty)$. (38)

The resulting momentum equation is

$$u\frac{\partial u}{\partial x}+U\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2} \qquad \textbf{(II-13)}$$

Where β is the coefficient of cubical expansion (equal to $1/T$ for gases–T in absolute units).

These two equations are to be solved to obtain the velocity distribution and hydrodynamic boundary layer thickness, the boundary conditions being $u = 0$ at $y = 0$ and $u = 0$ at $y = \delta$ (boundary layer thickness) (38)

The energy equation is the same as that in forced convections, with no additional terms involved. (19).

$$u\frac{\partial u}{\partial x}+U\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2} \qquad \textbf{II-14)}$$

The boundary conditions are $T = T_w$ at $y = 0$ and $T = T_\infty$ at $y = \delta$

An idea about the dimensionless numbers correlating the phenomenon can be obtained by non-dimensionalising these equations. In the Natural convection no quantity like free stream velocity u_∞ is encountered. So a reference velocity term u_x is introduced. The following definitions are used for nondimensionalising these equations (38)

$$x^* = x/L,\ y^* = y/L,\ u^* = u/u_x,\ v^* = v/u_x$$

and
$$T^* = \frac{T - T_\infty}{T_\omega - T_\infty} \qquad \textbf{(II-15)}$$

The momentum equation reduces to

$$u^* \frac{\partial u^*}{\partial x^*} + U^* \frac{\partial U^*}{\partial y^*} = \frac{g\beta(T_\omega - T_\infty)L}{u_x^2} T^* + \frac{1}{Re} \cdot \frac{\partial^2 u^*}{\partial y^{*2}} \qquad \textbf{II-16)}$$

The energy equation reduces to

$$u^* \frac{\partial T^*}{\partial x^*} + U^* \frac{\partial T^*}{\partial y^*} = \frac{1}{Re\ Pr} \cdot \frac{\partial^2 T^*}{\partial y^{*2}} \qquad \textbf{II-17)}$$

Where Re = Reynolds number = $u_x L/\nu$

Three dimensionless parameters identified in the process are *Re*, *Pr* and

$$\frac{g\beta(T_\omega - T_\infty)L}{u_x^2}$$

As u_x cannot be determined it is found convenient to eliminate the quantity by multiplying this term with Re^2

$$\frac{g\beta(T_\omega - T_\infty)L}{u_x^2} \frac{u_x^2}{v^2} = \frac{g\beta(T_\omega - T_\infty)L^3}{v^2} \qquad \textbf{II-18)}$$

This group can be recognised as Grashof number already defined.

The heat conducted at the fluid surface is equal to the heat convected to the fluid. This principle leads to the formulation of Nusselt number. (38)

$$-k \left(\frac{\partial T}{\partial y}\right)_{y=0} = h(T_\omega - T_\infty)$$

$\frac{\partial T}{\partial y}$ is solved for by using the energy equation involving *u* and *T*. The solution for *u* is obtained from the momentum and continuity equations. This analysis determines that the heat transfer correlations for natural convection of the form (38)

$$Nu = f(Gr \cdot Pr) \qquad \textbf{II-19)}$$

II.11.Overview on dimensional analysis

II.11.1.Introduction

Dimensional analysis is a mathematical technique which makes use of the study of the dimensions for solving several engineering problems. Each physical phenomenon can be expressed by an equation giving relationship between different quantities, such quantities are dimensional and non-dimensional. Dimensional analysis helps in determining a systematic arrangement of the variables in the physical relationship, combining dimensional variables to form non-dimensional parameters. It is based on the principle of dimensional homogeneity and uses the dimensions of relevant variables affecting the phenomenon. Dimensional analysis has become an important tool for analysing fluid flow problems. It is specially useful in presenting experimental results in a concise form. (39)

II.11.2.Uses of Dimensional Analysis:

- To test the dimensional homogeneity of any equation of fluid motion.
- To derive rational formulae for a flow phenomenon
- To derive equations expressed in terms of non-dimensional parameters to show the relative significance of each parameter
- To plan model tests and present experimental results in a systematic manner; thus making it possible to analyse the complex fluid flow phenomenon. (39)

II.11.3.Dimentions

The various physical quantities used in fluid phenomenon can be expressed in terms of fundamental quantities or primary quantities. The fundamental quantities are mass, length, time and temperature, designated by the letters M. L, T, θ respectively. Temperature is specially useful in compressible flow. The quantities which are expressed in terms of the fundamental or primary quantities are called derived or secondary quantities, (velocity, area,

acceleration etc.). The expression for a derived quantity in terms of the primary quantities is called the dimension of the physical quantity. (39)

II.11.4.Methods of dimensional analysis

With the help of dimensional analysis the equation of a physical phenomenon can be developed in terms of dimensionless groups or parameters and thus reducing the number of variables. The methods of dimensional analysis are based on the Fourier's principle of homogeneity. Out of several methods of dimensional analysis, the following two methods will be discussed. (39)

II.11.4.1.Rayleigh's method

This method gives a special form of relationship among the dimensionless group, and has the inherent drawback that it does not provide any information regarding the number of dimensionless groups to be obtained as a result of dimensional analysis. Due to this reason this method has become obsolete and is not favored for use Rayleigh's method is used for determining the expression for a variable which depends upon maximum three or four variables only. In case the number of independent variables become more than four, then it is very difficult to find the expression for the dependent variable

In this method a functional relationship of some variables is expressed in the form of an exponential equation which must be dimensionally homogeneous. Thus if X is a variable which depends on $X_1, X_2, X_3 \ldots . X_n$;the functional equation can be written as: (39)

$$X = f(\mathrm{X_1}, \mathrm{X_2}, \mathrm{X_3}, \ldots \mathrm{X_n}) \qquad \textbf{II-20)}$$

In the above equation X is a dependent variable, while $(\mathrm{X_1}, \mathrm{X_2}, \mathrm{X_3}, \ldots \mathrm{X_n})$ are independent variables. A dependent variable is the one about which information is required while independent variables are those which govern the variation of dependent variable. (39)

Equation (II-20)can also be written as

$$X = \left(X_1^a, X_2^b, X_3^c, \ldots X_b^n\right) \qquad \textbf{(II-21)}$$

where C is a constant and a, b, c, ... n are the arbitrary powers. The values of a, b, c, n are obtained by comparing the powers of the fundamental dimensions of both sides. Thus the expression is obtained for dependent variable. (39)

II.11.4.2.Buckinggham's it-method/theorem

When a large number of physical variables are involved Rayleigh's method of dimensional analysis becomes increasingly laborious and cumbersome. Buckingham's method is an improvement over the Rayleigh's method. Buckingham designated the dimensionless group by the Greek capital letter *(Pi).* It is, therefore, often called Buckingham -method. The advantage of this method over Rayleigh's method is that it lets us know, in advance of the analysis, as to how many dimensionless groups are to be expected. (39)

The Buckingham's π -theorem states as follows:

"If there are n variables (dependent and independent variables) in a dimensionally homogeneous equation and if these contain mn fundamental dimensions (such as M. L. T. etc.), then the variables are arranged into (n-m) dimensionless terms. These dimensionless terms are called π-terms". (39)

Mathematically, if any variable X_1,. depends on independent variables.$X_2, X_3, \ldots X_n$: the functional equation may be written as (39)

$$X_1 = f(X_2, X_3, X_4, \ldots X_n) \qquad \textbf{(II-22)}$$

Equation ((II-22) can be also be written as:

$$f_1(X_2, X_3, X_4, \ldots X_n) = 0 \qquad \textbf{II-23)}$$

It is a dimensionally homogeneous equation and contains a variables. If there are a fundamental dimensions, then according to Buckingham's π t-theorem, it II-23)can be written in terms of number of π-terms (dimensionless groups) in which number of π-terms is equal to (n-m). Hence Eqn. II-23) becomes as: (39)

Each dimensionless π-term is formed by combining m variables out of the total n variables with one of the remaining (n-m) variables each π-term contains (m+1) variables. These mn variables which appear repeatedly in each of π-term are consequently called repeating variables and are chosen from among the variables such that they together involve all the fundamental dimensions and they themselves do not form a dimensionless parameter. Let in the above case X_2, X_3, and X_4, are the repeating variables if the fundamental dimensions m (M, L, T) = 3. Then each term is written as: (39)

$$\begin{cases} \pi_1 = X_2^{a_1}, X_3^{b_1}, X_4^{c_1}, X_1 \\ \pi_2 = X_2^{a_2}, X_3^{b_2}, X_4^{c_2}, X_5 \\ \pi_{n-m} = X_2^{a_{n-m}}, X_3^{b_{n-m}}, X_4^{c_{n-m}}, X_n \end{cases} \quad \textbf{II-24)}$$

where $a_1, b_1, c_1, a_2, b_2, c_2$ etc. are the constants, which are determined, by considering dimensional homogeneity. These values are substituted in Eqn II-24). and values of $\pi_1, \pi_2 \pi_3, \ldots \pi_{n-m}$ are obtained. These values of 's are substituted in eqution. The final general equation for the phenomenon may then be obtained by expressing anyone of the π-term as a function of the other as: (39)

$$\begin{cases} \varphi(\pi_2, \pi_3, \pi_4, \pi_{n-m}) \\ \varphi(\pi_2, \pi_3, \pi_4, \pi_{n-m}) \end{cases} \quad \textbf{II-25)}$$

II.11.5.Advantages and limitation of dimensional analysis

II.11.5.1.Advantages

* It expresses the functional relationship between the variables in dimensionless terms.
* By the proper selection of variables, the dimensionless parameters can be used to make certain logical deductions about the problem.
* Design curves, by the use of dimensional analysis, can be developed from the experimental data or direct solution of the problem
* It enables getting up a theoretical solution in a simplified dimensionless form

* Dimensionless analysis provides partial solutions to the problems that are too complex to be dealt with mathematically.

* Dimensional analysis is a useful tool in the analysis and correlation of experimental data. in the planning of experiments and in the formulation of empirical correlation describing a particular phenomenon.

* The results of one series of tests can be applied, with the help of dimensional analysis, to a large number of other similar problems. (40)

II.11.5.2.Limitations

* Dimensional analysis does not give any clue regarding the selection of variables. If the variables are wrongly taken, the resulting functional relationship is erroneous. It provides the information about the grouping of variables. In order to decide whether selected variables are pertinent or superfluous experiments have to be performed.

* The complete information is not provided by dimensional analysis, it only indicates that there is some relationship between the parameters. It does not give the values of coefficients in the functional relationship. The values of coefficients and hence the nature of functions can be obtained only from experiments or from mathematical analysis.

* No information is given about the internal mechanism of the physical phenomenon.

* Generally it is desired to find the effect of one physical quantity upon a number of other physical quantities that are supposed to enter into a problem. It is not possible to get such information with the help of dimensional analysis. (40)

II.11.6.Dimensionless numbers and their physical significance

II.11.6.1.Reynolds number (Re):

It is defined as the ratio of the inertia force to the viscous force. (40)

$$Re = \frac{Inertia\ force}{Viscous\ force} = \frac{\rho U^2 L^2}{\mu UL} = \frac{UL}{v} \quad \textbf{(II-26)}$$

- Reynolds number signifies the relative predominance of the inertia to the viscous forces occuring in the flow systems.
- The higher the value of Re the greater will be the relative contribution of inertia effect. The smaller the value of Re, the greater will be the relative magnitude of the viscous stresses.
- Reynolds number is taken as an important criterion of kinematic and dynamic similarities in forced convection heat transfer.

II.11.6.2.Prandtl number (Pr):

It is the ratio of kinematic viscosity (v) to thermal diffusivity (α). (40)

$$Pr = \frac{\mu c_p}{k} = \frac{\rho v c_p}{k} = \frac{v}{\left(k/\rho c_p\right)} = \frac{v}{\alpha} \quad \textbf{(II-27)}$$

Kinematic viscosity indicates the impulse transport through molecular friction whereas thermal diffusivity indicates the heat energy transport by conduction process.

- Prandtl number provides a measure of the relative effectiveness of the momentum and energy transport by diffusion.
- Prandtl number is a connecting link between the velocity field and temperature field, and its value strongly influences relative growth of velocity and thermal boundary layers.

II.11.6.3.Nusselt number (Nu)

Nusselt number can be defined in several ways:

It is the ratio of heat flow rate by convection process under a unit temperature gradient to the heat flow rate by conduction process under a unit temperature gradient through a stationary thickness of L meters. Thus (40)

$$Nu = \frac{Q_{conv}}{Q_{cond}} = \frac{h}{k/L} = \frac{hL}{k} \quad \textbf{(II-28)}$$

It is the ratio of heat transfer rate, Q to the rate at which heat would be conducted within the fluid under a temperature gradient of $\Delta\theta/L$. Thus

$$Nu = \frac{Q}{(\Delta\theta . k)/L} = \frac{Q}{\Delta\theta} \cdot \frac{L}{k} = \frac{hL}{k} \quad \textbf{(II-29)}$$

It is the ratio of characteristic length L to the thickness Δx of a stationary fluid layer conducting the heat at the same rate under the same temperature difference as in the case of convection process. Thus

$$Q = k\frac{\Delta t}{\Delta x} = h.\Delta t$$

Or

$$\Delta x = \frac{k}{h}$$

So

$$Nu = \frac{L}{\Delta x} = \frac{L}{k/h} = \frac{hL}{k} \quad \textbf{II-30)}$$

The Nusselt number is a convenient measure of the convective heat transfer coefficient. For a given value of the Nusselt number, the convective heat transfer coefficient is directly proportional to thermal conductivity of the fluid and inversely proportional to the significant length parameter. (40)

II.11.6.4.Stanton number (Sf)

It is the ratio of heat transfer coefficient to the flow of heat per unit temperature rise due to the velocity of the fluid.

$$St = \frac{h}{\rho U c_p} \quad \textbf{II-31)}$$

Or

$$St = \frac{hL/k}{\left[\frac{\rho UL}{\mu}\right]\left[\frac{\mu c_p}{k}\right]} = \frac{Nu}{Re \times Pr} \qquad \textbf{II-32)}$$

Thus, Stanton number may also be defined as the ratio of Nusselt number and the product of Reynolds number and Prandtl number.

It is worth noting that Stanton number can be used only in correlating forced convection data (since the expression contains the velocity U) (40)

II.11.6.5.Peclet number (Pe)

It is the ratio of mass heat flow rate by convection to the flow rate by conduction under a unit temperature gradient and through a thickness L.

$$Q_{conv} = \rho U c_p;\ Q_{cond} = \frac{k}{1} \times \frac{1}{L} = \frac{k}{L}$$

$$Pe = \frac{Q_{conv}}{Q_{cond}} = \frac{\rho U c_p}{k/L} = \frac{\rho c_p}{k} \cdot \frac{LU}{1} = \frac{LU}{\alpha} \qquad \textbf{(II-33)}$$

The Peclet number can be written as

$$Pe = Re \times Pr = \frac{\rho LU}{\mu} = \frac{\mu c_p}{k} = \frac{\rho c_p}{k} \cdot \frac{LU}{1} = \frac{LU}{\alpha}$$

It indicates that the Peclet number can be written as a function of Re and Pr also. (40)

II.11.6.6.Graetz number (G)

It is related only for the heat flow to the fluid flowing through circular pipe. It is defined as the ratio of heat capacity of fluid flowing through the pipe per unit length of the pipe to the conductivity of the pipe

$$G = \frac{\left[\frac{mc_p}{L}\right]}{k} = \frac{mc_p}{Lk} \qquad \textbf{II-34)}$$

Or

$$G = \frac{\left(\frac{\pi}{4}D^2 \cdot V \cdot \rho\right)\frac{c_p}{L}}{k} = \frac{\pi}{4}\frac{\rho VD}{\mu} \cdot \frac{\mu c_p}{k} \cdot \frac{D}{L} \quad \textbf{II-35)}$$

Or

$$G = \frac{\pi}{4} \cdot Re \cdot Pr \cdot \frac{D}{L} \quad \textbf{II-36)}$$

Where D and L are the diameter and length of the pipe respectively.

This can be written in the other form as

$$G = Pe\left(\frac{\pi D}{4}\right) \quad \textbf{II-37)}$$

This shows that Graetz number is merely a product of Peclet number and a constant. (40)

II.11.6.7.Grashoff number (Gr)

Grashoff number is related with natural convection heat transfer. It is defined as the ratio of the product of inertia force and buoyancy force to the square of viscous force. Thus

$$Gr = \frac{(Inertia\ force\ ) \times (Buoyancy\ force\ )}{(Viscous\ force)^2}$$

So

$$Gr = \frac{\rho^2 \beta g \Delta t L^3}{\mu^2} \quad \textbf{II-38)}$$

Grashoff number has a role in free convection similar to that played by Reynolds number in forced convection. Free convection is usually suppressed at sufficiently small Gr, begins at some critical value of Gr depending upon the arrangement and then becomes more and more effective with increasing Gr. (40)

II.12.Conclusion:

This chapter has been dedicated to define some parameters that we will use during our study to understand the problem initiations and to be able to extract some clues that will help us to find solutions for our case.

Chapter III

General information on Nanofluid and Biosurfactant and MHD

III.1.Nanofluid

In recent years, several energy systems have been developed in the industrial field producing a very high heat flux, where conventional cooling fluids (water, ethylene glycol and oil) are not efficient. The idea of improving the thermo-physical properties of fluids is to introduce solid particles of very good thermal characteristics and nanometric size dispersed in a base fluid in order to improve some of its properties.

They were first introduced by Choi (41) in 1995. Nanofluids are generally classified according to the nature of the nanoparticles that compose them into three categories, namely, metallic, metal oxide and non-metallic. Their applications are found in several sectors, including domestic, engineering and biomedical.

III.2.Nanoparticles and carrier fluids

A nanoparticle is an assembly of a few hundred to a few thousand atoms, Leading to an object of which at least one of the dimensions is of nanometric size (1-100 nm), nanoparticles are located at the border between the microscopic scale and the atomic or molecular scale. They are of both fundamental and applied interest, and are currently being studied extensively.

The most commonly used base fluids are:

- Water.
- Ethylene glycol (EG)
- Huiles.
- Refrigeration fluids (R12, R22, etc.)

The nanoparticles most used to obtain nanofluids are:

- Nanoparticles in metal oxides:
- Copper oxide (CuO)
- Titanium oxide (TiO_2)

- Silicon oxide (SiO_2).
- Aluminum oxide (AL_2O_3)
- Metal nanoparticles :
- Aluminium (Al)
- Copper (Cu).
- Gold (Au).
- Silver (Ag).
- Non-metallic nanoparticles :
- Carbon nanotubes (CNT).
- The diamond (C).

Nanoparticles can also be classified according to their size in each of the three dimensions:

- Fullerenes, particles, etc. have their three dimensions in the nanometric domain (point).
- Nanotubes, dendrometers, nanowires, fibers and fibrils have two nanometric dimensions (line).
- Thin films have only one nanometric dimension (line).

III.3.Thermo-physical properties :

The thermo-physical properties (density, specific heat, thermal expansion, dynamic viscosity, and thermal conductivity) of the solutions are profoundly modified by the addition of the nanoparticles. Many parameters characterizing these nanoparticles can have a noticeable effect on the values of the thermo-physical parameters of the obtained nanofluid (the nature of the nanoparticles, their size, the volume fraction **φ,** the conductivity of the base fluid f and that of the nanoparticles, the temperature of the medium T.... etc).

III.3.1.Specific heat

Heat conductivity generally is an important property, mainly in our study because it plays a very important role in the phenomenon of heat transfer, it can clearly indicate the heat transfer efficiency of the fluid or solid, conductivity depends on the temperature.

III.3.2.Volumetric mass

Volumetric mass of a nanofluid for a given reference temperature

III.3.3.Heat conductivity

The specific heat or mass heat capacity, noted $\mathbf{c_p}$, is defined by the quantity of energy to be brought by heat exchange to raise by one degree Kelvin the temperature of the unit mass of a substance.

III.3.4.Dynamic viscosity:

Relative viscosity is the ratio of the viscosity of the nanofluid to that of the base fluid Suspensions of nanoparticles in a fluid, often called nanofluids, have interesting thermal interesting thermal characteristics compared to traditional base fluids

Tableau III-1: Thermophysical properties of deferential materials

	Nanoparticles and basic fluid	**K (w/m k)**	**(k g/m2)**	**Cp (J/kg k)**	**(Pas)**
Metallic (solids)	Cu	400	8954	383	
	Fe	80.2	7870	447	
	Ni	90.7	8900	444	
	Au	317	19.3	129	
	Ag	429	10.5	235	
	C (diamond)	2300	3500	509	
Oxide Metallic (solids)	SiO2	1.38	2220	745	
	TiO2	8.4	4157	710	
	Al2O2	36	3970	765	
	CuO	69	6350	535	
	SiC	490	3160	675	
Liquids no metallic	The water	0.613	1000	4183	0.0008513
	Ethylene glycol(EG)	0.258	1132	2349	0.0157

III.4.Studies on nanofluids

Considering the importance given to nanofluids, several studies carried out on their physical properties such as heat transfer coefficient and dynamic viscosity proved that nanofluids are very different from the base fluid and presented better thermophysical characteristics. Indeed, the addition of metallic particles in a base fluid has shown an improvement of its thermal capacities.

III.5.Techniques de fabrication

The manufacture of nanoparticles is an industry that requires a very precise technology, given the size and different shapes required by the experimenters to have more case studies, and the need for certain chemical surface treatments to keep them in suspension. The preparation of nanofluids must take into account especially a stable and durable suspension and a minimal agglomeration of the nanoparticles, and must ensure that they do not enter in chemical exchange with the base fluid. Nanofluids have many applications in the industry, which has prompted several researches, especially experimental ones

III.6.Preparation of nanofluids:

Experiments carried out on heat transfer fluids with micrometer size particles **(10-6m)** have shown that some problems could be caused by the use of the latter such as the problem of sedimentation of the particles, the increase of charge loss etc. ...while for particles of the order of nanometer **(10-9m),** these problems are practically insignificant. While assuming that the suspension is stable and durable, particle agglomeration is negligible, no chemical change of the fluid, the preparation of nanofluids can be done by two methods:

1. **First method :**

This method has only one step:

This method is based on the vaporization of a solid material under vacuum, then direct condensation of its vapor in the liquid

2. **Seconde method :**

This method has two steps:

This method consists first of the manufacture of a dry nanopowder, then the mixing and dispersion of this one in the liquid. These manufacturing processes are of physical or chemical nature. They are the subject of much research to improve the production cost which remains however high.

III.7.Effects on the thermo-physical properties of nanofluids :

The main parameters influencing the thermal conductivity of the nanofluid are:

- the volume concentration of the particles.
- the type of the particle.
- the temperature.

III.7.1.Effect of particle volume concentration:

The effect of particle volume concentration on the thermal conductivity enhancement of the nanofluid

III.7.2.Effect of temperature:

In general, the thermal conductivity of the nanofluid is temperature sensitive compared to the base fluid. Therefore, the thermal conductivity enhancement of the nanofluid is also temperature sensitive. Thus, the improvement in thermal conductivity increases with temperature.

III.7.3.Effect of the type of the nanoparticle

Fig group together the experimental studies of several researchers. They illustrate the effect of the type of nanoparticles on the thermal conductivity for two nanofluids, one is a metal oxide and the second is a metal, both diluted in water. All parameters (temperature and particle shape) are assumed constant.

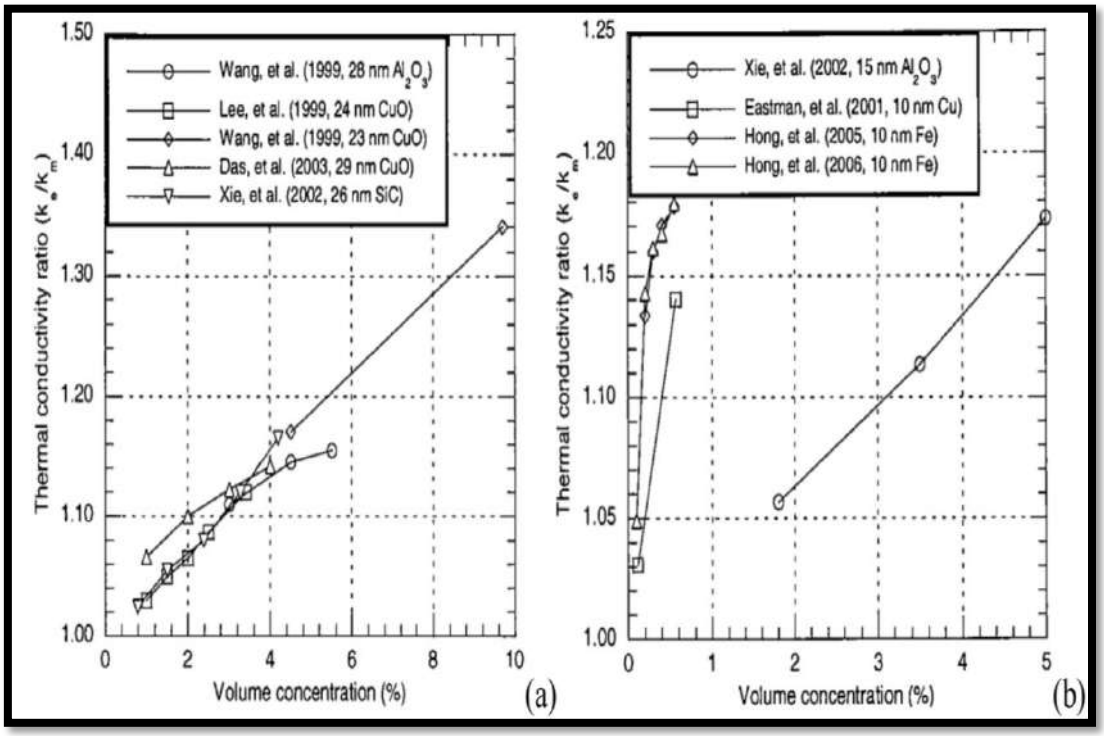


Figure III-1 : Effect of particle types on thermal conductivity

They found that the metal particles produced the same improvement as the metal oxides but at low volume concentration.

III.8.Domains of application of nanofluids :

Nanofluids can be used to improve heat transfer and energy efficiency in many thermal systems. In this section, some examples of applications will be presented such as transportation, microelectronics, defense, nuclear, space and biomedical.

III.8.1.Cooling of thermal systems :

Ethylene glycol mixture and water are used as coolant in vehicle engines. The addition of nanoparticles in these liquids improves the cooling rate. This point is studied by several groups of researchers, (Tzeng and al) (42) dispersed CuO and AL_2O_3 nanoparticles in the transmission engine cooling oil. In another application, (Zhang and Que) (43)-24reported a study to reduce wear (lubrication) with the help of nanoparticles, and improve tribological properties, and wear resistance with the reduction of friction between moving mechanical elements.

III.8.2.Cooling of electronic systems :

In integrated circuits, nanofluids have been considered as cooling fluids. For this purpose, several studies have been carried out. (Tsai and al) (44) Used a water-based nanofluid to cool a central processing unit in a microcomputer. (Ma and al) (45) Investigated the effect of the nanofluid on the heat transport capability of an oscillating heat pipe, they proved that at the input power of 80 W, and only for a volume concentration of φ=1%, the temperature difference between the vaporizer and the condenser is 16.6°C.

III.8.3.Cooling of military systems :

Examples of military applications include power electronics cooling and directed energy weapons. These involve very high heat fluxes (q >500 to 1000 W/cm2), where nanofluids have been shown to be effective in cooling these systems, and also other military systems, including military vehicles, submarines, and high power laser diodes.

III.8.4.Cooling of space systems :

For applications in space, have conducted studies to show that the presence of nanoparticles in the cooling fluid in general electronics plays a very important role in space applications where the power density is very high

III.8.5.Cooling of nuclear systems :

The Massachusetts Institute of Technology has set aside an interdisciplinary center solely for new nanotechnology (nanofluid) in the nuclear power industry. Currently, they are evaluating the potential impact of nanofluid use on neutron safety, and the economic performance of nuclear systems.

III.8.6.Biomedicine:

Nanofluids and nanoparticles have many applications in biomedicine. To avoid some side effects of traditional cancer treatment methods, iron-based nanoparticles have been used as drug carriers.

Also for safer surgery by producing effective cooling around the surgical area, (Jordan and al) (46) performed a study where nanofluids could be used to produce a higher temperature around tumors to kill cancer cells without affecting nearby healthy.

III.8.7.Other applications :

Microchip cooling :

Rapid heat dissipation is one of the main limitations to the development of smaller microchips. However, nanofluids can be used for liquid cooling of computer processors due to their high thermal conductivity. The next generation of computer chips is expected to produce a localized heat flux of more than 10 MW/m^2, with a total power of more than 300 W. In combination with thin-film evaporation, the oscillating nanofluid heat pipe (OHP) cooling system will be able to eliminate heat fluxes of more than 10 MW/m^2 and serve as a next-generation cooling device that will be able to handle the heat dissipation from the new technology.

III.9.Surfactants

Surfactants are substances derived from natural or synthetic resources (47) whose molecules have a so-called amphiphilic structure, which presents in its structure two distinct parts of different affinities:

- A hydrophobic part with apolar character soluble in oil: it is constituted by one or more aliphatic chains, branched or not and sometimes associated with aromatic rings. Its hydrophobic character varies with the number of carbon atoms, the number of instalments and the ramifications.

- A hydrophilic part with a polar character, ionized or not, having an affinity for charged surfaces and for liquids with a strong polar character such as water. Generally speaking, the molecular structure of a surfactant can be represented by a head which presents the polar group, while the tail is formed by the a polar group of the molecule (Fig).

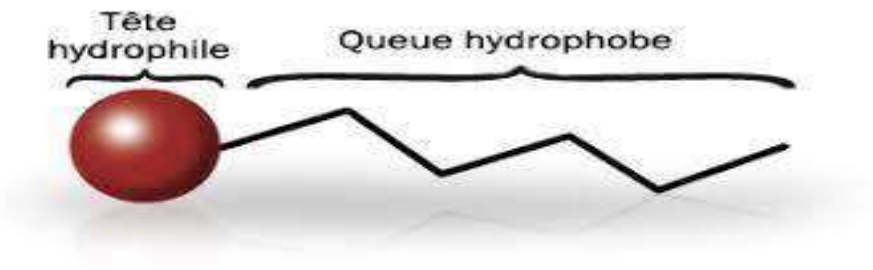


Figure III-2 : Schematic representation of a surfactant monomer

III.9.1.Natural surfactants

Today, many economic, psychological, environmental and regulatory factors favor the development of surfactants of plant or animal origin to the detriment of compounds of petroleum origin, a non-renewable source. They are known as natural surfactants or biosurfactants. (48)

Natural surfactants must be obtained by separation processes such as extraction precipitation or distillation, i.e. processes that do not cause pollution. No organic synthesis should be carried out. (49)

In reality, there are very few surfactants that meet these conditions. The limiting factor in the production of these natural surfactants is their much higher production cost than synthetic surfactants with equivalent properties, because these products are generally present in small quantities and the separation processes are laborious. In fact, surfactants synthesized from natural raw materials are generally qualified as natural.

III.9.2.Biosurfactants

Biosurfactants (or biological surfactants) are defined as amphiphilic molecules active on surfaces and produced by living cells: yeasts, bacteria and fungi. Their structure depends on the type of microorganism, the nature of the substrate and the conditions of production (50) (51) they are able to accumulate at the interface between two immiscible phases such as oil and water, reducing the surface tension, and therefore, they allow them to mix and interact more easily

III.9.3.Classification of biosurfactants

All biosurfactants are of the nonionic or anionic type. There are no literature reports of cationic structures; however in some instances the presence of nitrogen-containing character imparts a certain degree of cationic character to parts of the molecule. In common with all surface active species, biosurfactants contain one or several lipophilic and hydrophilic moieties. The lipophilic moiety can be a protein or a peptide with a high proportion of hydrophobic side chain of a fatty acid with 10 – 18 carbon atoms, although higher molecular weight fatty acids have been reported. The hydrophilic moiety can be an ester, a hydroxy, a phosphate or carboxylate group or a carbohydrate. Biosurfactants are classified in to five important categories (Zajic and al 1984) (52)

- Glycolipids.
- Sophorolipid.
- Rhamnolipids .
- Trehalolipids.
- Lipopeptide and Lipoprotein.
- Fatty acids, Phospholipids and Neutral Lipids.
- Polymeric Biosurfactants .
- Particulate Biosurfactants.

III.9.4.Parameters influencing the production of biosurfactants

The type and quantity of biotensioactives produced vary with the composition of the medium (carbon source, other nutrients) and the culture conditions (temperature, agitation, pH, etc)

- Source de carbone.
- Source of nitrogen and mineral salts.
- Growing condition.
- Extraction of biosurfactants from growing medium.

III.9.5.Production of biosurfactants

Biosurfactant-producing microorganisms grow aerobically in an aqueous medium containing several carbon sources such as carbohydrates, oils or hydrocarbons (53)

The structure and characteristics of a biosurfactant depend on the growth conditions, the carbon source used and the type of microorganism.

The various applications of biosurfactants require an easy, fast and reliable method to discover biosurfactant producing bacteria. The techniques used to evaluate biosurfactant production are :

a) Emulsifying activity .

b) Surface voltage.

c) Oil Displacement Test .

d) Hemolytic activity .

III.9.6.Physicochemical characterization of biosurfactants

- Emulsifying power.
- Wetting power.
- Foaming power.
- Minimum inhibitory concentration.

III.9.7.Use of biosurfactants

All surfactants are chemically synthesized, however, in recent years much attention has been paid to biosurfactants due to their wide range of functional properties, and the diverse synthetic capabilities of microbes. Most importantly, they are environmentally friendly, as they are readily biodegradable and have low toxicity compared to synthetic surfactants. These unique properties of biosurfactants allow their use and eventual replacement of chemical surfactants in a wide range of industrial operations. Most work on biosurfactant applications has focused on bioremediation of pollutants and microbial enhanced oil recovery. However, these microbial compounds have a variety of useful properties and applications in various pharmaceutical, biomedical and agri-food fields

III.9.8.Applications of biosurfactants in industry

- Food industry.
- Cosmetics industry.
- Therapeutic application.
- Oil industry:

The important sector for the application of biosurfactants is the extraction of rock adsorbed oil (MEOR: Microbial Enhanced Oil Recovery) from crude oil drillings.

This extraction is done after primary and secondary oil recovery, and is called tertiary recovery. It uses microorganisms and/or their metabolites to recover the residual oil (Banat 1995). (54)

For MEOR to be useful, bacteria must be able to grow in oil tanks under extreme conditions of high temperature, pressure and salinity.

The effectiveness of MEOR has been reported in field studies in several countries several countries.

(Banat and al) (55) Tested on a pilot scale the ability of biosurfactants to clean a reservoir and recover hydrocarbons from the emulsified sludge. They used two tons of Pseudomonas culture containing Rhamnolipids to treat 850m of sludge. They recovered about 91% (774m) of remaining recoverable crude oil, i.e. 76m of miscellaneous non-hydrocarbon containing marines.

Since microbial enhanced oil recovery reduces or eliminates the use of harsh chemicals, it represents an environmentally friendly method of tertiary oil recovery.

III.9.9.Benefits of Biosurfactants

According to (GAKPE and al) (56)(2007), biosurfactants have the same properties as their chemical those of their chemical counterparts; but they have many specific specific potential advantages :

- Biodegradability.
- Biocompatibility and digestibility.
- Availability of raw materials.
- Acceptable production savings.
- Use in environmental control.
- Specificity.

III.9.10.Disadvantages of biosurfactants:

According to (HEALY and al) (57)(1996), the main factor limiting the use of biosurfactants remains the economic aspect of large-scale production, whose main obstacles are:

- Low production yields relative to substrate(s).
- Significant capital investment.
- Low volume efficiency.
- Process control issues such as foam formation.
- Product recovery and purification problems.
- Problems of characterization of finished products due to their chemical complexity.

III.10.MHD

III.10.1.Introduction

Magnetohydrodynamics (MHD for short) is a discipline, like thermodynamics, that is a set of equations and models. MHD is the most spectacular and recent example of conducting fluids, it is the study of the motion of a conducting fluid in the presence of a magnetic field.

An MHD flow can differ significantly from an equivalent ordinary hydrodynamic flow. The movement of metal particles through magnetic field lines produces an electric current that interacts with the magnetic field to produce an electromagnetic (EM) driving force, which opposes the motion of the liquid. Even a weak magnetic field provides enough damping EM force to eliminate turbulence and instability in most of the motion involved, thus eliminating many micro-defects in the crystal. The damping rate will depend by virtue of the strength of the applied magnetic field as well as its orientation with respect to convective flow. (58)

III.11.Definition of magnetohydrodynamics

Definition of magnetohydrodynamics the word magnetohydrodynamics (MHD) has three sections which are mean magnetic field, liquid and motion. Fig represents the basic idea of MHD. Fig illustrates the mechanism of influence of Lorentz force on the fluid motion. The

right hand law is shown in this figure, which determines the direction of the Lorentz forces. In order to simulate MHD, Maxwell's equations should be solved and coupled to the Navier-Stokes equations.

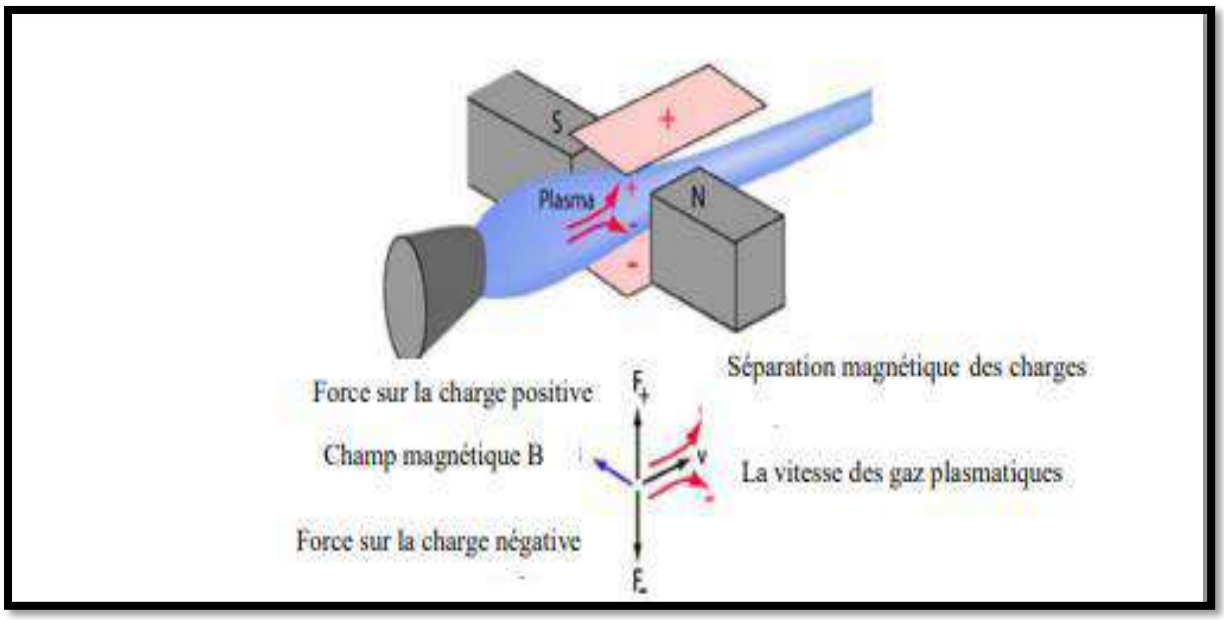


Figure III-3: Induced current in a conductive fluid in the presence of a magnetic field (59)

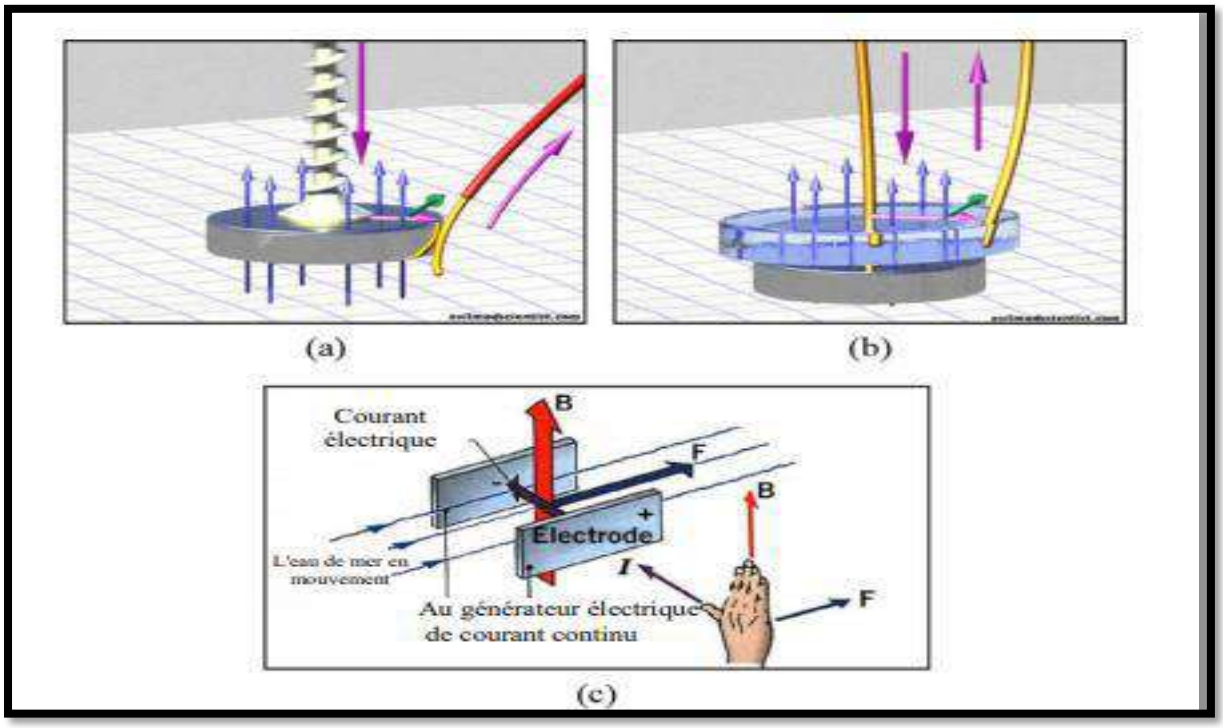


Figure III-4 : Effect of magnetic field on conductive fluid flow and hand law (59)

III.12.Mathematical model

In order to reach the mathematical model, the conductivity is considered as a constant scalar. Fig shows two important effects: Lenz's law.

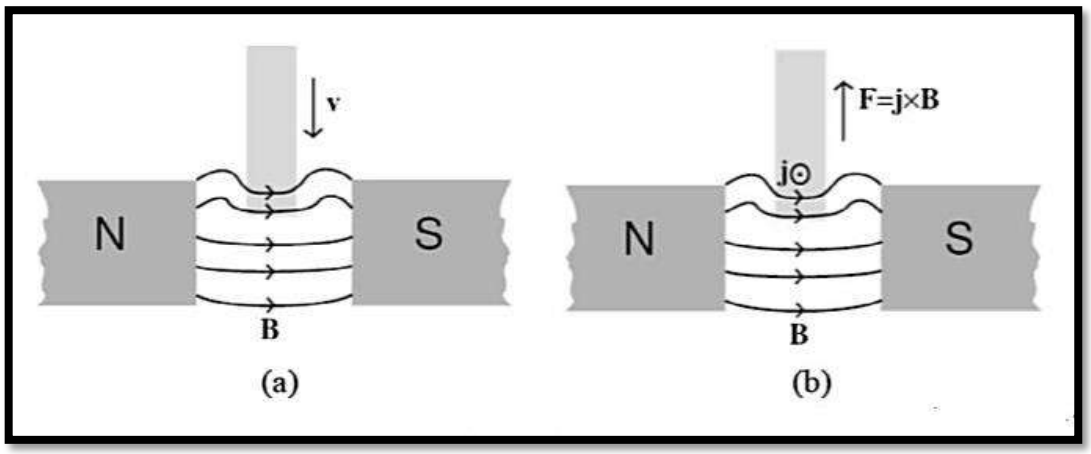


Figure III-5 : The tow key's physical effects occurring in MHD (59)

III.12.1.Loi de la force de Lorentz :

As a particle transports in the magnetic field, it experiences a force which can be calculated as:

$$\vec{F} = q(\vec{u} \times \vec{B}) \qquad \textbf{III-1)}$$

where $\vec{u}, q$ are the particle's velocity and charge

III.12.2.Maxwell's equations :

The governing formulas are:

$$\vec{\nabla} \cdot \vec{D} = \rho_c \qquad \textbf{III-2)}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \textbf{III-3)}$$

$$\vec{\nabla} \cdot \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \textbf{III-4)}$$

$$\overrightarrow{\frac{\partial \vec{D}}{\partial t} + \vec{j}} = \vec{V} \cdot \vec{H} \qquad \textbf{III-5)}$$

$$\vec{D} = \varepsilon \vec{E}, \vec{B} = \mu \vec{H} \qquad \textbf{III-6)}$$

($\boldsymbol{\varepsilon}, \boldsymbol{\mu}$)are the permittivity of the medium and the magnetic permeability.

III.12.3.The Navier-Stokes equation:

The momentum equation is:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla})\vec{u}\right) = -\vec{\nabla}p + \mu\nabla^2\vec{u} + other\ forces \qquad \textbf{III-7)}$$

and in the presence of electric and magnetic fields, we have:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla})\vec{u}\right) = -\vec{\nabla}p + \mu\nabla^2\vec{u} + \rho_c\vec{E} + \vec{j} \times \vec{B} + other\ forces \qquad \textbf{III-8)}$$

III.12.4.Ohm's law:

According to this law, the formula of $\vec{j}$ is as follows:

$$\vec{j} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right) \qquad \textbf{III-9)}$$

III.12.5.Magnetohydrodynamic approximation:

In usual uses, the speed is much lower than the speed of light, so according to equations III-3) and(III-5) we have:

$$\frac{E}{B} \approx \frac{L}{T} = U \qquad \textbf{III-10)}$$

$$\left|\frac{\partial \vec{D}/\partial t}{\vec{\nabla} \times \vec{H}}\right| \approx \frac{D/T}{H/L} = \frac{\varepsilon_0 E/T}{B/\mu_0 L} = \varepsilon_0 \mu_0 \frac{E}{B}\frac{L}{T} \approx \frac{1}{c^2}\left(\frac{L}{T}\right)^2 = \frac{U^2}{c^2} \qquad \textbf{III-11)}$$

$\partial \vec{D}/\partial t$ should be ignored because $U \ll c$

$$\vec{\nabla} \times \vec{H} = \vec{j} \qquad \textbf{III-12)}$$

According to equations (III-2)and (III-11) :

$$|\rho_c| \approx \frac{D}{L} \qquad \textbf{III-13)}$$

$$|\vec{j}| \approx \frac{H}{L} \qquad \textbf{III-14)}$$

Using equations (III-10),(III-13) and (III-14)

$$\left|\frac{\rho_c \vec{E}}{\vec{\mathrm{j}} \times \vec{B}}\right| \approx \frac{(D/T)E}{(H/L)B} = \frac{\varepsilon_0 E^2}{B^2/\mu_0} = \varepsilon_0 \mu_0 \frac{E^2}{B^2} \approx \left(\frac{U}{c}\right)^2 \qquad \textbf{III-15)}$$

Thus $\rho_c \vec{E}$ can be ignored with respect to $\vec{j} \times \vec{B}$

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+(\vec{u}\cdot\vec{\nabla})\vec{u}\right)=-\vec{\nabla}p+\mu\nabla^2\vec{u}+\vec{j}\times\vec{B}+other\ forces \quad \textbf{III-16)}$$

III.12.6.The magnetic induction equation:

According to the equations (III-9),III-11) and $\vec{B}=\mu_0\vec{H}$:

$$\vec{\nabla}\eta\ \times\vec{B}=\left(\vec{E}+\vec{u}\times\vec{B}\right) \quad \textbf{(III-17)}$$

$$\eta\ =\frac{1}{\mu_0\sigma}$$

Take $\vec{\nabla}\times$ (III-16)

$$\vec{\nabla}\times\left(\vec{\nabla}\eta\ \times\vec{B}\right)=\vec{\nabla}\times\left(\vec{E}+\vec{u}\times\vec{B}\right) \quad \textbf{III-18)}$$

$$\eta\left(\vec{\nabla}\left(\vec{\nabla}\cdot\vec{\mathrm{B}}\right)-\nabla^2\vec{\mathrm{B}}\right)=\vec{\nabla}\times\left(\vec{u}\times\vec{B}\right)+\vec{\nabla}\times\vec{E} \quad \textbf{III-19)}$$

According to the equations (III-3); (III-4)

$$-\eta\nabla^2\vec{\mathrm{B}}\ =\vec{\nabla}\times\left(\vec{u}\times\vec{B}\right)-\frac{\partial\vec{B}}{\partial t} \quad \textbf{III-20)}$$

$$\frac{\partial\vec{B}}{\partial t}=\eta\nabla^2\vec{\mathrm{B}}\ +\vec{\nabla}\times\left(\vec{u}\times\vec{B}\right) \quad \textbf{III-21)}$$

III.13.Conclusion :

We have devoted this chapter to present basic concepts and generalities about nanofluid , biosurfactant and magnetic field. Different experimental and numerical works available in the literature, which we have exposed in the bibliographic research section, have been performed in order to understand the characteristics of the flow, the transfer of nanofluids in the presence of biosurfactant and the magnetic field

Chapter IV

Results and discussion

IV.1.Introduction

During the past years, there has been a significant growth in the use of micropolar nanofluids, the need to improve heat transfer fluids has led to the development of nanofluids. These engineered particles dispersed in a base fluid have numerous applications such as in micro electromechanical systems (MEMS), nano electromechanical systems (NEMS), biomedical engineering (imaging and ablation), nuclear reactors, extraction of geothermal power, etc. of G.C. (Bourantas and al). (60)

These kinds of the fluids have been modelled firstly by Eringen (61) adding a supplementary equation representing the local angular momentum which operates also in the classical momentum equation.

Micropolar fluids have been used by many authors in the boundary layer flow and heat transfer for different geometries under several physical and thermal conditions, for example (Gorla and Nakamura) (62);(Lok and al) (63); (Aydın and Pop); (64)(Ishak and al) (65) (66)

Recently, the study of convective transport of nanofluids has gained considerable importance due to its applications. The importance of these mixed convection heat transfer in micropolar nanofuid has been discussed by (Rehman and al) (67)

A (Ishak et al) (68) analyses a micropolar fluid with MHD flow near a stagnation point. Thermal radiation and chemical reaction effects for the same type of fluid has been considered by Das (69),The first cited effect is also treated numerically by Mahmoud (70)considering a stretching surface with variable thermal conductivity. A numerical model is developed to examine the combined effects of Soret and Dufour on mixed convection magnetohydrodynamic heat and mass transfer in micropolar fluid-saturated Darcian porous medium in the presence of thermal radiation, non-uniform heat source/sink and Ohmic dissipation is presented by (Pal and Chatterjee) (71),(Seddeek and al) (72)derived an analytical solution for a magneto-micropolar fluid past a moving plate. Radiation, suction and blowing are the mechanisms incorporated. The steady laminar magnetohydrodynamic (MHD) boundary-layer flow past a wedge with constant surface heat flux immersed in an incompressible micropolar fluid in the presence of a variable magnetic field is investigated by

(Ishak and al) (73),(Mahmoud and Waheed) (74) examined an interaction between a MHD micropolar fluid and a moving surface with radiation. In the area of high temperature differences, Abd-El Aziz (75) studied the above effects on a moving semi-infinite plate with mixed convection flow of a micropolar fluid. The problem of the flow and heat transfer on a cylinder with a suction-case is discussed by (Elbarbary and Elgazery) (76) Unsteady MHD natural convection is studied by Chamkha (77) for a heated porous plate with combined effects.

Efforts to improve the heat exchangers in many industrial sectors (automotive, electronics ...) require the intensification of heat transfer by convection. Improvements called "passive", in exchange surfaces are a path already widely explored and reach their limits. New optimization pathways should be studied. One of them is to use new media able to increase heat transfer: the case of nanofluids. (78)

Nanofluid research has the fastest growth rate in science citation index (SCI) publications. These fluids are engineerly manufactured fluids by suspension of ultrafine size (10^{-9}–10^{-11} m) particles in the simple fluid. Choi (79) named these fluids as nanofluids due to the addition of nano-size particles. He concluded that the pumping cost of a heat exchanger system can be reduced several times, because these particles have a higher thermal conductivity than that of base fluids. In this context, (Reddy and al) (80) .presented analysis of the boundary layer for the mixed convection for the flow of a non-Newtonian nanofluid past in vertical cylinder. Solutions of the set of non-similarity equations are obtained using the finite difference method with implicit Keller box method of disposal.

A mass and heat transfer problem of a vertical permeable and the moving plate adjacent to micropolar fluid subject to a magnetic field is studied in the present paper. Motivated by the applications cited by Das (69) and considering the interesting case of moving the system, the present problem appears relatively new. The review of the published literature shows that the current problem has not yet received the attention of any researcher. All the mechanisms involved, namely the natural heat and mass transfer, the presence of a magnetic field and the velocity of the permeable plate necessitate a strong coupling and suggested an interesting behaviour to elucidate.

The goal of this work is to study the effect of MHD on regular convection and heat transfer, on a movable vertical flat plate embedded in a nanofluids micropolar including the effects of Brownian motion.

The resulting similarity solutions of the governing equations are obtained. Many results are presented and representative set is displayed graphically to illustrate the influence of the various dimensionless parameters.

The purpose assigned to this study is the understanding and exploration of structure dynamic and thermal fields and the quantification of heat transfer between the surface of the movable plate and the fluid **(**micropolar nanofluids).

IV.2.Mathematical formulation

Consider a steady laminar convective flow of electrically conducting incompressible micropolar nanofluids along a semi-infinite vertical plate. A transverse magnetic field B_0 is applied normally to the plate. The magnetic field varies in strength as a function of x. In this formulation, the magnetic dissipation is not ignored. The plate is permeable and received/loss fluid with a transverse velocity v_w and moves along x-direction with a constant velocity U. The wall is maintained at constant temperature and Nanoparticule volume fraction at the vertical plate, T_w and ϕ_w, and these values are assumed to be greater than the ambient temperature and ambient nanoparticule volume fraction attained as y tends to infinity, T_∞ and ϕ_∞, respectively. The x-direction which is taken along the plate is also the direction of the flow and y-axis is normal to it. The schematic diagram of the present physical problem is depicted in Fig

The hypotheses :

- Two dimensional laminar flow.
- Heat and mass transfer.
- Free convection.
- Nanofluide.
- Stationary regime.

- Vertical materials in Mvt (U0).
- The material is maintained at Tw and T∞.
- We assume that T_∞<T_w and C_∞<C_w.
- MHD effect.
- Geometry(Vertical plate).
- Addition surfactant stability.

Then, under these assumptions with Bossiness's approximation and regarding the model developed in the work of Das (69)

the governing conservation equations of mass, momentum and angular momentum, energy and species concentration can be written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \textbf{(IV 1)}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\left(\frac{\mu+K}{\rho}\right)\frac{\partial^2 u}{\partial y^2}+\frac{K}{\rho}\frac{\partial N}{\partial y}+g\beta(T-T_\infty)-\frac{\sigma B_0^2}{\rho}u \qquad \textbf{(IV 2)}$$

$$j\rho\left(u\frac{\partial N}{\partial x}+u\frac{\partial N}{\partial y}\right)=\gamma\frac{\partial^2 N}{\partial y^2}-K\left(2N+\frac{\partial u}{\partial y}\right) \qquad \textbf{(IV 3)}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}+\frac{(\rho c)_p}{(\rho c)_f}\left(D_B\frac{\partial \phi}{\partial y}.\frac{\partial T}{\partial y}+\left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2\right)+\frac{\sigma B_0^2}{(\rho c)_f}u^2 \qquad \textbf{(IV 4)}$$

$$u\frac{\partial \phi}{\partial x}+v\frac{\partial \phi}{\partial y}=\left(D_B\frac{\partial^2 \phi}{\partial y^2}+\left(\frac{D_T}{T_\infty}\right)\frac{\partial^2 T}{\partial y^2}\right) \qquad \textbf{(IV 5)}$$

Here T is the temperature in the boundary layer and N the component of microrotation vector normal to x-y plane. Others parameters and quantities are specified in the nomenclature. We follow the work of many recent authors as the work of Long Hsiao (81)by assuming that the spin gradient viscosity is $\gamma=(\mu+\kappa/2)j$.

The corresponding permeable wall and stream boundary conditions are defined as follows:

At $$\boldsymbol{y = 0 : u = U_0, v = \pm v_w, T = T_w, \phi = \phi_w \; and \; N = -n \, \partial u / \partial y} \qquad \textbf{(IV 6)}$$

For $y -> \infty : u = 0,\ T -> T_\infty, \phi = \phi_\infty, N -> 0$

In the above equation n=1/2 which represents a weak concentration of particle flows and indicates the vanishing of anti-symmetric part of the stress tensor, Ahmadi (82)

Following Yacob et al (83), dimensionless quantities are introduced to obtain the similarity solutions.

$$\eta = \left(U_0/\nu x\right)^{\frac{1}{2}} y \ , \ \psi = (\nu x U_0)^{\frac{1}{2}} f(\eta) \ , \ N = U_0 \left(U_0/\nu x\right)^{\frac{1}{2}} h(\eta)$$

While for the dimensionless temperature and stream function

$$\theta = (T - T_\infty)/(T_w - T_\infty) \ , \ S = (\phi - \phi_\infty)/(\phi_w - \phi_\infty)$$

Where η is the independent similarity variable, $f(\eta)$ is the dimensionless velocity function, $h(\eta)$ is the dimensionless microrotation, $\theta(\eta)$ is the dimensionless temperature and $\phi(\eta)$ Nanoparticule volume fraction. Further, ψ is the stream.

function which is defined in the usual way as: $u = \partial\psi/\partial y \ , \ v = -\partial\psi/\partial x$

Then, the velocity components become

$$u = U_0 f'(\eta) \; and \; v = \frac{1}{2}\left(\nu U_0/x\right)^{1/2} (\eta f' - f)$$

Using the non-dimensional quantities, the equations (IV 1-IV 5) with the boundary conditions

(6) can be further reduced to a set of ordinary differential equations for which numerical solutions will be more easily obtained

$$(\mathbf{1}+\boldsymbol{K})\boldsymbol{f}''' + \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{f}.\boldsymbol{f}'' - \boldsymbol{M}.\boldsymbol{f}' + \boldsymbol{K}.\boldsymbol{h}' + \boldsymbol{Gr_x}.\boldsymbol{\theta} = \mathbf{0} \quad \textbf{(IV 7)}$$

$$\left(\mathbf{1}+\frac{\boldsymbol{K}}{\mathbf{2}}\right)\boldsymbol{h}'' - \boldsymbol{K}(\mathbf{2}\boldsymbol{h}+\boldsymbol{f}'') + \frac{\mathbf{1}}{\mathbf{2}}(\boldsymbol{h}.\boldsymbol{f})' = \mathbf{0} \quad \textbf{(IV 8)}$$

$$\boldsymbol{\theta}'' + \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{Pr}.\boldsymbol{f}.\boldsymbol{\theta}' - \boldsymbol{Nb}.\boldsymbol{S}'.\boldsymbol{\theta}' - \boldsymbol{Nt}(\boldsymbol{\theta}')^{\mathbf{2}} + \boldsymbol{M}.\boldsymbol{Ec}.\boldsymbol{Pr}.\boldsymbol{f}'^{\mathbf{2}} = \mathbf{0} \quad \textbf{(IV 9)}$$

$$\boldsymbol{S}'' + \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{Pr}.\boldsymbol{Ln}.\boldsymbol{f}.\boldsymbol{S}' + \frac{\boldsymbol{Nt}}{\boldsymbol{Nb}}\boldsymbol{\theta}'' = \mathbf{0} \quad \textbf{(IV 8)}$$

The boundary conditions become:

$$\boldsymbol{\eta} = \mathbf{0} : \boldsymbol{f}'(\mathbf{0}) = \mathbf{1}\,, \boldsymbol{f}(\mathbf{0}) = \pm\boldsymbol{f_w}\,, \boldsymbol{h}(\mathbf{0}) = -\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{f}''(\mathbf{0}), \boldsymbol{\theta}(\mathbf{0}) = \boldsymbol{S}(\mathbf{0}) = 1 \quad \textbf{(IV 9)}$$

$$\eta -> \infty : f'(\infty) = 0,\ \ h(\infty) -> \ 0\,, \theta(\infty) -> 0\ \,, S(\infty) -> 0$$

Where, we have taken $j = \nu x/U_0$ as the microinertia density $f_w\ = -2v_w\sqrt{x/\nu U_0}$

represents suction/injection velocity at the plate.

The various parameters involved are defined by

$$\boldsymbol{Gr_x} = \boldsymbol{g\beta}(\boldsymbol{T_w} - \boldsymbol{T_\infty})\,\boldsymbol{x}/\boldsymbol{U_0}^{\mathbf{2}} \quad \textbf{(IV 10)}$$

$$K = \kappa/\mu \quad \textbf{(IV 11)}$$

$$Ln = \alpha_{nf}/D_B \quad \textbf{(IV 12)}$$

$$Nb = (\rho c)_p D_B(\phi_w - \phi_\infty)/(\rho c)_f \alpha_{nf} \quad \textbf{(IV 13)}$$

$$Nt = (\rho c)_p D_T(T_f - T_\infty)/(\rho c)_f T_\infty \alpha_{nf} \quad \textbf{(IV 14)}$$

$$M_x = Ha_x^2/Re_x = \sigma B_0^2 x/\rho U_0 \quad \textbf{(IV15)}$$

$$E_C = {U_0}^2/c_p\,(T_w - T_\infty) \quad \textbf{(IV 16)}$$

$$Pr = \nu/\alpha \quad \textbf{(IV 17)}$$

$$Sc = \nu/D \quad \textbf{(IV 20)}$$

Gr_x, K, Ln, Nb, Nt, M_x, Ec, Pr and Sc denote the local thermal Grashof number, the material parameter, Nanofluid Lewis number, Brownian motion parameter,the magnetic parameter , the Eckert number, the Prandtl number and the Schmidt number. Ha_x and Re_x linked to M_x are the known Hartman and Reynolds numbers, respectively.

IV.3.Results and discussion

The set of the coupled ordinary differential equations (IV 7) – (IV 10) is highly nonlinear and cannot be solved analytically. Together with the boundary conditions (IV 11), they form a two point boundary value problem, which can be solved using the finite difference method that implements the 3-stage Lobatto collocation formula. A continuous solution is provided by the collocation polynomial that is accurate up the fourth-order. Mesh selection and error control are linked with the residual of the continuous solution. Subintervals are generated to proceed of integration.

The flow regions are controlled by thermophysical parameters, namely Gr_xK, M_x, Ec, Pr and Sc. Numerical computations are carried out for different values of the parameters shown in all figures.

Next, numerical computations have been carried out for the velocity, microrotation, temperature and concentration profiles. To compare the behaviour of the strongly and weak micropolar fluid, the main results in all figures are displayed graphically for K = 0.1 and K = 6. A reference case is adopted with these parameters, Pr = 0.71; Sc = 0.3 and Ec = 0.1; while the local thermal Grashof number is 2.0.

The values of strength of the magnetic field are chosen 0.5 and 1.0 whereas M_x,= 0.0 corresponding to the flow without the magnetic field. Similarly, To illustrate the suction/injection flow through the permeable plate, the values f_w = +1 corresponds to the suction-case and f_w = - 1 is chosen for the injection-case. The impermeable-case is represented naturally by f_w = 0. Because various fluids are encountered, additional figures are plotted to show the effect of the Prandtl number on the interested profiles.

Tableau IV-1: Values of $\frac{1}{2}C_f\, Re_x^{1/2}$, $M_w\, Re_x$, $Nu_x\, Re_x^{-1/2}$ and $Sh_x\, Re_x^{-1/2}$, M and K with Gr_x = 2.0, Pr = 0.71, f_w=1.0, Ec =0.1, Sc =0.3

M	K	$\frac{1}{2}C_f Re_x^{1/2}$	$M_w Re_x$	$Nu_x Re_x^{-1/2}$	$Sh_x Re_x^{-1/2}$
0.0	0.1	-0.0697	0.1149	0.6197	0.1241
	3.0	-0.1387	0.3757	0.6710	0.1730
	6	-0.3020	0.3900	0.6829	0.1875
1.0	0.1	-0.5297	-0.0969	0.5589	0.1499
	3.0	-1.0470	-0.0190	0.5754	0.1659
	6	-1.4532	-0.0164	0.5829	0.1781
2.0	0.1	-1.0157	-0.2634	0.5059	0.1513
	3.0	-1.6777	-0.3290	0.5169	0.1649
	6	-2.2232	-0.3488	0.5214	0.1766
1.0	0.1	-0.4881	-0.0840	0.5652	0.3012
	3.0	-0.9822	-0.0042	0.5787	0.3186
	6	-1.3752	-0.0016	0.5847	0.3303
	0.1	-0.5297	-0.0969	0.5589	0.1499
	3.0	-1.0470	-0.0190	0.5754	0.1659
	6	-1.4532	-0.0164	0.5829	0.1781
	0.1	-0.5759	-0.1108	0.5495	0.0043
	3.0	-1.1235	-0.0350	0.5704	0.0172
	6	-1.5468	-0.0328	0.5803	0.0296

Tableau IV-2: Values of $\frac{1}{2}C_f\,Re_x^{1/2}$, $M_w Re_x$, $Nu_x Re_x^{-1/2}$ and $Sh_x\,Re_x^{-1/2}$, f_w *and* K with Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec =0.1, Sc =0.3

f_w	K	$\frac{1}{2}C_f Re_x^{1/2}$	$M_w Re_x$	$Nu_x Re_x^{-1/2}$	$Sh_x Re_x^{-1/2}$
-1.0	0.1	-0.1261	0.0464	0.1368	0.1519
	3.0	-0.0710	0.1815	0.1376	0.1527
	6	-0.2960	0.2016	0.1383	0.1545
0.0	0.1	-0.1363	0.0483	0.3184	0.1517
	3.0	-0.5242	0.1312	0.3252	0.1594
	6	-0.8652	0.1304	0.3293	0.1660
+1.0	0.1	-0.5297	-0.0969	0.5589	0.1499
	3.0	-1.0470	-0.0190	0.5754	0.1659
	6	-1.4532	-0.0164	0.5829	0.1781

Tableau IV-3: Values of $\frac{1}{2}C_f\,Re_x^{1/2}$, $M_w Re_x$, $Nu_x Re_x^{-1/2}$ and $Sh_x\,Re_x^{-1/2}$, Pr and K with Gr_x = 2.0, Pr = 0.71, M= 1.0, f_w= 1.0, Ec =0.1, Sc =0.3

Pr	K	$\frac{1}{2}C_f Re_x^{1/2}$	$M_w Re_x$	$Nu_x Re_x^{-1/2}$	$Sh_x Re_x^{-1/2}$
0.5	0.1	-0.3600	-0.0431	0.4376	0.2031
	3.0	-0.7972	-0.0420	0.4465	0.2194
	6	-1.1588	-0.0432	0.4513	0.2278
0.75	0.1	-0.5572	-0.1056	0.5813	0.1398
	3.0	-1.0867	-0.0292	0.5994	0.1565
	6	-1.4988	-0.0268	0.6074	0.1692
1.0	0.1	-0.7042	-0.1528	0.7187	0.0819
	3.0	-1.2942	-0.0870	0.7465	0.1019
	6	-1.7344	-0.0828	0.7566	0.1181

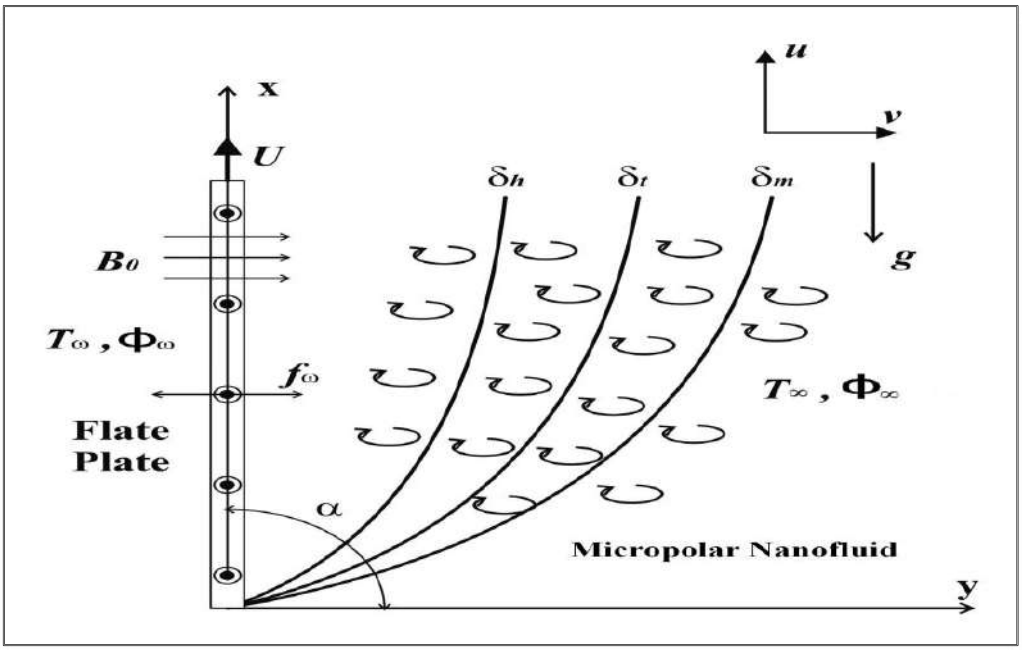


Figure IV-1 : Physical model and coordinate system

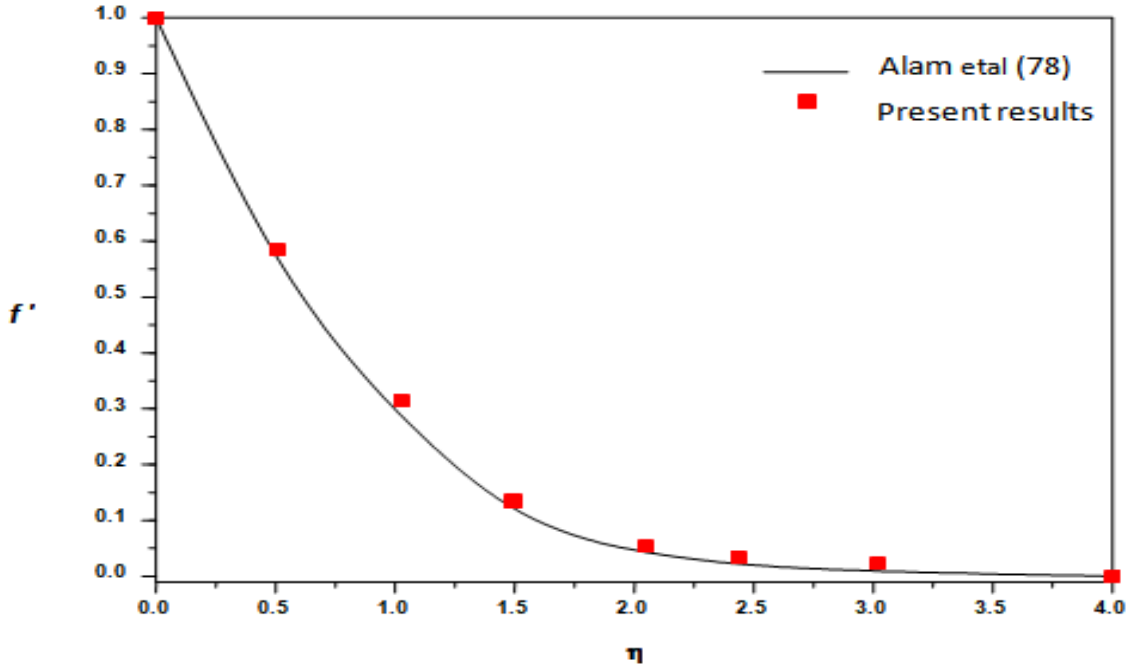


Figure IV-2 : Velocity profiles $f'(\eta)$ for comparison with results of Alam and al. [2009].

IV.3.1.Effect of the magnetic parameter *M* and the material parameter *K*

Typical curves are obtained for the velocity of the fluid, Figure . From this figure, it can observe that increasing the magnetic parameter M decreases the velocity f' inside the hydrodynamic boundary layer. This is due to the Lorentz force which acts and decelerates the motion of the fluid. The useful comparison between a weak and strongly micropolar fluids shows that this magnetic effect is more important for a true micropolar fluid. The magnetic field develops the Lorentz force which perturbs not only the main flow but also the microrotation of the particles.

Fig depicts the angular velocity profile. As it can see, the effect of M on the micropolar fluid is more pronounced neat the moving plate, where the increase of the magnetic field corresponds to a substantial increase of the angular velocity. At a representative zone $\eta > 2$, less effect is observed. Although the same effect encounters in the same zone for a weakly micropolar fluid, the tendency is such that the angular velocity falls more dramatically with M. This is explained by the difference in concentration of the particles and in the two cases.

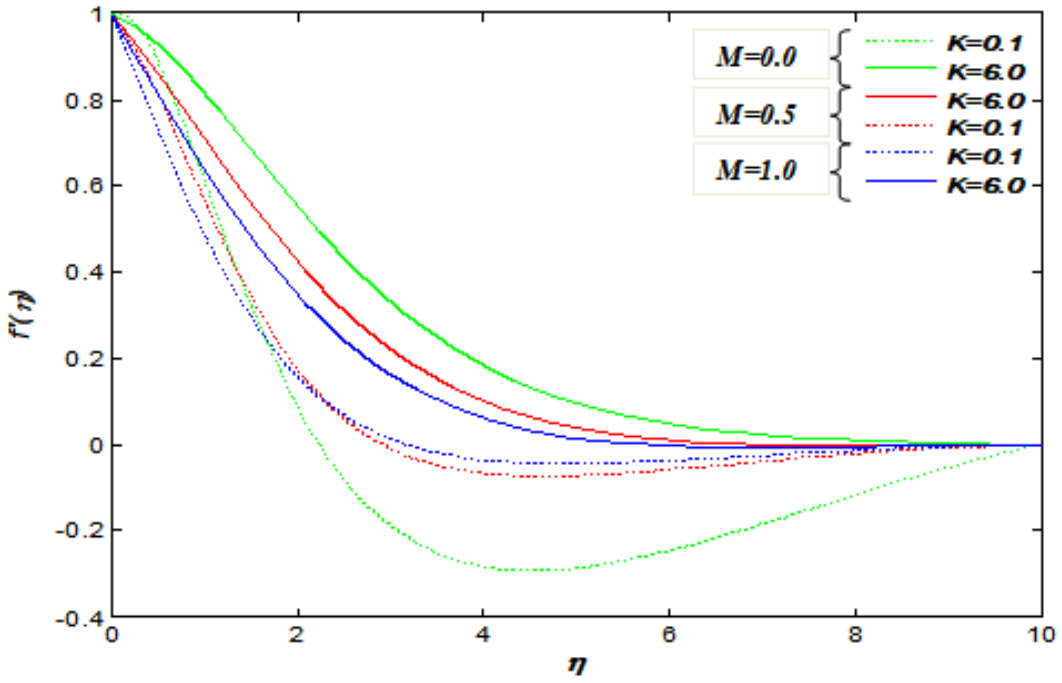


Figure IV-3 : Velocity profiles $f'(\eta)$ for different values of M.

(Gr_x = 2.0, Pr = 0.71, f_w= 1.0 Ec = 0.1, Sc = 0.3).

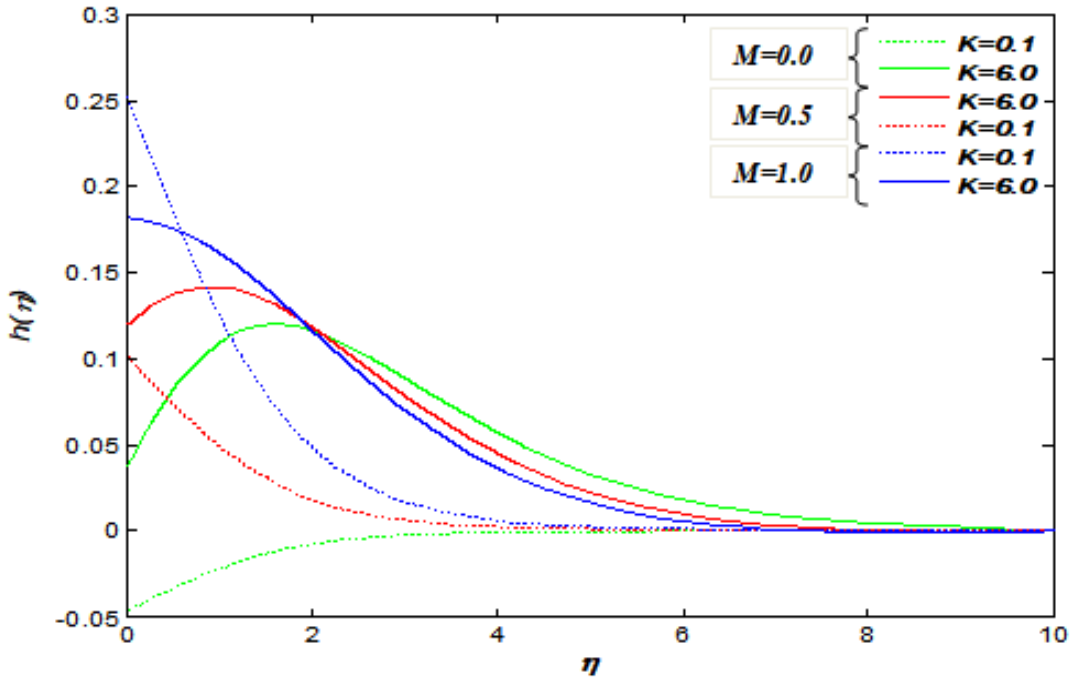


Figure IV-4 : Microrotation profiles $h(\eta)$for different values of M.

(Gr_x = 2.0, Pr = 0.71, f_w= 1.0, Ec = 0.1, Sc = 0.3)

It noted from Fig that applying a magnetic field to the flow leads to an increase of the temperature profile with the increase of M. This is attributed to the reduced velocity, as commented above. Then, the heat exchanged with the moving plate is reduced, causing in turn an increased temperature in the thermal boundary layer. Comparatively, the corresponding profiles a weakly micropolar fluid exhibit a greater temperature and a thicker boundary layer. As a whole, this indicates that extensive heat can be obtained by a micropolar fluid rather than a classical fluid.

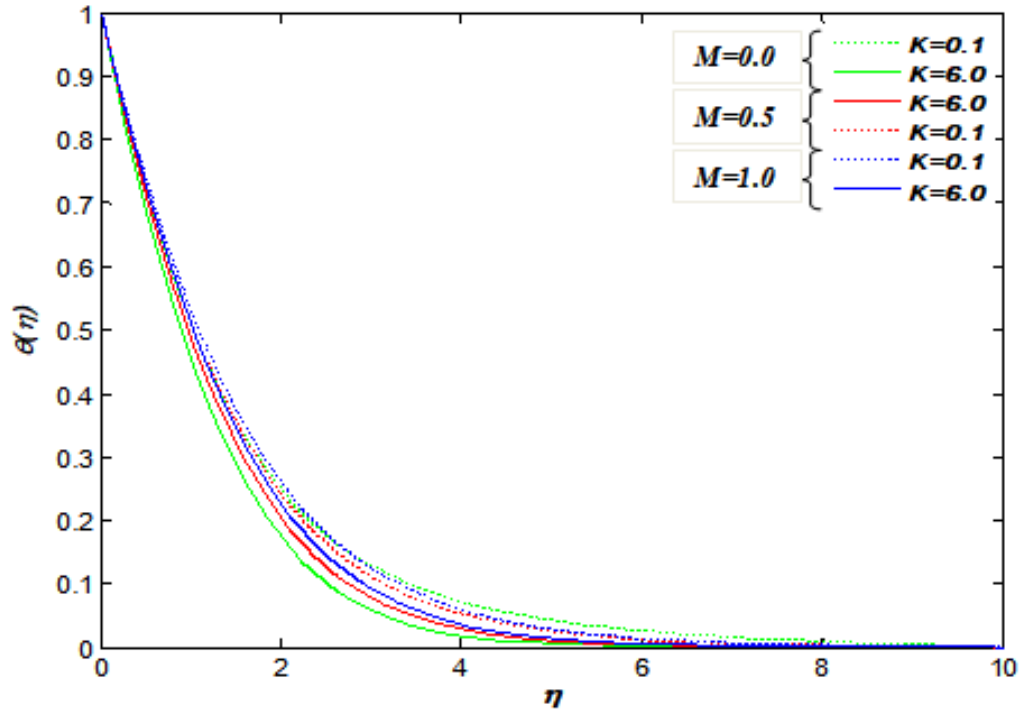


Figure IV-5 : Temperature profiles $\theta(\eta)$ for different values of M.

(Gr_x = 2.0, Pr = 0.71, f_w= 1.0, Ec = 0.1, Sc = 0.3)

Fig displays the concentration profiles under the effect of M. here again the use of a micropolar fluid is an interesting way to enhance the mass transfer. For the present conditions experienced and a classical fluid, it is worth mentioning that the temperature profiles are insensible to change of M. Like the temperature inside the thermal boundary layer, it can also see from this figure that the concentration of the fluid in the similar mass boundary layer increases as M increases. The ticker boundary layer is synonymous of slow mass exchange, caused by the retarded velocity or the presence of the Lorentz force.

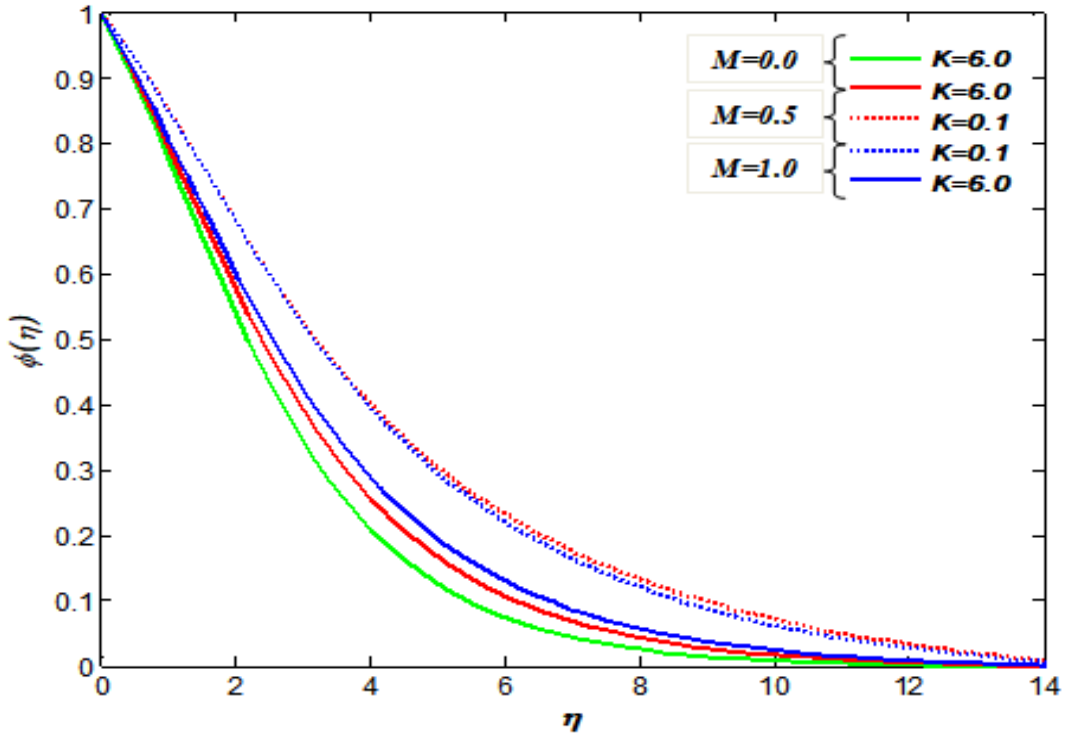


Figure IV-6 : Concentration profiles $\phi(\eta)$ for different values of M.

(Gr_x = 2.0, Pr = 0.71, f_w= 1.0, Ec = 0.1, Sc = 0.3)

IV.3.2.Effect of the suction/injection parameter f_w and the material parameter K

The effects of suction/injection in conjunction with a micropolar fluid are depicted in Fig The passage of suction to injection leads to enhance the hydrodynamic boundary layer, as reported in Fig. It is evident that the velocity of the fluid decreases when suction occurs and vice-versa. Conversely, the thickness of the hydrodynamic boundary layer is less in the suction case than in the injection case. The results show that the micropolar fluid presents more resistance to flow, as expected. However, this effect can be reversed in the injection case with a strong micropolar fluid

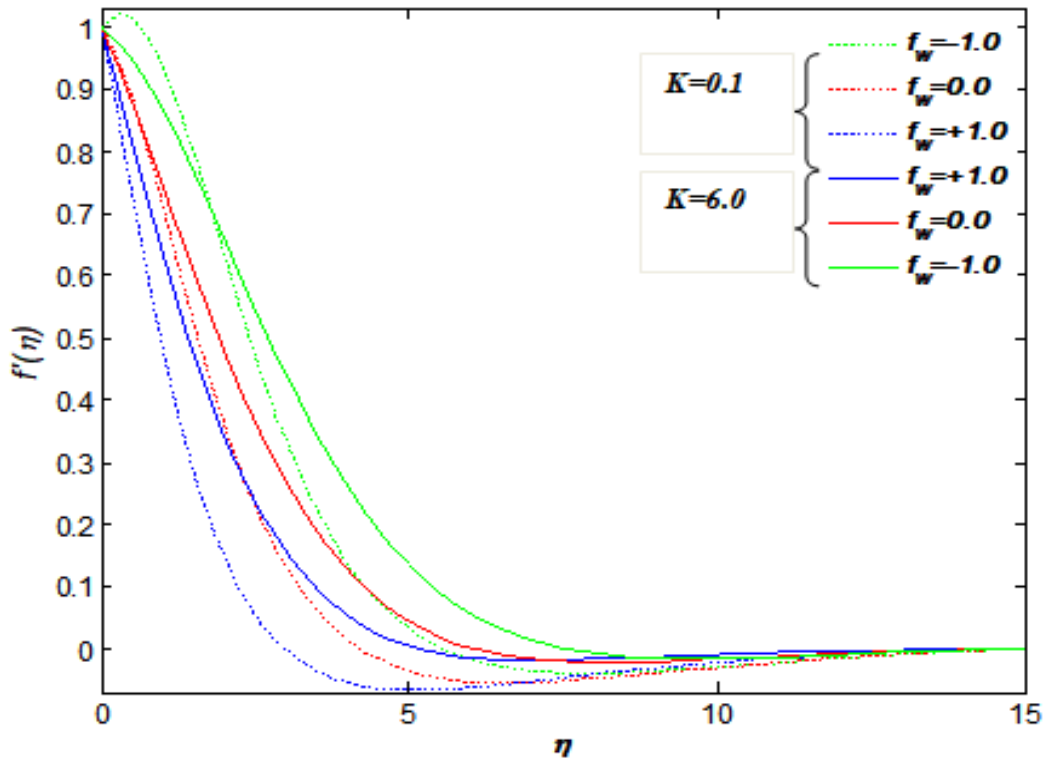


Figure IV-7 : Velocity profiles $f'(\eta)$ for different values of f_w.

(Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec = 0.1, Sc = 0.3)

Fig displays the opposite tendency for the microrotation, particularly in the first region near the moving permeable plate. It should be noted that the angular velocity starts from a minimum value to reach a peak value and then starts decreasing. Such behavior is not appearing for a micropolar fluid in the suction case. It is interesting to note that a negative value of the angular velocity is observed for a weak micropolar fluid in the injection case

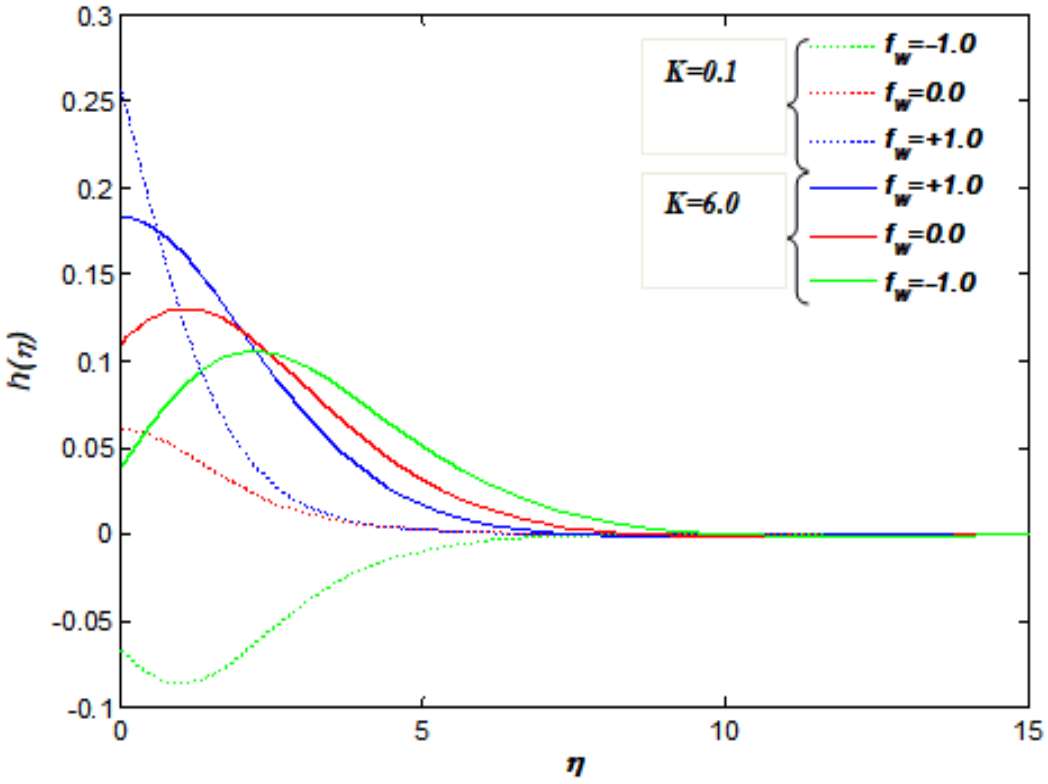


Figure IV-8 : Microrotation profiles $h\,(\eta)$ for different values of f_w.

(Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec = 0.1, Sc = 0.3)

It is interesting to note that a negative value of the angular velocity is observed for a weak micropolar fluid in the injection case. These results demonstrate that the microrotation is intensive in the middle of the boundary layer, depending to K and f_w. The influence of the suction/injection parameter f_w on the temperature profile is shown in Fig

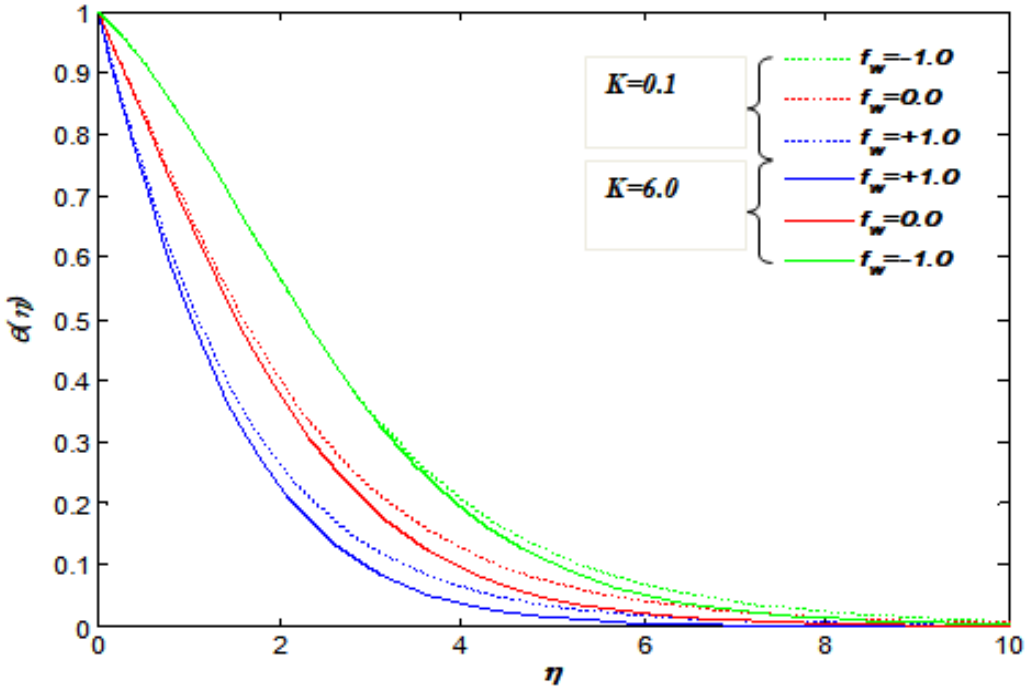


Figure IV-9 : Temperature profiles $\theta(\eta)$ for different values of f_w.

(Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec = 0.1, Sc = 0.3)

In the suction case the temperature decreases while opposite effect is seen in the injection case. Hence, slight improvement of the heat transfer with the micropolar fluid is encountered in these conditions. A similar trend is remarked from the concentration profile, as plotted in Fig

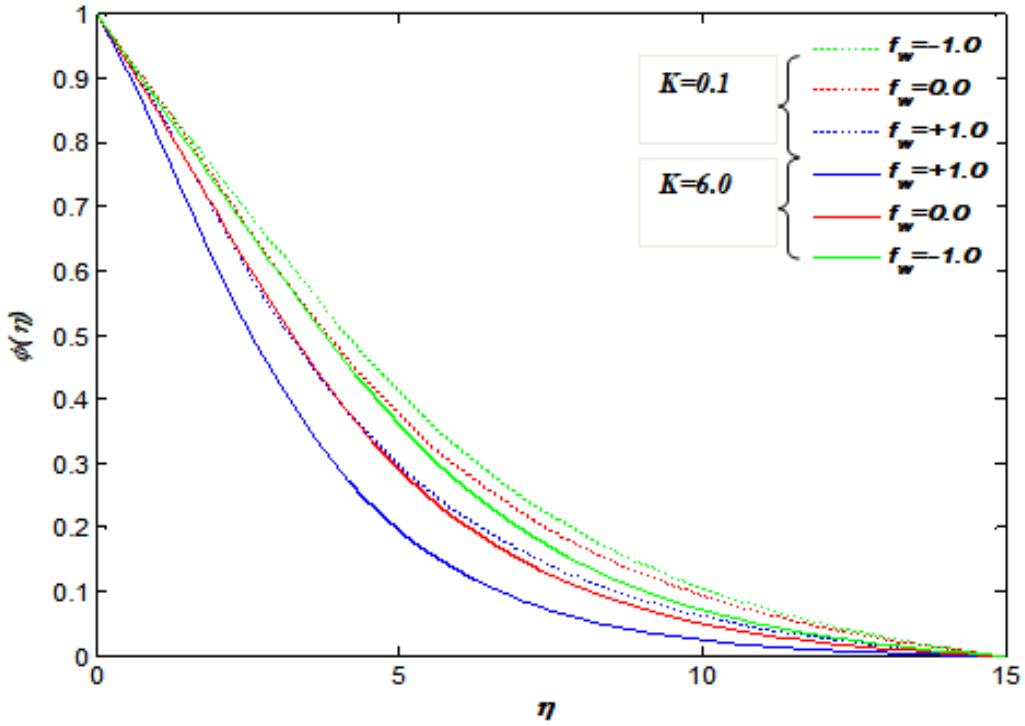


Figure IV-10 : Concentration profiles $\phi(\eta)$ for different values of f_w.

(Gr_x = 2.0, Pr = 0.71, M= 1.0, Ec = 0.1, Sc = 0.3)

IV.3.3.Effect of the Prandtl number Pr and the material parameter K

For various fluids, the effects of the Prandtl number on the profiles are prepared in the Fig. Because the vortex viscosity, it is evident that a strong micropolar fluid exhibit a greater hydrodynamic boundary layer than a weakly micropolarity of the fluid, Fig. On the other view, more is Pr less is the resistance to the flow. A competitive work is observed between Pr and K to determine the level of the velocity that the flow can reach

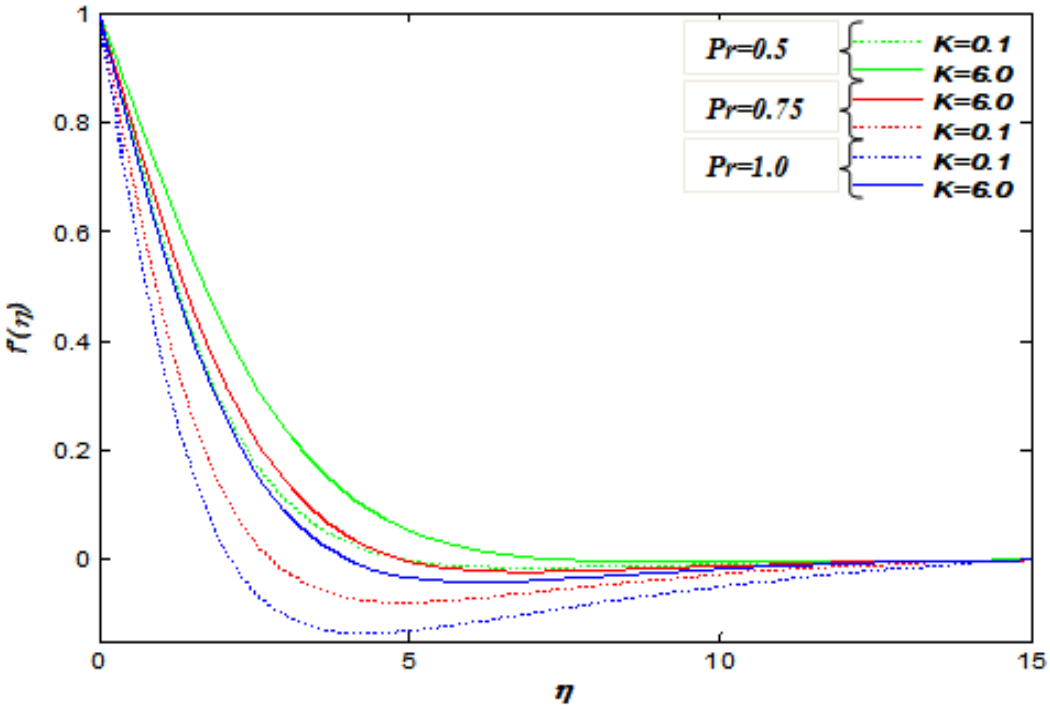


Figure IV-11 : Velocity profiles $f'(\eta)$ for different values of *Pr*.

(Gr_x = 2.0, f_w= 1.0, *Sc* = 0.3, *M*= 1.0, *Ec*=0.1)

In the Fig the value of the angular velocity depends also on *Pr* and *K*. It can see that the behavior of the profile under *Pr* is identical to f_w, exposed in Fig . In the preceding curves, as *Pr* increases, *f'* decreases while *h* increases. This finding is -in our opinion- rather correct in a physically sense than the stated angular velocity decreases with *Pr*

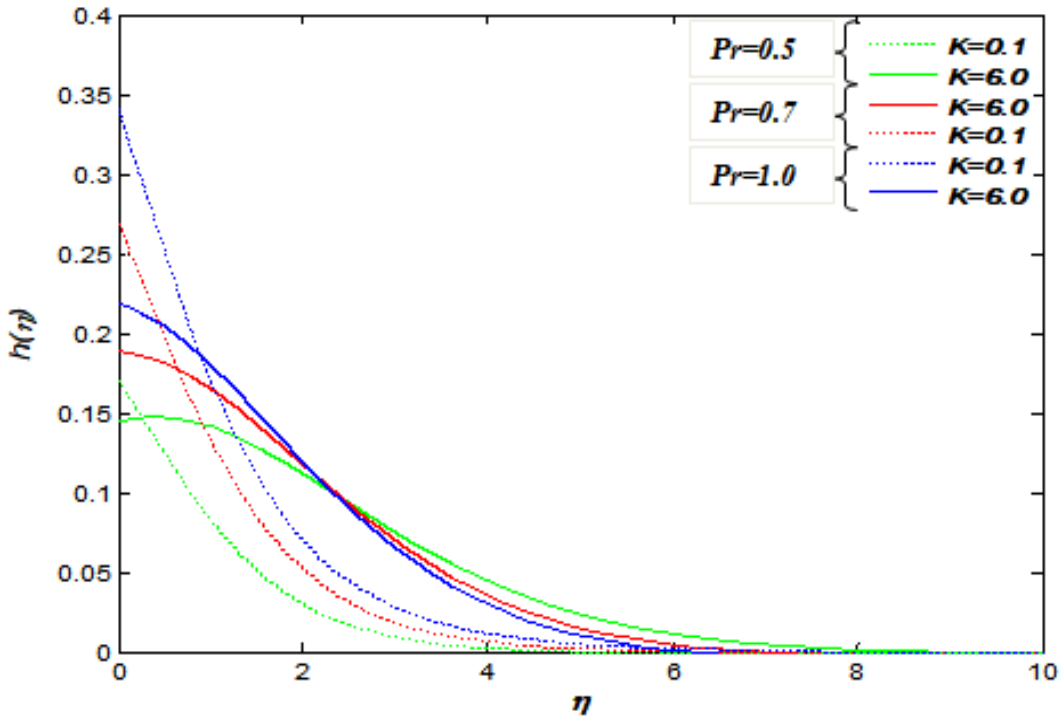


Figure IV-12 : Microrotation profiles $h(\eta)$ for different values of *Pr*.

(Gr_x = 2.0, f_w= 1.0, *Sc* = 0.3, *M*= 1.0, *Ec*=0.1)

Inside the thermal boundary layer, the increase of *Pr* is accompanied by the decrease of the temperature, as displayed in Fig . Low values of *Pr* are equivalent to great thermal conductivities of the fluid and furthermore more heat flux is diffused from the plate, giving high temperatures.

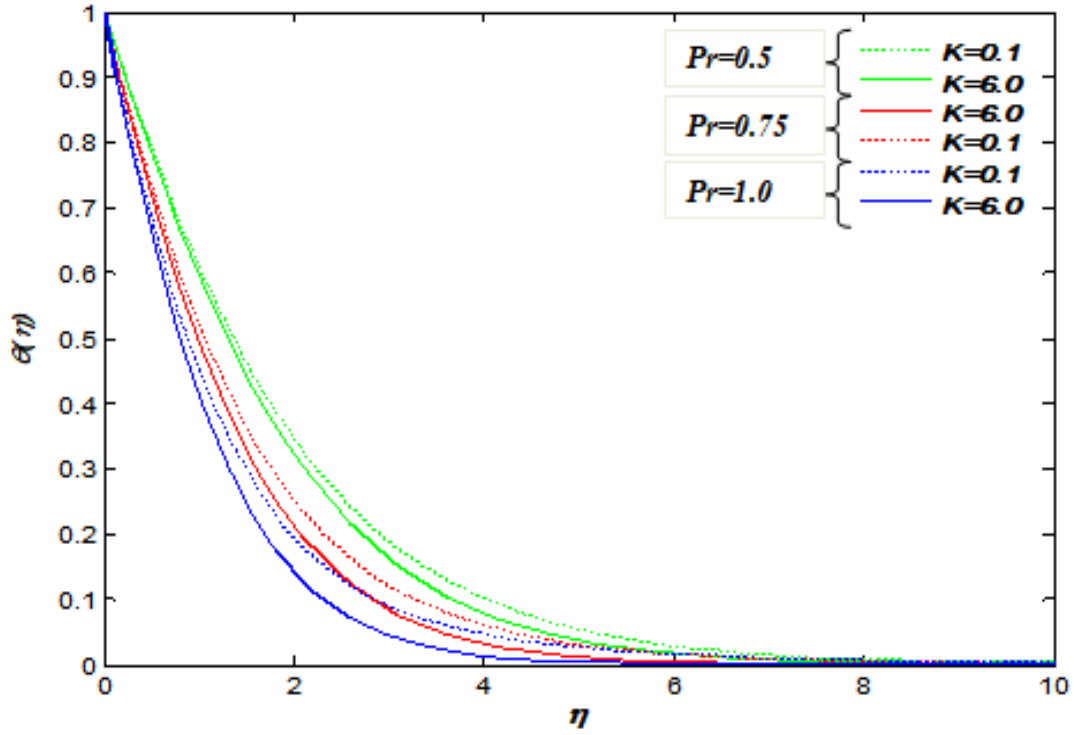


Figure IV-13 : Temperature profiles $\theta(\eta)$ for different values of *Pr*.

(Gr_x = 2.0, f_w= 1.0, *Sc* = 0.3, *M*= 1.0, *Ec*=0.1)

The trend observed in Fig is inverted for the species concentration profile, as revealed by the results displayed in Fig :

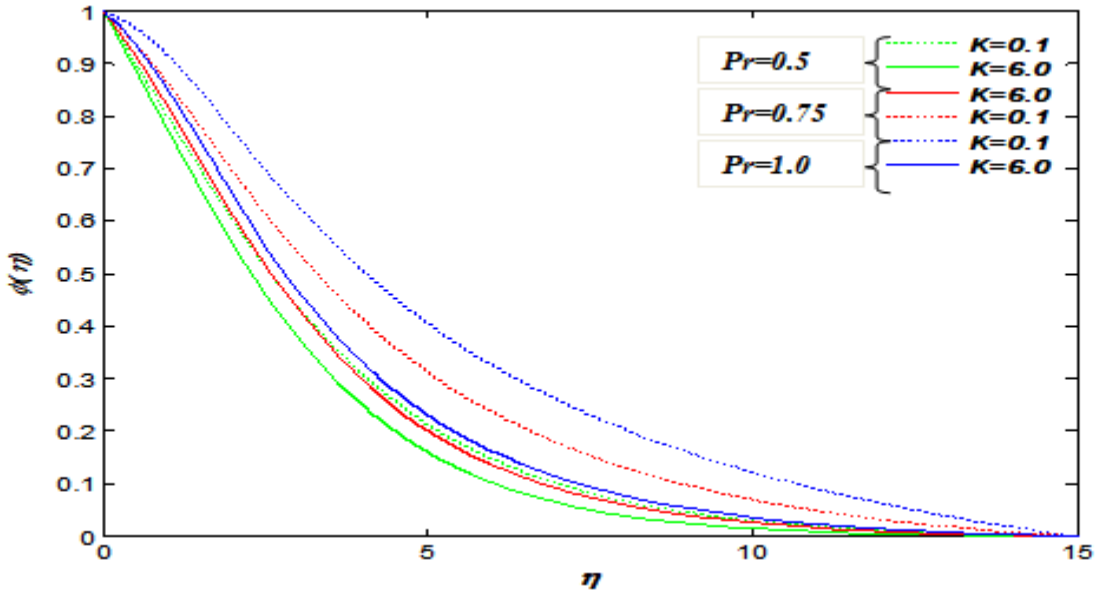


Figure IV-14 : Concentration profiles $\phi(\eta)$ for different values of *Pr*.

(Gr_x = 2.0, f_w= 1.0, *Sc* = 0.3, *M*= 1.0, *Ec*=0.1,).

General conclusion

Conclusion

The effects of magnetic field effect on steady laminar boundary layer flow of an incompressible electrically conducting micropolar fluid over a permeable vertical moving plate are studied. The similarity transformations are involved and the governing system of non linear partial differential equations is converted into a set of non linear ordinary differential equations. Numerical results are presented and we can conclude the following from our investigation:

The magnetic parameter has a strong effect on the characteristics of the micropolar fluid flow. It plays other dissipation effect which can affect substantially the multiple exchanges of the mass and energy transfers.

Working with high microplar leads to modifying the temperature, angular velocity and species mass profiles, which in turn affect the rates of heat and mass, but the effect is more perceptible for the flow velocity, and greater influence is observed for the skin friction coefficient.

It is clear that the suction/injection of the permeable plate can be modified the flow, angular velocity and dimensionless temperature and mass.

Bibliographic reference

Bibliographic – Reference

(1): G.C. Bourantas, V.C. Loukopoulos. Modeling the natural convective flow of micropolar nanofluids,International Journal of Heat and Mass Transfer. (2014), Vol 68, pp 35–41.

(2) : Eringen, A.C. Theory of micropolar fluids, Journal Mathematical Mechanics. (1) (1966), Vol. 16, pp 1–18.

(3) : E. Priyadarshini, N. Pradhan, A. K. Pradhan, and P. Pradhan. Label free and high specific detection of mercury ions based on silver nano-liposome, Spectrochim. Acta A Mol. Biomol. Spectrosc. (2016), Vol 163,pp 127–133.

(4) : Synthesis of silver nanoparticles by sophorolipids: effect of temperature and sophorolipid structure on the size of particles, J. Chem. Sci. M. B. Kasture, P. Patel, A. A. Prabhune, C. V. Ramana, A. A. Kulkarni, and B. L. V. Prasad. (2008), Vol 120, pp 515–520.

(5) : C. G. Kumar, S. K. Mamidyala, B. Das, B. Sridhar, G. S. Devi, and M. S. L. Karuna. Synthesis of biosurfactant-based silver nanoparticles with purified rhamnolipids isolated from Pseudomonas aeruginosa BS-161R. J. Microbiol. Biotechnol.. 2010, Vol 20, pp 1061–1068.

(6) : Mixed Convection Heat Transfer in Micropolar Nanofuid over a Vertical Slender Cylinder, Chin. Phys. Lett. A. Rehman, S. Nadeem. 2012, Vol 29, pp 1-5.

(7) : A. Ishak, R. Nazar, I. Pop. Magnetohydrodynamic (MHD) flow of a micropolar fluid towards a stagnation point on a vertical surface, Computational Mathematical Applications. 2008, Vol 56, pp 3188–3194.

(8) : Das, K. Influence of thermophoresis and chemical reaction on MHD micropolar fluid flow with variable fluid properties, International Journal Heat mass transfer. 2012, Vol 55, pp 766-774.

(9) : Mahmoud, M.A.A. Thermal radiation effects on MHD flow of a micropolar fluid over a stretching surface with variable thermal conductivity, Physica A. 2007, pp 401–410.

(10) : D. Pal, S. Chatterjee. Mixed convection magnetohydrodynamic heat and mass transfer past a stretching surface in a micropolar fluid-saturated porous medium under the influence of Ohmic heating, Soret and Dufour effects, Communications Nonlinear Science Numerical Simulation. 2011, Vol 16, pp 1329–1346.

(11) : M.A Seddeek, S.N Odda, M.Y akl, M.S Abdelmeguid. Analytical solution for the effect of radiation on flow of a magneto-micropolar fluid past a continuously moving plate with suction and blowing, Computational Materials Science. (2009), Vol 45, pp 423– 428.

(12) : Ishak, R. Nazar, I. Pop. MHD boundary-layer flow of a micropolar fluid past a wedge with constant wall heat flux, Communications Nonlinear Science Numerical Simulation. 2009, Vol 14, pp 109–118.

(13) : M.A.A Mahmoud, S.E Waheed. MHD stagnation point flow of a micropolar fluid towards a moving surface with radiation, Meccanica. (2012), Vol 47, pp 1119–1130.

(14) : Aziz, M. Abd-El. Thermal radiation effects on magnetohydrodynamic mixed convection flow of a micropolar fluid past a continuously moving semi-infinite plate for high temperature differences, Acta Mechanica. 2006, Vol 187, pp 113–127.

(15) : E.M Elbarbary, N.S Elgazery. Flow and heat transfer of a micropolar fluid in an axisymmetric stagnation flow on a cylinder with variable properties and suction, Acta Mechanica. 2005, Vol 176, pp 213–229.

(16) : A.J Chamkha, R.A Mohamed , S.E Ahmed. Unsteady MHD natural convection from a heated vertical porous plate in a micropolar fluid with Joule heating, chemical reaction and radiation effects, Meccanica. 2011, Vol 46, pp 399–411.

(17) : J.P Ribeiro, J.A Grüss. Nanofluides pour les applications thermiques, Techniques de l'Ingénieur; nm5115. 2009.

(18) : Choi, S. Enhancing thermal conductivity of fluids with nanoparticles in developments and applications of non-Newtonian flows, edited by D.A. Siginer, H.P. Wang. 1995, Vol 66, pp 99–105.

(19) : G. R. S Reddy, K. Mahes. Combined Convection on a Vertical Cylinder in a Non-Newtonian Nanofluid, Journal of Nanofluids. 2013, Vol 2, pp 157-164.

(20) : Karwa, Rajendra. HEAT AND MASS TRANSFER. Second Edition. India : Springer Nature Singapore Pte Ltd, 2020. pp 1041-1042.

(21) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 656-657.

(22) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 772-773.

(23) : Karwa, Rajendra. HEAT AND MASS TRANSFER. Second Edition. s.l. : Springer Nature Singapore Pte Ltd, 2020. pp 1043-1044.

(24) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 662-663.

(25) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 800-801.

(26) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 664-665.

(27) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. s.l. : S.CHAND & COMPANY LTD, 2012. pp 678-679.

(28) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 1-2.

(29) : Karwa, Rajendra. HEAT AND MASS TRANSFER. Second Edition. India : Springer Nature Singapore Pte Ltd, 2020. pp 1-2.

(30) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 1-2.

(31) : HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 10-11.

(32) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 8-9.

(33) : Karwa, Rajendra. HEAT AND MASS TRANSFER. Second Edition. India : Springer Nature Singapore Pte Ltd, 2020. pp 3-4.

(34) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 285-286.

(35) : HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 293-294.

(36) : HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 434-435.

(37) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 507-508.

(38) : C.P.Kothandraman. HEAT AND MASS transfer. Third Edition. s.l. : NEW AGE INTERNATIONAL PUBLISHERS, 2006. pp 437-438.

(39) : Er.R.K.RAJPUT. HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 352-353.

(40) : HEAT AND MASS TRANSFER. Fifth Edition. India : S.CHAND & COMPANY LTD, 2012. pp 363-364.

(41) : Eastman, Stephen U. S. Choi and Jeffrey A. enchancing thermal conductivity of fluids with nanoparticules,developments and application of non-Newtonian flow. s.l. : ASME International Mechanical Engineering Congress & Exposition, 1995, Vol FED-Vol.231/MD-Vol.66, pp 2-9.

(42) : TZENG, S.-C., LIN, C.-W., et HUANG, K. D. Heat Transfer Enhancement of Nanofluids in Rotary Blad Coupling of Four-Wheel-Drive Vehicles. s.l. : Department of Mechanical Engineering,Chienkuo Technology University, 1 Cheih Shou N Rd, Chang Hua, 500, Taiwan, R.O.C, 23/11/2005, Vol 179, pp 11-23.

(43) : Zhang, Zhijun Zhang and Qunji Xue and Jun. Synthesis, Structure and Lubricating Properties of Dialkyidithiophosphate-Modified Mo-S Compound Nanoclusters. s.l. : Chemistry Department, Henan University, Kaifeng 475001 Henan, PR China, Auguest 1997, Vol 209, pp 8-12.

(44) : Chen, C.YTsai and H.T. Chien and P.P. Ding and B. Chan and T.Y. Luh and P.H. Effect of structural character of gold nanoparticle in nanofluid on heat pipe thermal performance. s.l. : Department of Chemistry, National Taiwan University, Taipei 10617, Taiwan, ROC, March 2004, Vol 58, Issue 9, pp 1461-1465.

(45) : Murli.Tirumala, H.B.Ma and C.Wilson and B.Borgmeyer and K.Park and Q.Yu and S.U.S.Choi. Effect of nanofluid on the heat transport capability in an oscillating heat pipe. s.l. : Intel Corporation, Hillsboro, Oregon 97124.American Institute of Physics., 07 December 2005 Accepted: 09 March 2006 Published Online: 05 April 2006.

(46) : Felix, Andreas Jordan and Regina Scholz and Peter Wust and Horst Fähling and Roland. Magnetic Fluid Hypothermia (MFH): Cancer Treatment with AC Magnetic Field Induced Excitation of Biocompatible Super paramagnetic Nanoparticles. s.l. : Department of Radiation Oncology (WE 07), University Clinic Charité, Medical Faculty of the Humboldt Universität zu Berlin, Campus Virchow-Klinikum, SFB 273, Augustenburger Platz 1, 13353 Berlin, Germany, July 1999, Vol 201, pp 413-419.

(47) : SALAGER, Jean-Louis. Surfactants types and uses. FIRP booklet. s.l. : Mérida-Venezuela, 2002. Vol 300.

(48) : Bewa, H. Etude ALCIMED pour l'ADEME. s.l. : Marché actuel des bioproduits industriels et des biocarburants & évolutions prévisibles à échéance 2015/2030, Avril 2007.

(49) : Rondel, C. Thèse de doctorat. s.l. : France (2009).

(50) : BOUKHATEM, Asma, and Rabiaa AOUF. Contribution à l'étude des propriétés anti – oxydative et de l'éfficacité anticorrosive sur l'acier API 5L X52 d'une prodigiosine d'une souche de Serratiamarcescens. 2016.

(51) : Parthipan, P., Sabarinathan, D., Angaiah, S., and Rajasekar, A.,Glycolipid biosurfactant as an eco-friendly microbial inhibitor for the corrosion of carbon steel in vulnerable corrosive bacterial strains. Journal of Molecular Liquids. s.l. : Environmental Molecular Microbiology Research Laboratory, Department of Biotechnology, Thiruvalluvar University, Serkkadu, Vellore, Tamil Nadu 632 115, India, 1 July 2018, Vol 261, pp 473-479.

(52) : Zajic, J. E., William Seffens, and Chandra Panchal. Biosurfactants. Critical Reviews in Biotechnology 1.2. 1983, Vol 1, pp 87-107.

(53) : Pacwa-Płociniczak, M., Płaza, G. A., Poliwoda, A., & Piotrowska-Seget, Z. Characterization of hydrocarbon-degrading and biosurfactant-producing Pseudomonas sp. P-1 strain as a potential tool for bioremediation of petroleum-contaminated soil. Environmental Science and Pollution Research. s.l. : Department of Microbiology, University of Silesia, Jagiellońska 28, 40-032, Katowice, Poland, 2014, Vol 21, pp 9385-9395.

(54) : BANAT, IBRAHIM M. Biosurfactants production and possible uses in microbial enhanced oil recovery and oil pollution remediation: a review. Bioresource technology. s.l. : Department of Biology, United Arab Emirates University, PO Box 17551, Al-Ain, Abu-Dhabi, United Arab Emirates, 1995, Vol 51, pp 1-12.

(55) : Banat, Ibrahim M., Ravinder S. Makkar, and Swaranjit Singh Cameotra. Potential commercial applications of microbial surfactants. Applied microbiology and biotechnology. s.l. : Biotechnology Group, Faculty of Science, University of Ulster, Coleraine, BT52 1SA, Northern Ireland, 2000, Vol 53, pp 495-508.

(56) : Hatha, A. A. M., Gakpe Edward, and K. S. M. Pattanathu Rahman. Microbial biosurfactants–review. 2 July 2007, Vol 3, pp 1-17.

(57) : Healy, M. G., C. M. Devine, and R. Murphy. Microbial production of biosurfactants. Resources, conservation and recycling. s.l. : Department of Chemical Engineering, The Queen's University of Belfast, David Keir Building, Stranmillis Road, Belfast, N. Ireland, UK, November 1996, Vol. 18, pp. 41-57.

(58) : Bessaïh Rachid and Marty Philippe and Kadja, Mahfoud. Hydrodynamics and Heat transfer in disk driven flows under axial magnetic fields. s.l. : International Journal of Transport Phenomena, 2003/01/01, Vol 5, pp 259-278.

(59) : Rokni, Mohsen Sheikholeslamiet And Houman B. Simulation of nanofluid heat transfer in presence of magnetic field,International Journal of Heat and Mass Transfe. 2017, Vol 115, pp 1203-1233.

(60) : Bourantas, V.C. Loukopoulos. Modeling the natural convective flow of micropolar nanofluids,Journal of Heat and Mass Transfer. s.l. : Department of Physics, University of Patras, Patras, 26500 Rion, Greece, January 2014, Vol 68, pp 35-41.

(61) : Eringen, A. C. Theory of micropolar fluids, Journal of Mathematics and Mechanics. s.l. : Indiana University Mathematics Department, 1966, pp 1-18.

(62) : Subba Rama, Reddy Gorla, and Shoichiro Nakamura. Mixed convection of a micropolar fluid from a rotating cone, International journal of heat and fluid flow. s.l. : Mechanical Engineering University, Cleveland State University, Cleveland, OH, USA, 1995, Vol 16, pp 69-73.

(63) : Lok, Yian Yian, Norsarahaida Amin, and Ioan Pop. Unsteady mixed convection flow of a micropolar fluid near the stagnation point on a vertical surface. International journal of thermal sciences. s.l. : Center for Academic Services, Kolej Universiti Teknikal Kebangsaan Malaysia, 75450 Ayer Keroh, Melaka, Malaysia, December 2006, Vol 45, pp 1149-1157.

(64) : Aydın, Orhan, and Ioan Pop. Natural convection in a differentially heated enclosure filled with a micropolar fluid. International Journal of Thermal Sciences. s.l. : Department of Mechanical Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey, October 2007, Vol 46, pp 963-969.

(65) : Ishak, Anuar, Roslinda Nazar, and Ioan Pop. Stagnation flow of a micropolar fluid towards a vertical permeable surface.International Communications in Heat and Mass Transfer. s.l. : School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, March 2008, Vol 35, pp 276-281.

(66) : Ishak, Anuar, Roslinda Nazar, and Ioan Pop. Dual solutions in mixed convection boundary layer flow of micropolar fluids, Communications in Nonlinear Science and Numerical Simulation. s.l. : School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, April 2009, Vol 14, pp 1324-1333.

(67) : Rehman, Abdul, and S. Nadeem. Mixed convection heat transfer in micropolar nanofluid over a vertical slender cylinder. Chinese Physics Letters 124701. s.l. : Department of Mathematics, University of Balochistan, Quetta, Pakistan, 2012, Vol 29, p 12.

(68) : Ishak, Anuar, Roslinda Nazar, and Ioan Pop. Magnetohydrodynamic (MHD) flow of a micropolar fluid towards a stagnation point on a vertical surface. Computers & Mathematics with Applications. s.l. : School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, December 2008, Vol 56, pp 3188-3194.

(69) : Das, Kalidas. Influence of thermophoresis and chemical reaction on MHD micropolar fluid flow with variable fluid properties. International journal of heat and mass transfer. s.l. : Department of Mathematics, Kalyani Government Engineering College, Kalyani, Nadia, West Bengal 741235, India, November 2012, Vol 55, pp 7166-7174.

(70) : Mahmoud, Mostafa AA. Thermal radiation effects on MHD flow of a micropolar fluid over a stretching surface with variable thermal conductivity. Physica A: Statistical Mechanics and its Applications. s.l. : Department of Mathematics, Faculty of Science, Benha University, Benha 13518, Egypt, 1 March 2007, Vol 410, pp 375-401.

(71) : Pal, Dulal, and Sewli Chatterjee. Mixed convection magnetohydrodynamic heat and mass transfer past a stretching surface in a micropolar fluid-saturated porous medium under the influence of Ohmic heating, Soret and Dufour effects. Communications in Nonlinear Science and Numerical Simulati. s.l. : Department of Mathematics, Visva-Bharati University, Santiniketan, West Bengal 731235, India, March 2011, Vol 16, pp 1329-1346.

(72) : M.A Seddeek, S.N Odda, M.Y akl, M.S Abdelmeguid. Analytical solution for the effect of radiation on flow of a magneto-micropolar fluid past a continuously moving plate with suction and blowing. Computational Materials Science. s.l. : Department of Mathematics, Faculty of Science, Qassim University, P.O. Box 237, Burieda 81999, Saudi Arabia, April 2009, Vol 45, pp 423-428.

(73) : Ishak, Anuar, Roslinda Nazar, and Ioan Pop. MHD boundary-layer flow of a micropolar fluid past a wedge with constant wall heat flux. Communications in Nonlinear Science and Numerical Simulation. s.l. : School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, January 2009, Vol 14, pp 109-118.

(74) : Waheed, Mostafa A. A. Mahmoud and Shimaa E. MHD stagnation point flow of a micropolar fluid towards a moving surface with radiation, Meccanica. s.l. : Department of Mathematics, Faculty of Science, Benha University, Benha, 13518, Egypt, 2012, Vol 45, pp 1119-1130.

(75) : Aziz, Abd-El. Thermal radiation effects on magnetohydrodynamic mixed convection flow of a micropolar fluid past a continuously moving semi-infinite plate for high temperature differences. Acta Mechanica. s.l. : Department of Mathematics, Faculty of Science, Helwan University, P. O. Box 11795, Cairo, Egypt, 2006, Vol 187, pp 113-127.

(76) : Elbarbary, E. M. E., and N. S. Elgazery. Flow and heat transfer of a micropolar fluid in an axisymmetric stagnation flow on a cylinder with variable properties and suction (numerical study). Acta Mechanica. s.l. : Department of Mathematics, Faculty of Education, Ain Shams University, Roxy Hiliopolis, Cairo, Egypt, 2005, Vol 176, pp 213-229.

(77) : Chamkha, A.J., Mohamed, R.A. and Ahmed, S.E. Unsteady MHD natural convection from a heated vertical porous plate in a micropolar fluid with Joule heating, chemical reaction and radiation effects. Meccanica. s.l. : Manufacturing Engineering Department, The Public Authority for Applied Education and Training, Shuweikh, 70654, Kuwait, 2011, Vol 46, pp 399–411.

(78) : Gruss, J. A., and J. P. Ribeiro.;Nanofluides pour les applications thermiques. Techniques de l'Ingénieu,nm5115. 2009.

(79) : Choi, S. U. S., Singer, D. A., & Wang, H. P. Developments and applications of non-Newtonian flows. Asme Fed. 1995, Vol 66, pp 99-105.

(80) : Gorla, Rama Subba Reddy et Kumari, Mahesh. Combined convection on a vertical cylinder in a non-Newtonian nanofluid. Journal of Nanofluids. s.l. : American Scientific Publishers, June 2013, Vol 2, pp 157-164.

(81) : Hsiao, Kai-Long. Heat and mass transfer for micropolar flow with radiation effect past a nonlinearly stretching sheet. Heat and mass transfer. s.l. : Department of the Electrical Engineering, Diwan University, 87-1, Nansh Li, Madou Jen, T'ainan, Taiwan, Republic of China, 2010, Vol 46, pp 413-419.

(82) : Ahmadi, Goodarz. Self-similar solution of imcompressible micropolar boundary layer flow over a semi-infinite plate. International Journal of Engineering Science. s.l. : Department of Physics, University of Saskatchewan, Saskatoon, Canada and School of Engineering, Pahlavi University, Shiraz, Iran, 1976, Vol 14, pp 639-646.

(83) : Yacob, Nor Azizah, and Anuar Ishak.,MHD flow of a micropolar fluid towards a vertical permeable plate with prescribed surface heat flux. Chemical engineering research and design. s.l. : Faculty of Computer and Mathematical Sciences, Universiti Teknologi MARA Pahang, 26400 Bandar Tun Razak Jengka, Pahang, Malaysia, November 2011, Vol 89, pp 2291-2297.