

الجمهورية الجزائرية الديمقراطية الشعبية

PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

وزارة

التعليم

البلد
البحث العلمي

Ministry of higher education and scientific research

جامعة أبي بكر بلقايد - تلمسان

Aboubakr Belkaïd University of Tlemcen
Faculty of Technology



THESIS

Submitted in partial fulfilment of the requirement for the degree of master in mechanical engineering

Specialization: Energetics engineering.

By MUSA Marah

Topic:

Comparative study between single nanofluids and hybrid nanofluids for the performance enhancement of flat plate solar collector's

Defended publically on the 21st June 2026 before the jury compose of :

Pr Benahmed Lamia	Prof	University of Tlemcen	President
Pr Mostefaoui Amina	Prof	University of Tlemcen	Examinator
Dr Sichaib Amel	MCA	University of Tlemcen	Supervisor
Pr Alliane Khalid	Prof	University of Tlemcen	Co-supervisor

Academic year : 2025/2026

ACKNOWLEDGEMENT

First and foremost, I would like to thank Allah, the Almighty, for his direction, favor, and heavenly grace in finishing this work.

I would like to take this opportunity to express my sincere gratitude to the governments of Algeria and Sierra Leone for providing me with this fully funded scholarship. I would especially like to thank the mechanical engineering department head and staff at the University of Tlemcen for their unwavering support throughout my academic career.

I sincerely thank my brilliant supervisor, Professor Sichaid Amel, and my wonderful co-supervisor, Professor Aliane Khalid, for believing in me and providing me with the chance to work on this project. I was able to grow as a numerical and experimental investigator as well as a researcher thanks to this opportunity. They provided me with academic support and guidance at little or no cost during this journey. I continued to be appreciative.

I want to express my gratitude to Mr. Hassan F. Dabor for his priceless assistance. Additionally, I would like to express my gratitude to Alimamy M. Mansaray, Mr. Abdulia Koroma, Eng. Madie Kamara, and Eng. Moriba Berete, all of whom were instrumental in the entire project. I want to thank my friends and fellow Sierra Leonean students in Algeria for their support. For this, I owe you all.

Lastly, I want to express my sincere gratitude to my parents for their encouragement and support. May God bless you all.

DEDICATION

I dedicate this entire work to my parents, Mr. Hassan Foday Dabor, and my entire family in appreciation of their unwavering love. I also dedicate it to my adorable, kind, encouraging, and loving coworkers and friends. I sincerely appreciate all of your help and inspiration throughout my research. Many thanks to all of you.

Absract :

This work presents a comparative numerical study of the thermophysical performance of simple and hybrid nanofluids. The main objective is to evaluate the effect of adding nanoparticles on the improvement of heat transfer in a forced flow. Two types of nanofluids were considered: a simple nanofluid based on AL₂O₃ nanoparticles dispersed in water and a hybrid nanofluid composed of AL₂O₃ and Cu.

We conducted a numerical simulation using the FLUENT code to model turbulent flow in a rectangular channel. The K- ϵ model was chosen for this task.

The results obtained show that the use of nanofluids significantly improves thermal performance compared to the base fluid, while the hybrid nanofluid exhibits superior efficiency over the simple nanofluid due to its enhanced thermophysical properties. This study confirms the potential of hybrid nanofluids for thermal management and heat exchange applications.

Keywords:

Simple nanofluid, hybrid nanofluid, heat transfer, numerical simulation, thermal performance.

Résumé :

Ce travail présente une étude numérique comparative des performances thermophysiques des nanofluides simples et hybrides. L'objectif principal est d'évaluer l'effet de l'ajout de nanoparticules sur l'amélioration du transfert de chaleur dans un écoulement forcé. Deux types de nanofluides ont été considérés : un nanofluide simple à base de nanoparticules d'AL₂O₃ dispersées dans l'eau et un nanofluide hybride composé d'AL₂O₃ et de Cu.

Nous avons réalisé une simulation numérique à l'aide du code FLUENT pour modéliser un écoulement turbulent dans un canal rectangulaire. Le modèle K- ξ a été retenu pour cette tâche.

Les résultats obtenus montrent que l'utilisation des nanofluides améliore significativement les performances thermiques par rapport au fluide de base, tandis que le nanofluide hybride présente une efficacité supérieure au nanofluide simple grâce à ses propriétés thermophysiques améliorées. Cette étude confirme le potentiel des nanofluides hybrides pour les applications de gestion thermique et d'échange de chaleur.

Mots clés :

Nanofluide simple, nanofluide hybride, transfert de chaleur, simulation numérique, performance thermique.

المـلـخـص :

يقدم هذا العمل دراسة عددية مقارنة للأداء الحراري والفيزيائي للسوائل النانوية البسيطة والهجينة. الهدف الرئيسي هو تقييم تأثير إضافة الجسيمات النانوية على تحسين نقل الحرارة في التدفق القسري. تم اعتبار نوعين من السوائل النانوية: سائل نانوي بسيط (Al_2O_3) مشتت في الماء، وسائل نانوي هجين يتكون من (Al_2O_3) والنحاس (Cu).

أجريت محاكاة عددية باستخدام كود FLUENT لنمذجة التدفق المضطرب في قناة مستطيلة، وتم اختيار نموذج $K-\epsilon$ لهذه المهمة.

تظهر النتائج المستخلصة أن استخدام السوائل النانوية يحسن الأداء الحراري بشكل كبير مقارنة بالسوائل الأساسي، بينما يظهر السائل النانوي الهجين كفاءة متفوقة على السائل النانوي البسيط بفضل خصائصه الحرارية والفيزيائية المحسنة. تؤكد هذه الدراسة على إمكانيات السوائل النانوية الهجينة في إدارة الحرارة وتطبيقات التبادل الحراري.

الكلمات المفتاحية: سائل نانوي بسيط، سائل نانوي هجين، نقل الحرارة، محاكاة عددية، الأداء الحراري.

Table of contents

ACKNOWLEDGEMENT	i
DEDICATION	ii
Absract :	iii
GENERAL INTRODUCTION	1
GENERAL INTRODUCTION.....	2
CHAPTER I: General information on flat panel solar collectors	5
Chapter 1: General information on flat panel solar collectors	6
I.1 Introduction:	6
I.2 General Overview of Flat Plate Solar Collector System:	6
I.2.1 Components of a Flat Plate Collector:	9
I.2.2 Some important definitions:	12
I.2.3 Installation procedure of flat plates solar collector:	13
I.2.3.1 Planning and marking:	13
I.2.3.2 Ditching the Area:	13
I.2.3.3 Laying the pipes:	13
I.2.3.4 Refilling and compacting:	13
I.2.3.5 The heat pump's attachment:	13
I.2.4 Thermal evaluation of solar collectors with flat plates:	14
I.2.4.1 Eneegy Balance and heat gain:	14
I.2.4,2 Collector thermal efficiency (η_c)	14
I.2.5 FPSC Working Principle:	15
I.2.5.1 Absorption of sunlight:	15
I.2.5.2 Transfer of heat to tubes:	15
I.2.5.3 Storage:	15
I.2.5.4 Reheating cooler fluid	15
I.2.6 Types of Flat Plate Collectors:	15
I.2.6.1 Types of Flat Plate Collectors Based of Glazed:	15
I.1.6.2 Types of flat plates solar collector base on fluid:	18

I.1.6.3 Types of Flat Plate Collectors in accordance with configuration:	19
I.1.7 Solar-powered water heating systems:	19
I.1.8 Influencing factors of flat plate solar collector performance:	20
I.1.8.1 Light from the Sun (Solar Irradiation):	20
I.1.8.2 The Ambient Temperature:	21
I.1.8.3 Flow Rate of the Heat Transfer Fluid:	21
I.1.8.4 Collector Tilt and Orientation	21
I.1.8.5 Absorber Coating and Glazing	21
I.1.8.6 Quality of Insulation	22
I.1.8.7 Age and Maintenance of Collector:	22
I.1.8.8 Selective Surfaces:	22
I.1.8.9 Dust on Cover Plate:	22
Chapter 2: Literature review	24
II.1 Introduction:	24
II.2. History of Nanofluids:	24
II.3 The evaluations of Nanofluid Research:	27
II.3.1 Influence of Nanoparticle Size on Nanofluid Behaviour (The Size of the Particles Matters):	27
II.3.2 Concept and applications of nanofluids:	27
II.3.3 Classification of nanofluids :	29
II.4 Heat Transfer Modelling on Nanofluids:	30
II.4.1 Model of Dispersion:	30
II.4.2 Modelling of Particle Migration:	30
II.4.3 Modelling with Two Components:	30
II.4.4 Modelling with a Single Component:	31
II.5 Preparation of nanofluids:	32
II.5.1 Single-step approach:	32
II.5.2 Two-step approach:	33
II.5.3 Some Other Methods:	33
II.6 Thermophysical properties of nanofluids:	34
II.6.1 Thermal conductivity:	34

II.6.2 Dynamic viscosity:	35
II.6.3 Density and specific heat of nanofluids :.....	35
II.7 Thermodynamic properties (Rho, Cp, K):.....	36
II.7.1 Combination types (Al ₂ O ₃ /TiO ₂ /graphene):.....	36
II.8 Applications of Nanofluids:	37
II.8.1 Applications in Biological and Biomedical:	37
II.8.2 Solar Industry:.....	37
II.8.3 Industrial Cooling Applications:	38
II.8.4 Smart Fluid:	38
II.9 Stability of nanofluids :.....	38
II.9.1 Chemical treatment for enhance nanofluid stability:	39
II.9.2 Physical treatment for enhance nanofluid stability:	40
II.10 Advantages of using nanofluid in the solar collectors:	40
II.11 Use of nanofluids in flat plate solar collector system:	41
II.12 Computational fluid dynamics:	41
II.13 COMPARATIVE SYNTHESIS OF THE LITERATURE	43
II.14 SCIENTIFIC GAP IN THE LITERATURE:	44
II.15 Summary of literature review:	45
CHAPTER III: Research Methodology	46
III.1 Introduction:	47
III.2 Simulation Procedure and Presentation of the Physical Model:	47
III.2.1 Architecture of the collector and domain idealisation	47
III.2.2 Nanofluids Systems Studied:	48
III.3 Theoretical Background for Thermophysical Properties	48
III.3.1 Basic Assumptions:	49
III.3.2 Mathematical Modeling	49
III.3.2.1 Governing Equations for Single-Phase Fluid Flow:	49
III.3.3 Thermophysical Property Correlations of water and water base nanofluid	51
III.3.4 Pressure Drop and Pumping Power of Nanofluid:	53
III.3.5 Efficiency of FPSC :	54

III.4 Boundary Conditions:	54
III.5 Principle of finite volume method:	55
III.6 Advantages of the finite volume method:	55
III.7 Mesh concept:	55
III .8 Presentation of the FLUENT software:	56
III .8 .1 Introduction:	56
III.9 Presentation of Gambit:	56
III.9.1 Starting Gambit:	56
III.9.2 Geometry Construction:	57
III.9.3. Mesh:	57
III .9.3.1 Structured mesh (quadra/hexa):	58
III.9.3.2 Unstructured mesh (triang):	58
III.9.4 Definition of Boundaries:	59
III.10 Presentation of Fluent:	60
III .10.1 Importing the Geometry:	60
III .10.2 Verification of the imported mesh:	60
III .10.4 Choice of Solver:	60
III .10.5 The energy equation:	61
IV.10.6 Choice of Turbulence Model:	61
Figure III.7: “Turbulence Model”.	61
III.10.7 Definition of fluid characteristics:	62
III .10.8 Operating conditions :	62
III.10.9 Boundary Conditions:	63
III.10.10 Choice of order of equations and the algorithm:	65
III.10.11 Initialisation:	66
III.10.12 Initialisation of calcul	66
III .10.13 Launching the calculation:	67
Conclusion:	68
CHAPTER IV: Results and discussion	68
IV.1 Introduction:	69

IV.2 The Mesh :	69
IV.4 Velocities Distribution:	71
IV.4.1 Single nanofluid ($\text{Al}_2\text{O}_3/\text{H}_2\text{O}$):	72
IV.4.3 General comparison:	72
IV.5 Distribution of the total pressure of the total pressure:	74
IV.6 Temperature Distribution:	75
Chapter 5 CONCLUSION: AND RECOMMENDATION	79
General conclusion.....	80
Recommendation	81
REFERENCE	82

List of figures

FIGURE I.1 WORKING PRINCIPLE OF FLAT PLATES SOLAR COLLECTOR.....	7
FIGURE.I.2:CLASSIFICATION OF FPSC(18)	9
FIGURE.I.3:STRUCTURE OF FPSC	10
FIGURE.I.4: PARTS OF FLAT PLATE SOLAR COLLECTORS.....	12
FIGURE .I.5:UNGLAZED COLLECTORS (BARE PLATE SOLAR COLLECTOR), NORTON & EKECHUKWU (14)".	16
FIGURE.I.6:FRONT PASS SOLAR COLLECTOR	17
FIGURE.I.7: BACK PASS SOLAR COLLECTOR.....	17
FIGURE.I.8:PARALLEL PASS SUSPENDED SOLAR COLLECTOR.....	18
FIGURE.1.9: DOUBLE PASS [SUSPENDED AIR HEATING SOLAR COLLECTOR]	18
FIGURE. I.10: TYPES OF SOLAR WATER HEATING SYSTEMS	20
FIGURE. II.1: "NANOFLUID PREPARATION METHOD".	26
FIGURE.II.2: "NFs APPLICATIONS".	28
FIGURE. II.3. "CLASSIFICATION OF NANOFLUIDS (28)	29
FIGURE. II.4 "DESCRIPTION OF THE SINGLE-STAGE APPROACH (31)"	32
FIGURE. II.5: "DESCRIPTION OF THE TWO-STEP APPROACH (32)".	33
FIGURE II.6: "ULTRASONIC TYPES. (A) PROBE ULTRASONIC (B) BATH ULTRASONIC ".	40
<i>figure III.1: "Launching Gambit"</i>	56
FIGURE III.2: "THE OPERATIONS TO CONSTRUCT A GEOMETRY"	57
FIGURE III.3: "THE FRAMEWORK OF OUR STUDY".	59
FIGURE III.4: "MESH EXPORT"	59
FIGURE III.5: "SOLVER SELECTION".	60
FIGURE III.6: "ENERGY EQUATION".	61
FIGURE III.7: "TURBULENCE MODEL".	61
FIGURE III.8: "DEFINITION OF FLUID CHARACTERISTICS	62
FIGURE III.9: "CHOICE OF REFERENCE PRESSURE"	62
FIGURE III.10: "FLUID INLET VELOCITY.....	63
Figure III.11: "Boundary Conditions at the Border"	64
FIGURE III.12 : « PRESSURE OUTLET ».....	65
FIGURE III.13: "CHOICE OF ORDER OF EQUATIONS AND THE ALGORITHM".	66
<u>FIGURE III.14: " RESIDUAL GRAPH "</u>	67
FIGURE III.15: "ITERATION OF THE SOLUTION"	67
FIG. IV.1 "MESH OF THE GEOMETRIES.....	69
FIG. IV.2 : « STREAMLINES FOR A SINGLE NANOFLUID».....	70
FIG. IV.3 : « STREAMLINES FOR A HYBRID NANOFLUID».	70
FIG. IV.4 : « VELOCITY DISTRIBUTION FOR A SINGLE NANOFLUID".	71
FIG. IV.5: « VELOCITY DISTRIBUTION FOR A HYBRID NANOFLUID	71
FIG. IV.6: "VELOCITY PROFILES FOR THE TWO CONFIGURATIONS AT DIFFERENT SECTIONS AT POSITIONS $x=50\text{mm}$, $x=150\text{mm}$, $x=270\text{mm}$, AND $x=600\text{mm}$ ".	73
FIG. IV.7 : « TOTAL PRESSURE FOR SINGLE NANOFLUID».....	74
FIG. IV.8: « TOTAL PRESSURE FOR HYBRID NANOFLUID».	75
FIG. IV.9: « TOTAL TEMPERATURE FOR SINGLE NANOFLUID».	76
FIG. IV.10: « TOTAL TEMPERATURE FOR HYBRID NANOFLUID».	76
FIG. IV.11: «PROFIL OF TEMPERATURE FOR SINGLE NANOFLUID AT DIFFERENT SECTIONS AT THE POSITION $x=50\text{mm}$, $x=150\text{mm}$, $x=270\text{mm}$ ET $x=600\text{mm}$ ».	77

List of table

TABLE II.1: "A SUMMARY OF RECENT STUDIES ON FPSC USING NANOFLUIDS".	ERREUR ! SIGNET NON DEFINI.
TABLE II.2: "COMPARISON OF NANOPARTICLES"	ERREUR ! SIGNET NON DEFINI.
TABLE III.1: THERMOPHYSICAL PROPERTIES OF BASE FLUIDS AND NANOPARTICLES AT 25°C. (MWCNT AXIAL CONDUCTIVITY; EFFECTIVE SUSPENSION VALUE SUBSTANTIALLY LOWER DUE TO CONTACT RESISTANCE AND ORIENTATION EFFECTS.	ERREUR ! SIGNET NON DEFINI.
TABLE IV.1: "COMPARISON OF THE RESULTS OF VELOCITY, TOTAL PRESSURE, AND TEMPERATURE"	ERREUR ! SIGNET NON DEFINI.

Nomenclature

SYMBOL	DESCRIPTIONS	UNITS
A_c	Absorber plate area	m^2
A	Absorber plate absorptance coefficient	–
T_a	Ambient temperature	$^{\circ}C$
H_c	Collector thermal efficiency	
T_{st}	Collector stagnation temperature	$^{\circ}C$
ρ	Density	kg/m^3
Q_{in}	Energy gain rate	W
τ	Glass cover transmittance coefficient	–
T_{in}	Inlet temperature	$^{\circ}C$
$\dot{m}$	Mass flow rate of working fluid	Kg/s
T_{fm}	Temperature mean of an fluid absorber plate	$^{\circ}C$
T_m	Mean temperature	$^{\circ}C$
T_{out}	Outlet temperature	$^{\circ}C$
U_t	Overall heat loss coefficient	$W/(m^2 \cdot ^{\circ}C)$
C_p	Specific heat capacity	$J/(kg \cdot K)$
G	Solar irradiance	W/m^2
I_T	Solar irradiance incident on the absorber plate	W/m^2
K	Thermal conductivity	$W/(m \cdot K)$
$\tau\alpha$	Transmittance–absorptance product	–
Q_u	Useful heat gain	W

Abbreviations

Abbreviation	Meaning
Al_2O_3	Aluminium Oxide
Al_2O_3 -cu	Aluminium Oxide-copper
ANSYSFluent	Numerical simulation software
CFD	Computational Fluid Dynamics
Cu	Copper
CuO	Copper Oxide
FVM	Finite Volume Method
FPSC	Flat Plate Solar Collector
NF	Nanofluid
HNF	Hybrid Nanofluid
NP	Nanparticle
Nu	Nusselt number
Pr	Prandtl number
SWHS	Solar Water Heating Sy

GENERAL INTRODUCTION

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Globally, energy is an important and necessary resource. People are becoming more serious about renewable energy as an alternative to fossil fuels because of the worsening of environmental pollution brought on by the enormous and disorganized use of carbon-based fossil fuels. One form of sustainable energy is solar energy, which has no temporal constraints and is eco-friendly (1). Previous research stated that solar radiation can be heated by using a solar collector, Solar collectors come in a variety of forms, including flat plates, evacuated tubes, direct absorption, composite parabolic concentrators, and more(2).

Solar thermal energy is one of the most sustainable renewable energy resources for domestic and industrial heating applications (3). The flat plate solar collector (FPSC) is one of the widely used forms of Solar Thermal systems due to its simple construction, low cost, and reliable performance. However, the majority of FPSCs currently deployed are prohibitively low in thermal efficiency because of the limited thermal conductivity of regular heat transfer fluids (water, ethylene glycol), energy lost from the absorber plate and lowered convective heat transfer rates (4).

Nanofluids are fluids, containing nanoparticles which have been proposed and researched in detail to enhance their thermal performance as advanced heat transfer media(5).

Nanofluids are recently developed advanced heat transfer fluids that consist of nanometer-sized solid particles in ordinary base fluids, such as water, ethylene glycol or oil. These nano-particles typically having size of range 1 to 100 nano meter which leads to the significant enhancement in thermophysical properties of the base fluid (thermal conductivity, convective heat transport) making them capable of loading more energy as compared with normal fluids(6).

Nanofluids with enhanced thermal performance are believed to result from increased nanoparticle surface area, improved energy transport pathways, and intensified micro-scale fluid motion around dispersed particles, which facilitate effective heat exchange (7).

Nanofluids are divided into two types: single (mono) nanofluid and hybrid nanofluid. Hybrid nanofluids are a mixture of two or more types of particles dispersed in a single base fluid whereas single nanofluids are prepared by dispersing a single type of nanoparticle in a base fluid. The application of hybrid nanofluids is widely studied because the mixture of two or more different materials can improve the thermal properties of the nanofluids and it is expected to

GENERAL INTRODUCTION

show better performance than that of single nanofluids(8). However, their nature is more complicated and stability, viscosity and flow properties should be taken into account carefully, however the flat plate solar collectors' efficiency remains low. One of the principal factors that influences their efficiency is the type of working fluid through which heat is transferred. Plain fluid like water, ethylene glycol are also widely used as they are readily available and stable. Their ability to absorb and transfer heat efficiently is limited due to their low thermal conductivity when compared with the thermal conductivity of water, which also limits the overall system performance. To address these limitations, researchers are focus on the enhancement of the heat transfer fluids. These fluids are a base fluid in which extremely small solid particles called nanoparticles are suspended

Recent developments in the study of solar collectors show that experts are growing more interested in using nanotechnology in solar devices to boost efficiency. In actuality, research on the use of nanofluids in heat transfer for solar collectors has only focused on a small number of particular nanofluids (9). Each study also employed a different methodology and yielded a different outcome. The investigations were predicated on the utilization of diverse approaches and strategies, and they also yielded a range of outcomes. The studies also used the first law of thermodynamics, which shed light on qualitative performance.

The research will be limited to an examination of flat plate solar collectors.

- 1) study involves selected mono nanofluid ($\text{Al}_2\text{O}_3/\text{water}$) as well as hybrid nanofluid ($\text{Al}_2\text{O}_3 + \text{CuO}/\text{water}$).
- 2) Their performances are evaluated based on thermal efficiency, heat transfer coefficient, and pumping power.
- 3) The study does not include other types of collectors like parabolic solar collectors, CPC solar collectors, and evacuated tube solar collectors.

The study will add valuable information to the research by systematically arranging, reviewing, assessing single and hybrids nanofluid performance and comparative analysis, which will assist fellow researchers and engineers to understand the performances and direct future research towards designing better solar thermal systems .

- This research work will offer practical suggestions to enhance FPSC performance.
- The study will bridge and identify the gaps and comparative evaluation on single and hybrid nanofluids used in solar collectors.

GENERAL INTRODUCTION

- This work will add knowledge on how to make use of renewable energy and increase efficiency; this can be of great benefits to places where there is high solar radiation.

This memory is divided as follows:

In Chapter 1, general information of flat plate solar collector, its principle of the working, its basic components and performance parameters are introduced.

In chapter 2, the concepts and properties of nanofluids with a particular focus on single and hybrid nanofluids, as well as recent progress in this area are reviewed. The methodology used in this study is described in Chapter 3.

Chapter 4 describes the simulation results. The conclusions along with suggestions for future work are included in Chapter.

CHAPTER I: General information on flat panel solar collectors

Chapter 1: General information on flat panel solar collectors.

I.1 Introduction:

An overview of flat plate solar collectors, the structure of FPSCs, heat transfer components, and FPSC applications are the main topics of this chapter. This chapter covers the production of nanofluids, their primary thermophysical characteristics, and their potential uses in a range of thermal devices. Additionally, the fundamentals of the topic of nanofluids are reviewed and discussed, along with its significance and application. This section will cover a number of recent theoretical, experimental, and numerical studies on the use of common nanofluid types as solar fluid in FPSC. Therefore, the goal of this study was to fill in the gaps and go over the challenges in the body of recent literature, which is thought to have been the motivation for starting this investigation.

One kind of solar thermal collector is a flat plate solar collector (FPSC), which gathers solar energy and transforms it into heat for a variety of uses, including heating water and air for industrial and household processes. Because of its great efficiency, affordability, and durability, it is the most widely used solar collector in residential and commercial solar heating systems. It is made out of a flat, often black plate that absorbs solar radiation and transfers it to a working fluid, such as water or antifreeze, that passes via tubes affixed to the collector's surface.

I.2 General Overview of Flat Plate Solar Collector System:

Thermal circulation devices called solar energy collectors transform sunlight into direct energy in solar fluids. It is the focal point of every solar system. Concentrated and nonconcentrated (stationary) solar collectors are the two main varieties. A non-concentrated collector typically has the same area for collecting and absorbing solar energy(10). Conversely, a concentrated collector for sun tracking usually has concave surfaces that reflect and concentrate sunbeam radiation on a smaller area while increasing flux. In solar systems, the FPSC is a stationary collector and exchanger system that generates thermal energy from sunlight. According to Kalogirou et al when solar radiation passes through the glazing and reaches the

absorber plate, heat is transferred to the fluid that moves through the absorber flow tubes to raise the temperature (3). According to Duffie and Beckman FPSCs are flat, unglazed glass plates(1).

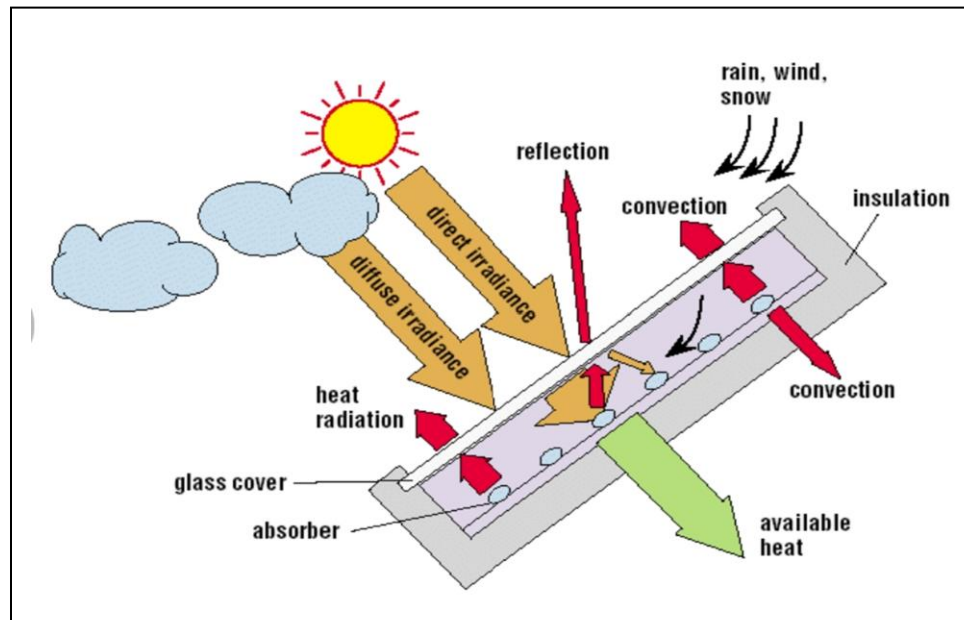


Figure I.1 “Working principle of Flat Plate Solar Collector.”

In Africa, FPSCs have poor thermal efficiency in the winter due to low insolation and ambient temperatures. Among the FPSC's drawbacks include heat losses, circulation loops for heat transfer, and insufficient thermal insulation.

According to previous studies (11), the amount of heat energy lost from a solar energy flat-plate collector's surface affects its performance. These losses are typically difficult to calculate. An empirical formula for computing U_t , the top loss coefficient (12) . Researchers from all across the world have made several changes to this. The difference between the solar energy incident on a solar collector and the amount of heat lost from the collector is the potential usable energy that can be collected from the collector. And existing show that the collector's material characteristics, the surrounding environment, the collector's position and configuration, wind direction and speed, and absorber temperature all have an impact on the overall heat-loss coefficient, or U_t . Numerical and approximation procedures are the two ways to compute U_t (13)

According Kalogirou et al (3) when designing or modelling the performance of collectors, it is crucial to calculate the heat losses they cause to the surrounding area. Convection and upward radiation losses from the absorber plate are taken into account when assessing it.

However, the approximate solution has been widely accepted by solar thermal system researchers. An existing introduced the empirical formula for estimating U_t of the flat plate collectors. The empirical formula that offers a strong correlation with emittance at the absorber plate was later modified by Klein (12). Converting incident solar insolation into usable heat energy is the goal of solar flat collectors. A range of solar flat collectors, including concentrating and flat-plate models, can be made. The applications of the heat energy produced indicate which type should be used; it was discovered that the concentrating type produced more heat energy than the flat plate type. For example, a simple flat-plate solar collector can generate just enough heat energy to dry crops at the proper moisture content.

A simple flat-plate solar energy collector has an absorbing surface that is usually painted black to absorb insolation and transfer it to the working fluid. Meanwhile, previous studies have shown that solar energy collectors are special kinds of heat exchangers that transform solar radiation energy into the internal energy of the transport medium, usually water or air (3). A flat plate with several covers is usually used when high temperatures are required; a single cover is used when low temperatures are required. When comparing their results with previous research, they discovered a low percentage of error because they used empirical relations rather than numerical solutions, and they concluded that the error in their findings was significantly lower than that of the earlier findings. It was the best estimate of U_t and the highest loss coefficient in the literature. The water, the air conditioning system, or a thermal energy storage tank that can be used at night or on cloudy days receive the collected solar energy from the circulating fluid (14).

(15) Previous study examined how air recycling affected double flat-plate solar collectors that included interior fins acting as heat sinks. Conducted an experimental study of three distinct types of solar air heaters employing flat plates with fins connected and others without fins (16). One of the fin-equipped heaters in their experiment had one glass cover, while the other had two.

They came to the conclusion that the heater with a double cover and fin was more effective in terms of the temperature differential between the air at the inlet and the outlet. Other researchers discovered that chevron pattern absorbers, V-grove flat plate collectors, and fin-air

collectors were less effective. The V-corrugated pattern performed better than the others under the same conditions, while the flat plate collector performed the worst (17).

The performance of flat plate collectors is affected by the climate of the test area or location. The length and intensity of sunshine determine the plates' efficiency. Dust, dirt, shadows, and constant rain are additional factors that impair their performance. The performance of solar flat plate collectors is influenced by their location. Tropical regions with an average daily sunshine duration of up to twelve hours have higher efficiencies than rainforests areas like Sierra Leone during raining season.

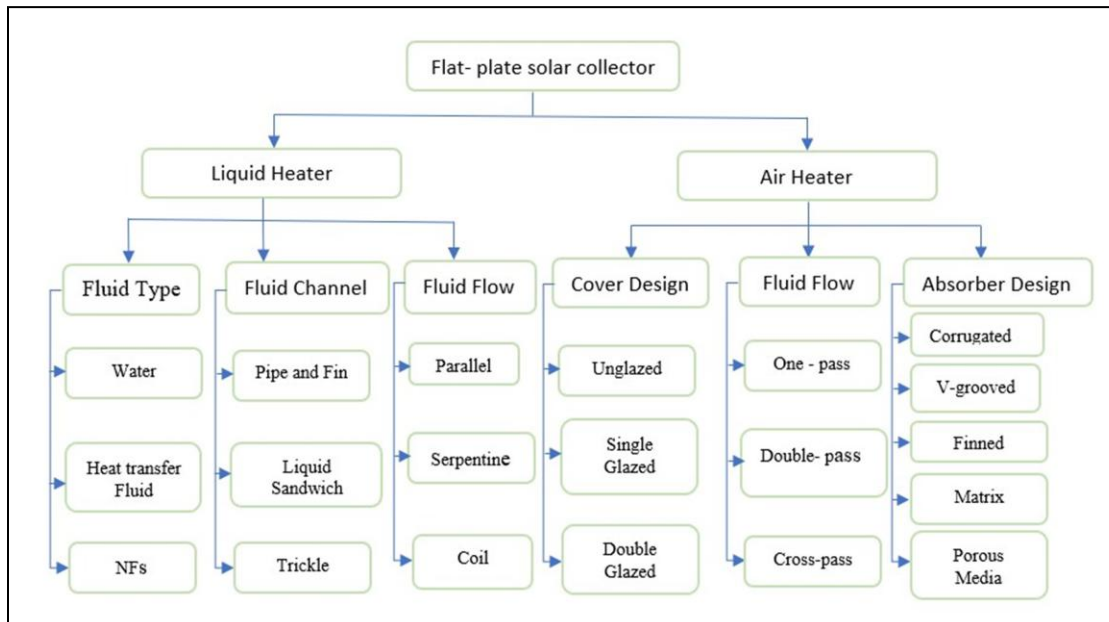


Figure I.2: "Classification of FPSC (18)"

I.2.1 Components of a Flat Plate Collector:

A flat plate collector typically comprises the following main components:

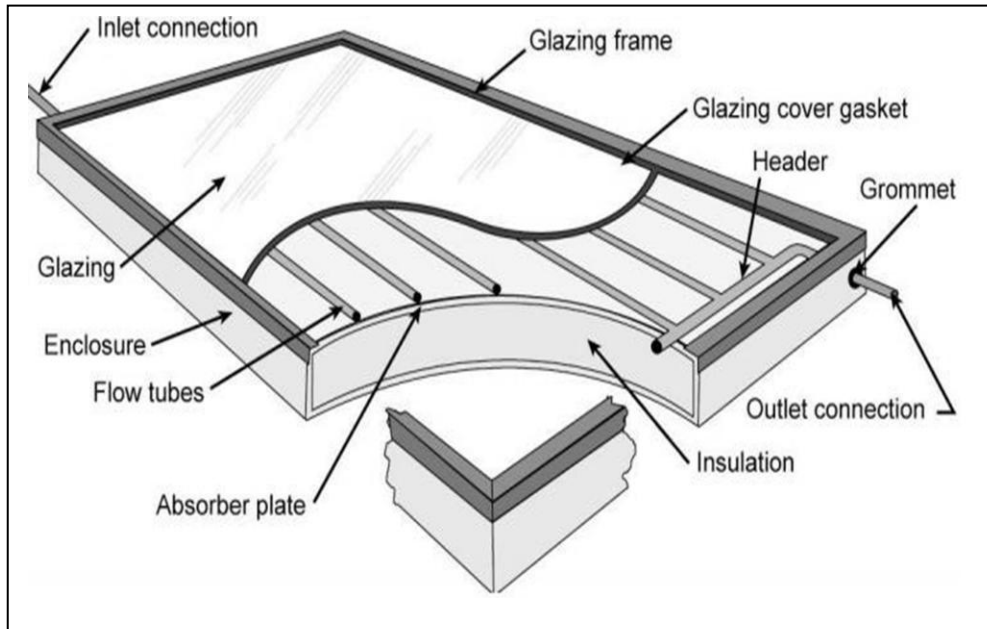


Figure I.3 “Structure of FPSC”

- **Frame:** The frame provides strength to the collector and acts as a container for all parts. It is typically constructed from weatherproof materials such as aluminium or steel.
- **Absorber metal plate:** This is the solar radiation to thermal energy converting primary element of the collector. The absorber plate is heated when the sun shines on it. Cooling the plate with an appropriate working fluid removes the heat that has accumulated in the plate material from the collector. In water collectors, the working liquid flows through pipes (risers) fastened to the plate; in air collectors, the passages are fastened to the plate. The absorber plate is composed of a high thermal conductivity metal, such as copper or aluminium, and the side that faces the sun typically has a high absorptivity to short wave radiation from the sun and a low emissivity surface to long wave radiation emitted by the plate. Cooling the plate with an appropriate working fluid removes the heat that has accumulated in the plate material from the collector. In water collectors, the working

liquid flows through pipes (risers) fastened to the plate; in air collectors, the passages are fastened to the plate. The absorber plate is composed of a high thermal conductivity metal, such as copper or aluminium, and the side that faces the sun typically has a high absorptivity to short wave radiation from the sun and a low emissivity surface to long wave radiation emitted by the plate.

- **Transparent cover:** An air gap of two to ten centimeters must be left between a transparent sheet of glass and the absorber plate. The glass cover absorbs incident solar radiation through a process called the "greenhouse effect," which makes it transparent to short-wave solar radiation and opaque to long-wave radiation that the plate reemits. As a result, thermal radiation losses are greatly decreased by the greenhouse effect. The air gap between the plate and the cover also minimizes convection thermal losses from the environment. Environment. A transparent cover, usually made of glass or polycarbonate, is placed over the absorber plate. Its primary function is to retain heat within this sector while allowing sunlight to enter. By creating a greenhouse effect inside the collector, this prevents heat from escaping and ensures the system's efficiency.
- **Insulated Backing:** The collector's back is insulated to reduce heat loss. The insulation material, which is typically made of fiberglass or foam, increases the efficiency of the system by helping to retain the heat that the collector absorbs and preventing it from escaping to the outside world.
- **Working Fluid Pipes/Springs:** These pipes are mechanically or tightly welded to the absorber plate to maximize heat transfer to the working fluid shown on the left. For water collectors, these tiny pipes, which range in diameter from 0.5 to 1.5 cm, are referred to as "risers." The risers are connected to a common bottom header that evenly supplies working fluid to the risers and a top header that gathers the hot working fluid from each riser. The fluid tubes that are screwed to the absorber plate carry the heat transfer fluid, which is typically water or an aqueous antifreeze solution. These pipes are in charge of drawing heat from the absorber plate and pumping the liquid through the collector. The heated liquid is then either stored or used for heating.
- **Insulation layer:** The absorber plate and the working fluid pipes should have sufficient insulation to minimize thermal losses to the environment. There are additional layers on

the sides of the absorber plate in addition to an insulating layer that is 5 to 10 cm thick on the back side.

- **Assembling case:** Every collector component is put in a suitable wooden or metal case to guarantee mechanical durability and thermal insulation.

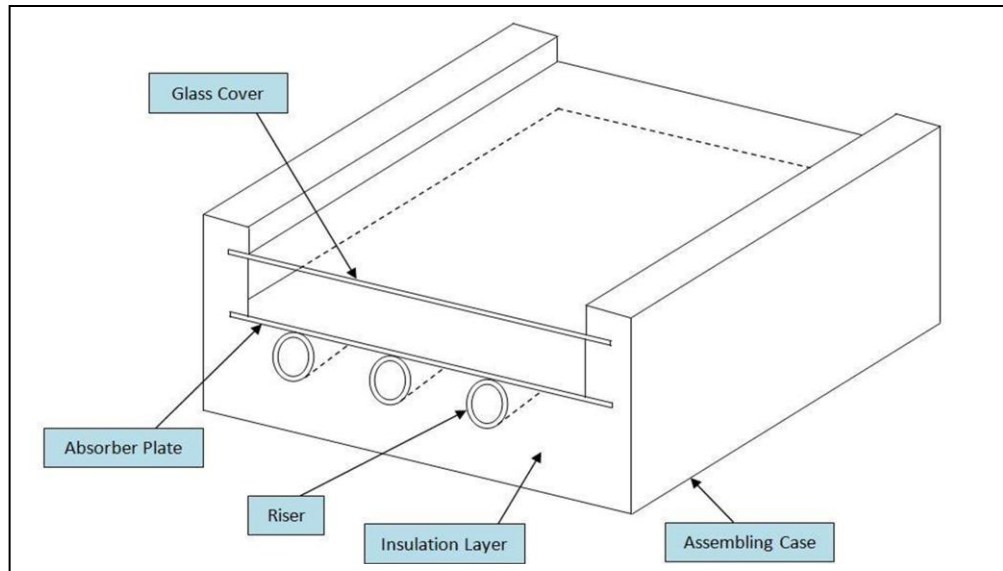


Figure I.4 “Parts of a flat-plate solar collector”.

I.2.2 Some important definitions:

Transmittance Coefficient (τ): It is the percentage of solar radiation that reaches the glass cover out of all the radiation that hits it. Its value, which is always less than one, is determined by the incidence angle and glass purity.

Absorptance Coefficient (α): It is the ratio of the solar radiation absorbed by the absorber plate to the solar radiation reaching the plate. The value of (α) is always less than one and depends on the nature of the absorber plate surface. It is a common practice to paint the surface with a (selective coating) that has a high absorptance to solar radiation in the short-wave domain and low emissivity to the long-wave radiation out of the absorber surface. The coefficients (τ) and (α) are usually combined as a single factor called transmittance absorptance product ($\tau\alpha$).

The overall heat loss coefficient (UL): It is a heat transfer coefficient that considers all thermal losses that take place by the collector at a representative temperature called the mean plate temperature (T_{pm}).

The mean plate temperature (T_{pm}): The working fluid passing through the risers creates a temperature distribution in the absorber plate that is mathematically averaged throughout.

The mean fluid temperature (T_{fm}) is the mathematical average of the temperature distribution of the working fluid inside a single riser along the flow direction.

I.2.3 Installation procedure of flat plates solar collector:

Installing a geothermal flat plate collector requires careful planning, which should be done by a professional after consulting with you. However, with professional help, you can also finish some of the other jobs, such as excavating or filling the space.

I.2.3.1 Planning and marking:

Will that be sufficient distance from the buildings? As for how far back from the buildings, how far from the buildings should the flat-plate collector be located? A professional planner or heating technician can perform these convictions, so consult them when answering these queries.

I.2.3.2 Ditching the Area:

If you know your way around the groundwork, you can dig down to a depth of 1.3 m with the right equipment. to ensure an even removal of soil and ultimate good compaction, it is best to consult." If the land is sloping or the weather unusually tough, get a professional opinion.

I.2.3.3 Laying the pipes:

The PE pipes(polyethylene pipe) are laid in meanders or loops. This work, if at all possible, should be performed by a professional heat pump company, because the hydraulic design, pipe laying distance and avoidance of kinks is essential for performance in the future.

I.2.3.4 Refilling and compacting:

You can refill on your own, but it's important to add the soil in layers and compact it completely. However, experts know how to build up the soil to prevent settlement and enhance heat transfer.

I.2.3.5 The heat pump's attachment:

This step must always be carried out by a professional. Professionals must finish the brine distributor, pressure testing, system filling and venting, and electrical connection to avoid additional damage or loss of efficiency.

I.2.4 Thermal evaluation of solar collectors with flat plates:

I.2.4.1 Eneegy Balance and heat gain:

Any solar collector's thermal analysis entails calculating the collector's useful heat gain, or (Q_u). The energy balance in flat-plate collectors can be expressed as follows: Irradiance reaching the absorber minus thermal losses from the absorber equals useful heat gain. In terms of mathematics:

$$Q_u = \tau \times \alpha \times IT \times A_c - UL \times A_c (T_{pm} - T_a) \dots\dots\dots(I.1)$$

$$Q_u = A_c \times [\tau \alpha \times IT - UL \times (T_{pm} - T_a)] \dots\dots\dots(I.2)$$

Where:

Q_u : Useful Heat gain (W)

A_c : Absorber plate area (m^2)

τ : Glass cover transmittance coefficient

α : Absorber plate absorptance coefficient

IT : Irradiance incident normal to the absorber plate (W/m^2)

UL : Overall heat loss coefficient ($W/ (m^2 \text{ } ^\circ C)$)

T_{pm} : Absorber plate mean temperature ($^\circ C$)

T_a : temperature ambient ($^\circ C$)

I.2.4.2 Collector thermal efficiency (η_c)

It is the ratio of the incident irradiance of the solar collector to the useful heat gain (Q_u) of the working fluid, more precisely:

$$\eta_c = \frac{Q_u}{A_c \times IT} = \frac{A_c \times [\tau \alpha \times IT - UL \times (T_{pm} - T_a)]}{A_c \times IT} \dots\dots\dots(I.3)$$

$$\eta_c = \frac{\tau \alpha - UL \times (T_{pm} - T_a)}{IT} \dots\dots\dots(I.4)$$

The useful heat gain Q_u can be represented in terms of working fluid mass flow rate (m), inlet and outlet temperatures T_{fi} and T_{fo} , respectively, as follows:

$$Q_u = m \times C_p f (T_{fo} - T_{fi}) \dots\dots\dots(I.5)$$

Collector stagnation temperature (T_{st}):

When the mass flow rate is zero, the solar collector reaches its maximum temperature. The useful heat gain is zero since the thermal losses at stagnation temperature are equal to the incident solar radiation

$$Qu = 0 \dots\dots\dots (I.6)$$

$$0 = \tau \times \alpha \times Ac - UL \times Ac (T_{st} - T_a) \dots\dots\dots (I.7)$$

$$T_{st} = \frac{T_a + \tau \times \alpha \times IT}{UL} \dots\dots\dots (I.8)$$

I.2.5 FPSC Working Principle:

The working principle of Flat Plate Solar Collectors involved this following;

I.2.5.1 Absorption of sunlight:

Sunlight is received by the glazing cover on top of the flat plate and transferred to the dark-coloured absorber plate. The plate heats up quickly because there is little heat loss.

I.2.5.2 Transfer of heat to tubes:

The plate is moved to the tubes that are attached after it has been heated. This causes the fluid usually water that is kept in the tubes to heat up.

I.2.5.3 Storage:

Through pipes, the heated fluid travels to a storage tank or a heat exchanger. This is then used for bathing in households.

I.2.5.4 Reheating cooler fluid

The cooler fluid returns to the collector after the heat is transferred to the tank, and the heating process is repeated.

Heat loss is prevented by the insulation and the transparent top cover. This makes it possible for the flat plate collectors to operate effectively.

I.2.6 Types of Flat Plate Collectors:

I.2.6.1 Types of Flat Plate Collectors Based of Glazed:

There are two main types of solar energy flat plate collector's base on glazed:

I.2.6.1.1 Bare-plate collectors are another name for unglazed solar energy collectors:

Glazed collectors are solar collectors that have covered plates.

Bare-plate solar energy collectors, often called unglazed collectors, are frequently utilised for lower-temperature applications, such heating swimming pools. These are the most basic solar collectors; because they lack a transparent cover, they are less effective but less expensive to produce. The absorber plate is the topmost surface, with an air duct and insulation at the back .

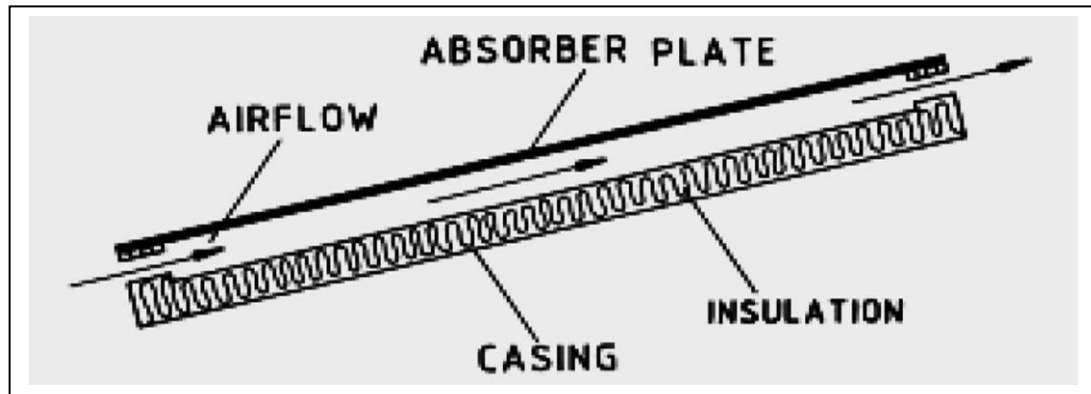


Fig.1.5 “unglazed collectors (Bare plate solar collector), Norton & Ekechukwu (14)”.

They are extensively utilised in the drying of agricultural food. Optical loss, which makes up around 10% of the insolation, is caused by the transmission reduction of incoming solar light as it passes through the transparent cover .

1.1,6.1.2 Glazed collectors, also known as covered-plate solar collectors

It is frequently used for water heating and other applications needing higher temperatures. They have a translucent cover and by decreasing heat loss, the cover improves efficiency.

The upward heat loss from the collectors is decreased by using one or more transparent cover materials. Although glass has become more popular, plexiglass, and clear plastics are the most commonly utilised materials. In addition to being transparent so that solar insolation can fall directly onto the plate, the cover material also prevents convective heat loss, lowers long-wave radioactive heat losses, and protects the plate from cooling, particularly during wet seasons. The covered plate has an advantage over the bare plate because it functions more efficiently. Norton and Ekechukwu, (14), describe four different kinds of covered plate solar heaters

I.1.6.1.2.1 Front pass solar collector:

Heat that is transfer to air stream is occur through the front side of the absorber plate and since the headed air pass through the duct between the absorber plate and the material cover, which has the insulation at the back side.

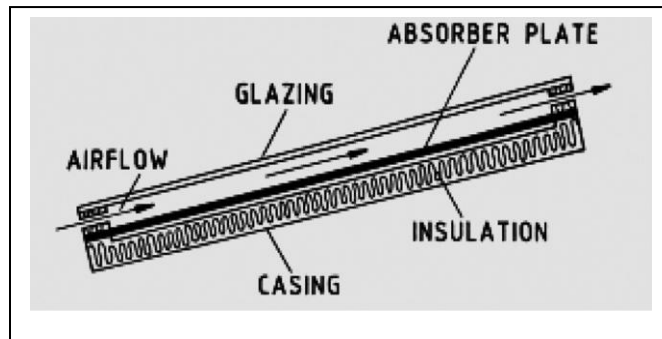


Fig. 1.6 “Front pass solar collector”.

I.1.6.1.2.2. Back pass solar collector [Back pass air heating solar energy collector]:

Transparent cover is place directly behind the absorber plate and it is separated from it- by-it layer, Heat is transferred through by the back of the absorber plate as the heater air moves between the insulation layer, absorber plate and the inner surface of the collector.

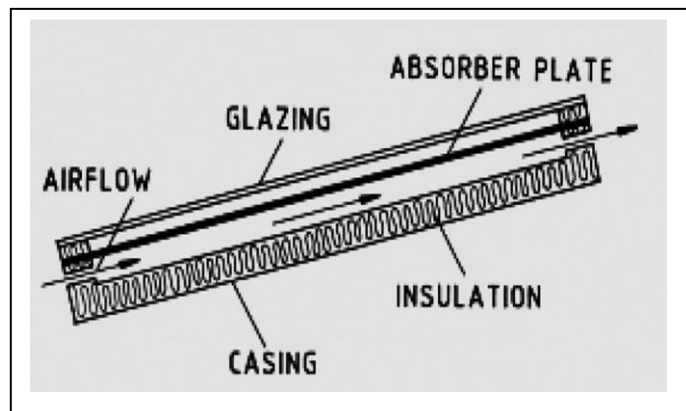


Fig. 1.7 “Back pass solar collector”

I.1.6.1.3 Parallel pass suspended solar heater collector:

It is a very effective thermal device in which the absorber plate is physically suspended inside casing .it is mostly used as suspended plate solar air heater. The incoming fluid usually air is divided into 2 portions, which flow symmetrically above and below the heated absorber plate.

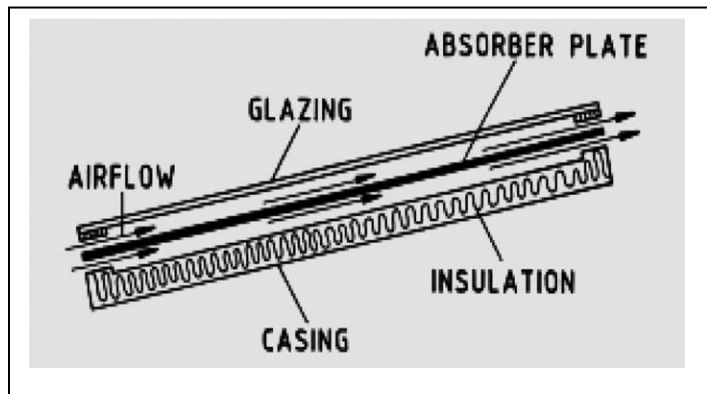


Fig 1.8 “parallel pass suspended solar collector”.

I.1.6.1.2.4 Double pass suspended solar collector:

Is an advanced solar collector which is used to increases the thermal efficiency of the system by reducing the heat transfer with the ambient

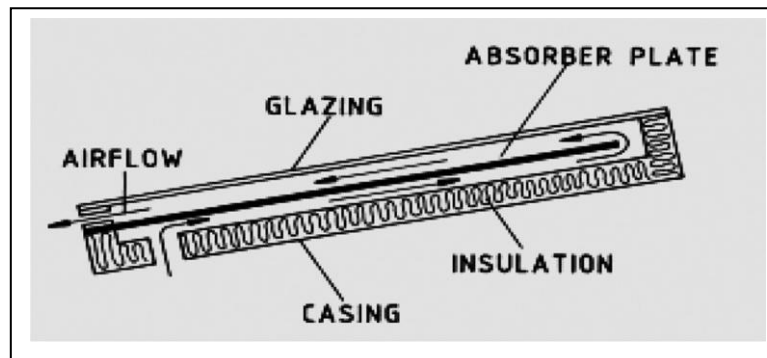


Fig. 1.9 “Double suspended air heating solar collector” pass [

I.1.6.2 Types of flat plates solar collector base on fluid:

Liquid flat plate collectors: These devices heat domestic water by using water or anti-freeze liquids.

Air flat plate collectors: They work well for space heating because they transfer heat via air.

I.1.6.3 Types of Flat Plate Collectors in accordance with configuration:

Parallel absorbing plates: Heat can be distributed through a greater volume of fluid when parallel absorbing plates are used in large apartment buildings.

Series absorbing plate: In this case, there is less fluid in circulation. They only have one continuous circuit.

I.1.7 Solar-powered water heating systems:

These days, FPSC applications make extensive use of solar water-heating systems. Thermal technology is used by the solar heating system to transform solar energy into heat, which is then transferred to an air or water transfer medium (19). Conventional water heating systems, such those that use fossil fuels, can frequently be replaced with this method. Larger systems are utilised for industrial processes, whereas smaller systems are used for domestic water and space heating applications (20).

The solar collector, storage tank, working fluid, pump (only needed in the active system), piping units, heat exchanger, and auxiliary heating unit are some of the essential parts of SWHS. The fundamental idea of SWHS is that when a fluid comes into contact with a dark surface, heat is absorbed and its temperature rises. This fluid can be created by either directly heating water (a direct system) or indirectly transferring heat via a heat exchanger. On the other hand, the passive system makes use of both the inbuilt collector storage system and the thermo syphon system. One kind of active system is a fluid heater collector, which moves working fluids through the collectors using electrical pumps, controllers, and valves. This approach is known as forced circulation (FC) and can be used to both closed-loop (indirect) and open-loop models.

A passive system definition must be founded on two pillars .The fundamental obligation is, first and foremost, on the storage and collectors of the structure. For instance, windows and rooms can serve as efficient collectors, and storage can moderately heat the building's structure and its contents during temperature swings. Second, this system does not create moving (mechanical) fluid, even when temperature gradients caused by radiation absorption transfer energy and fluid (21).

The passive method uses natural convection heat transfer to move solar liquids from the collector to the tank without the need for mechanical parts and it is utilised in the following domains:

Space heating: Heats buildings using radiant or air heating systems.

Heating of Swimming Pools: The collector circulates water to heat swimming pools.

Industrial Process Heating: For industries that require low- to medium-temperature heat, like food processing and textiles.

Applications in agriculture: Used to keep greenhouse temperatures stable or dry crops.

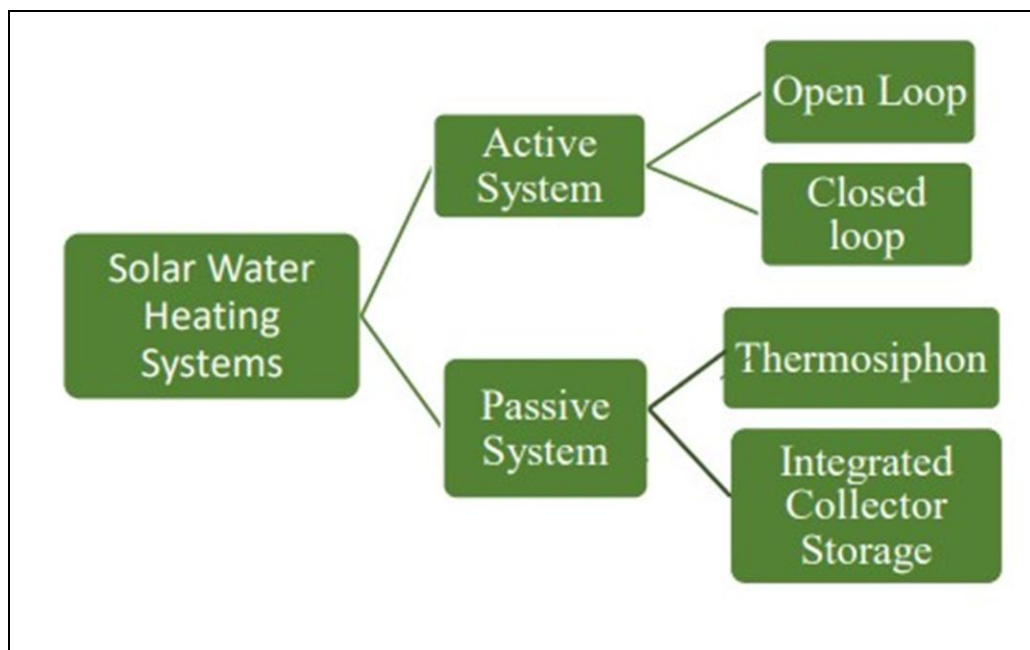


Fig. 1.10 “Types of solar water heating systems”.

I.1.8 Influencing factors of flat plate solar collector performance:

The efficiency of flat plate solar collectors is influenced by climate, design elements, and operational parameters. These are specifics that need to be fully understood in order to enhance the system’s thermal properties. The efficiency of flat plate solar collectors is influenced by operational, design, and environmental factors. These characteristics must be identified, and the parameters optimized for solar thermal energy systems to be successful and dependable (22).

I.1.8.1 Light from the Sun (Solar Irradiation):

The primary factor influencing collector output is solar irradiance (G) at the collector surface. The solar energy per unit area on the collector’s surface. The intensity of solar radiation

determines how much energy the solar collector absorbs. Thermal performance is therefore significantly impacted by variations in solar irradiance caused by seasonal air masses or cloud passages (23). For instance, collectors may produce more heat in areas with high mean irradiance values than in areas with low solar insolation.

I.1.8.2 The Ambient Temperature:

The ambient temperature (T_a) affects the heat transfer from the collector to the outdoor air. A larger temperature difference between the working fluid and the surrounding air is linked to heat loss through conduction through the enclosure material and convection and radiation in the working fluid and enclosure. Good insulation and a suitable collector box will be necessary to minimize heat loss and maintain unhindered flow for maximum system output, especially in winter.

I.1.8.3 Flow Rate of the Heat Transfer Fluid:

The working fluid flow rate m in the absorber tube bundle has an impact on the thermal efficiency and outlet temperature. High flow rates lead to higher energy extraction and lower fluid outlet temperatures, whereas low flow rates cause the fluid to be hotter with less energy transferred. In order to balance the rate of energy transfer and thermal efficiency, it is crucial to select an ideal flow rate.

I.1.8.4 Collector Tilt and Orientation

The achievable incident solar energy on the collector surface is influenced by the collector's orientation, tilt angle, and design geometry. The collector that faces the equator and is tilted at an angle near the location's latitude yields the best results because it maximizes solar heat all year round. Any deviation from the ideal angle lowers the effective irradiance and, consequently, the thermal output.

I.1.8.5 Absorber Coating and Glazing

The absorber plate and the optical characteristics of the glazing have a significant impact on the thermal performance of flat plate solar collectors. Good solar energy absorption and minimal radiative heat losses are the outcomes of selective absorber coatings' high absorptivity and low emissivity. In addition to acting as a greenhouse enclosure, the glazing layer lets

incident solar radiation enter the collector and stops convective heat loss. Dust or grime build up on the glazing could drastically lower the collector's effectiveness.

I.1.8.6 Quality of Insulation

The collector's sidewall and back insulation reduce thermal losses to the environment. To enhance heat preservation in the collector, low thermal conductivity materials, such as mineral wool or polyurethane foam, are commonly used for both internal and external insulation. The collector thermal efficiency is directly impacted by the overall heat loss coefficient (U), a crucial design parameter related to the collector insulation performance.

I.1.8.7 Age and Maintenance of Collector:

Thermal degradation of flat plate solar collectors is caused by fouling, corrosion, and material degradation due to aging. Frequent maintenance, such as checking the absorber plate and cleaning the glazing, can keep the performance near the theoretical maximum.

I.1.8.8 Selective Surfaces:

Selective surfaces can increase absorption if the surfaces are very sensitive to radiation. The selective surface should be non-corrosive, stable at high temperatures (300–400°C), and free of oxidation.

I.1.8.9 Dust on Cover Plate:

The efficiency of the collector decreases with dust particles on the cover plate because the transmission radiation decreases by 1%. Frequent cleaning is required to obtain the maximum efficiency of the collector.

Chapter II: Literature review

Chapter 2: Literature review

II.1 Introduction:

Choi (5) chose the term nanofluid for a combination of nanoparticles and a liquid later in 1995. It should be remembered that the creation of a nanofluid necessitates specific physical and chemical processes in order to produce a uniform and effective dispersion of particles for long-term applications, rather than just adding nanoparticles to water or oil and stirring the mixture, like mixing sugar and tea. Nanofluid is a fluid that combines nanoparticles, which are particles the size of manometers.

These fluids are created by suspending nanoparticles in a base fluid in a colloidal manner. Numerous materials, including aluminum oxide (Al_2O_3) and aluminum oxide – and composite materials like alloyed nanoparticles, core-polymer shell composites, are used to create nanofluids. Furthermore, entirely new materials and structures, as well as nonmetallic, metallic, and other materials for nanoparticles, may have advantageous properties. Solutions with suspended solid nanoparticles (usually ranging in size from 10 to 100 nm) are known as nanofluids. Since their introduction over 10 years ago, nanofluids have garnered significant attention due to their potential to display superior thermal properties compared to basic liquids.

Nanofluids are promise for applications in thermal management in a variety of fields because of these improved thermal characteristics. Additionally, nanofluids are being developed for a variety of uses, including patterning technology and medical applications. Some of the aforementioned tendencies have been described in recent review publications that summarised the state of the art in the use of nanofluids for thermal applications.

The idea that particles could change from millimeters to micrometers in the late 19th century has evolved into a part of the current journey into the new world of nanoparticles, which is the very small. S U S Choi (25) had predicted the emergence of a new class of fluid and the term "nanofluid" at the beginning of the 1990s.

II.2. History of Nanofluids:

A novel class of fluids with improved thermophysical characteristics and heat transfer efficiency is known as nanofluids. They may be useful for a wide range of scientific and

engineering applications. According to estimates, the potential market for nanofluids in heat transfer applications is worth over \$2 billion annually and is expected to increase much more over the coming years. This article will provide a comprehensive assessment of the existing literature on nanofluids.

The debate will begin with their definition and their importance in science and engineering before moving on to the literature. The most notable recent studies in thermal conductivity, viscosity, heat convection, and specific heat will be reviewed, along with a number of hypotheses regarding the implications of the findings. Large solid particles, however, lead to problematic issues like surface abrasion, micro channel clogging, pipeline erosion, and pressure drop swelling, which significantly restricts the useful applications. In actuality, liquid suspension was essentially a theoretical treatment of some hypothetical interest, and other researchers' subsequent investigations yielded negligible results.

The two most significant limiting factors were the size of the particles and the challenge of creating small particles. When Choi and Eastman at Argonne National Laboratory returned to this field with their novel concept of nanoscale metallic particle and carbon nanotube suspensions, the situation became productive. Although the results of their experiments with different metal and metal oxide nanoparticles in various base fluids were encouraging, many details about these suspensions of nanostructured materials remained unclear(26).

Nanotechnology and miniaturization trends are closely linked to the development of nanofluids as a new field of nanoscale heat transfer in liquids. A brief overview of Argonne National Laboratory's (ANL) history demonstrates how the program has embraced a broad range of size regimes (from meters to nanometers) and how a broad range of research has narrowed, beginning at large scale and moving down through microscale to nanoscale, culminating in the creation of nanofluids.

Microchannel technology was introduced by D. B. Tuckerman in 1981 and A plan to create advanced fluids was started by Argonne National Laboratory in 1985. In 1991 Choi develops a microchannel heat exchanger for the settled photon at Argonne National Laboratory. 1992 saw a reduction in funding for the Argonne National Fluid Program, which began working from micro to nano. Thus, 12 years after Tuckerman introduced microchannel technology. Choi submits a first proposal for nanofluids in May, followed by a second proposal with Eastman. The third nanofluid proposal was submitted in 1994. At the American Society of Mechanical

Engineers Winter Annual Meeting in San Francisco, California, from November 12 to 17, 1995, Choi delivered a groundbreaking paper on the idea of nanofluids. From 1998 to the present, the Office of Basic Energy Science at the U.S. Department of Energy (DOE) has provided funding for Argonne nanofluids research. BES and the Office of Transportation Technologies will work on the principles and uses of nanofluids.

The first SCI article on nanofluids was published by Lee's group in 1999. 2000: The United States' National Nanotechnology Initiative is announced by President William Jefferson "Bill" Clinton. (NNI) in January at Caltech. Choi reviews proposals for the National Science Foundation and DOE and BES. Additionally, he works on the NNI's initial proposals for Nanoscale Science, Engineering, and Technology(26)

Choi and Eastman's team published two papers in Applied Physics Letters in 2001 (71). 2002–2003 DOE's Office of Basic Energy Sciences ranked the nanofluids research as the best in both 2002 and 2003.

as well as 2003. In 2007, it was the first conference on nanofluids with a single theme. Nanofluids: Foundations and Uses, Engineering Conferences International, Copper Mountain, CO, September 16–20, 2007.

Wiley publishes Nanofluids: Science and Technology, the first book on nanofluids. From 2008 to the present, scientists worldwide have been working to come to a consensus by disseminating their theoretical and experimental studies to ensure that the application of nanofluids will be successful as previously anticipated.

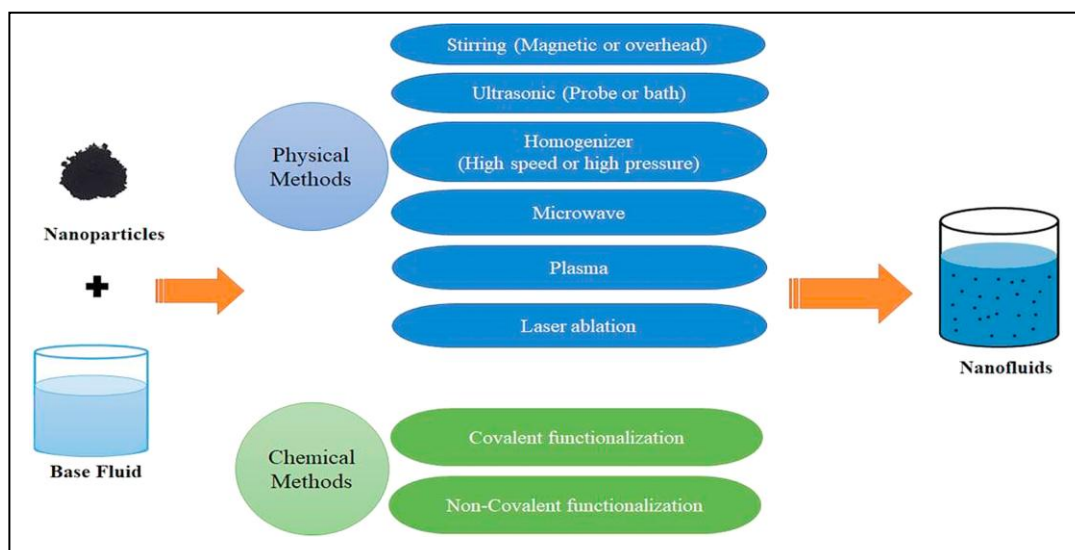


Figure. II.1: “Nanofluid preparation method”.

II.3 The evaluations of Nanofluid Research:

Actually, the idea of nanofluids has been around for hundreds of years. History claims that mediaeval craftspeople, unaware of their own secrets, employed a dispersion of gold nanoparticles to give their windows a deep crimson hue. Italian ceramicists produced sparkling pottery in the fifteenth century by dispersing metallic nanoparticles in a liquid (27). These craftspeople exploited the particles for lustre and colour without realising how big they were. Nanofluids are a kind of colloidal dispersion, despite their significant differences from regular colloids. Although they may be a kind of colloidal dispersion, nanofluids differ from colloidal dispersions in terms of particle size, phase, fundamental physical characteristics, fundamental processing methods, and important applications.

II.3.1 Influence of Nanoparticle Size on Nanofluid Behaviour (The Size of the Particles Matters):

Particle size is important in the development of practical nanofluids before delving into the specifics of the thermal properties of heat transfer fluids based on nanotechnology. There are several reasons why base fluids should have set particle sizes. The stability of nanofluids is initially influenced by particle size. Dense nanoparticles can be suspended in liquids because their surface interaction with the liquids is strong enough to overcome density discrepancies due to their extremely high surface area to volume ratio. Moreover, interactions between particles are prohibited because nanoparticles are charged. Second, when creating nanofluids with unique characteristics, size is important. Nanoscale transport systems may be impacted by the extremely small particle size. Nanoscale dynamics as well as the features of nanoscale surface and interface structures govern the properties of nanofluids. Lastly, the usefulness of nanofluids depends on the size of the particles. For instance, because nanoparticles and biomolecules are comparable in size, nanofluids can be employed in biomedical applications including medication delivery and nanofluid-based biological function control.

II.3.2 Concept and applications of nanofluids:

The problem of a decreased rate of heat transmission is linked to the use of traditional fluids with poorer thermal conductivity. Experts are developing methods that improve heat transfer

performance in response to the growing use of heat transfer systems. These investigations led to the discovery of nanofluids, which were found to improve heat systems' performance in terms of heat transfer. In light of this circumstance, the application of nanofluids is seen to be a successful way to avoid such problems. Heat transmission has improved greatly since the invention of nanofluids. Colloids or mixes made of a base fluid with scattered nanoparticles are known as nanofluids. Single nanofluids and hybrid-based kinds are the two categories of nanofluids. Only one nanomaterial is present in conventional nanofluids, also known as mono nanofluids.

Hybrid nanofluids are created to increase the efficiency of nanofluids that comprise multiple nanomaterial. When it comes to heat transfer applications, nanofluids are preferred over additives with millimeter and micrometer diameters. Additionally, it was discovered that nanofluids outperform conventional base fluids in terms of heat transfer performance. Commonly used base fluids include water, ethylene glycol, and engine oil. The main properties of nanofluids that make them preferable for use in heat transfer applications include higher stability and higher thermal conductivity. Such novel fluids have recently been the subject of increased focus among scientists due to their capability to facilitate perceptible transfer of heat compared with standard fluids.

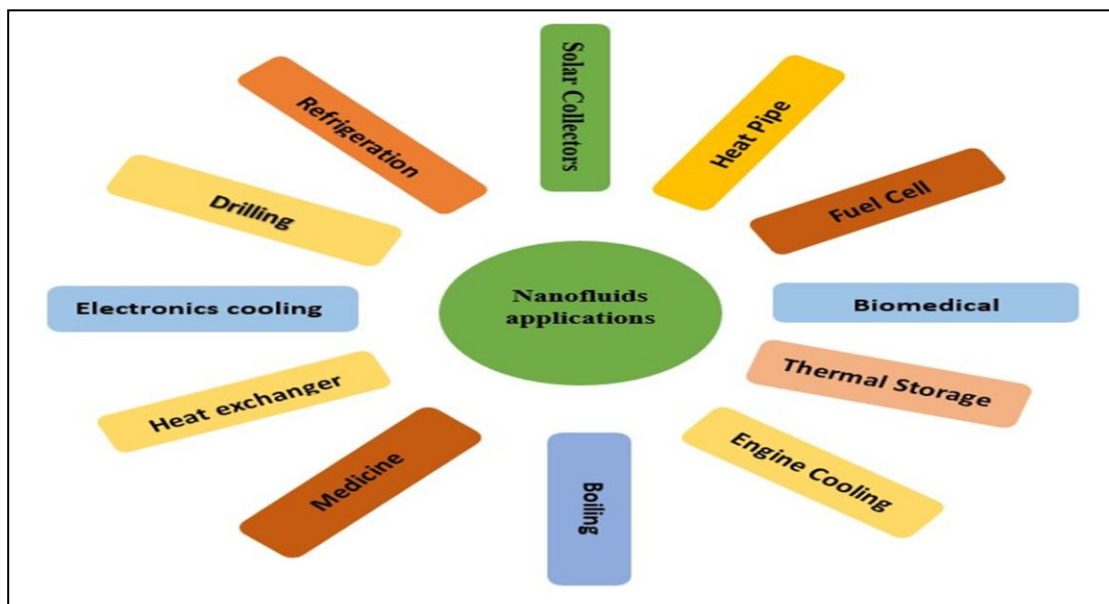


Figure.II.2: “NFs applications”.

II.3.3 Classification of nanofluids :

Fluids with dispersed particles at the nanoscale are referred to as nanofluids. Depending on the kinds of nanoparticles, Nanofluid are divided into multiple classes. Fig. II.2 shows how NFs are categorized. The distribution of different kinds of NPs in a basic fluid determines the transportation properties of nanofluid. Nanoparticle are differ in density, heat capacity, and thermal conductivity due to their physical characteristics and chemical properties. The two groupings can be divided into single nanofluids and hybrid nanofluids.

Since S U S Choi (5) initially proposed the idea of single nanofluids in 1995, it has been the standard for NFs for suspension with a single type of NPs .Several writers claim that this kind of nanoflow works better because its thermophysical properties are far superior to those of its fundamental fluid. Furthermore, a complex nanoparticle contained in a base fluid with several different kinds of nanoparticles is known as a hybrid nanoparticle. The purpose of these nanofluids was to increase thermal conductivity.

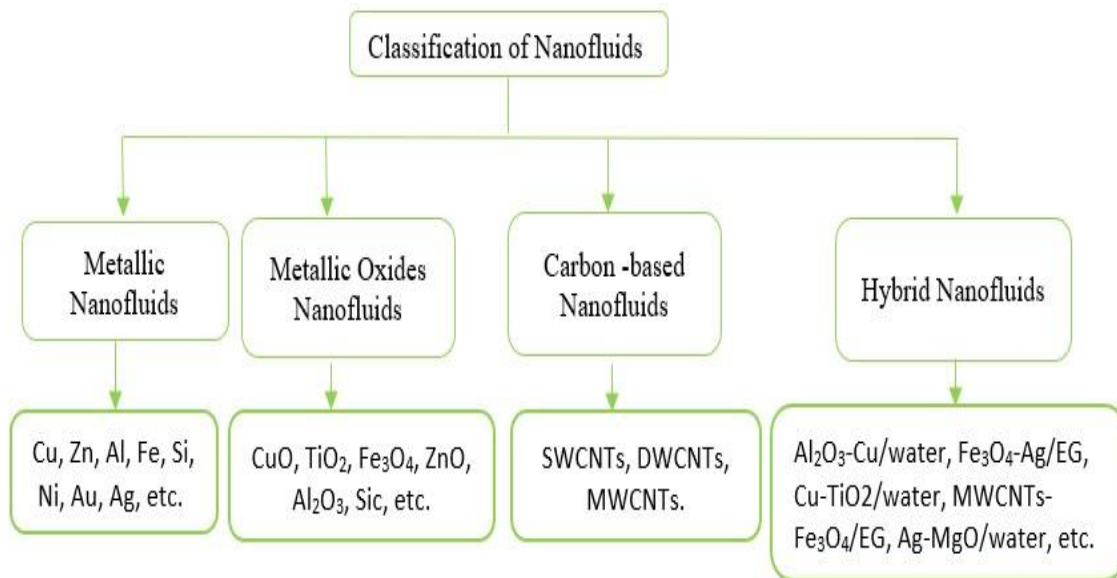


Figure II.3. "Classification of Nanofluids (28)".

II.4 Heat Transfer Modelling on Nanofluids:

One of the biggest obstacles to comprehending the behaviour and uses of nanofluids is modelling heat transfer in them. Heat transfer modelling in nanofluids currently comes in four varieties.

II.4.1 Model of Dispersion:

This approach is based on the notion that convective heat transfer enhancement in nanofluids is influenced by two elements. Two examples are enhanced thermal conductivity and stable dispersion of nanoparticles. Previous research examined concepts for correlations in nanofluid heat transfer.

This was the first time this strategy was used. After discussing the conventional approach to modelling nanofluids, they proposed a dispersion model to address the thermal dispersion caused by the unpredictable movement of the nanoparticles. They postulated that the unpredictable motion of the ultrafine particles marginally changes the temperature and velocity of the nanofluids.

II.4.2 Modelling of Particle Migration:

An existing research identify three mechanisms that lead to particle migration in non-uniform shear flows. These include:

- * Brownian motion-induced self-diffusion, in which particles move from areas of higher concentration to areas of lower concentration.
- * Shear-induced migration, where particles move from areas with higher shear rates to areas with lower shear rates;
- * Viscosity gradient-induced migration, where particles move from areas with higher viscosities to areas with lower viscosities. Wen and Ding were the first to employ these mechanisms of particle migration in nanofluids.

They also developed a theoretical model to predict particle migration in pressure-driven laminar pipe flows of relatively diluted nanofluids.

II.4.3 Modelling with Two Components:

The commonly utilised two-component method considers the roles of the fluid phase and solid phase in the heat transfer process when examining the augmentation of heat transfer by nanoparticle suspension in a fluid.

The absolute velocity of nanoparticles can be calculated by adding the base fluid velocity and the relative velocity. Previous research use an alternative two-component to develop the model in an effort to overcome the shortcomings of the dispersion and homogeneous models, was the first to present this approach. He pointed out that, in comparison to heat conduction and convection, heat transfer related to nanoparticle dispersion is insignificant. Compared to the dispersion models, his novel model provides a more mechanistic explanation of the impact of the nanoparticles and base-fluid comparative velocity.

He underlined that the energy equation and the nanoparticle continuity equation must be coupled. Lastly, he demonstrated how Brownian diffusion and thermophoresis could be significant slip mechanisms. Additionally, he talked about seven slip mechanisms. His mathematical model was solve in various ways by other authors, who then applied it to various geometries and flow conditions. Recently study examined Buongiorno's two-component model and discovered important effects of thermophoresis parameters and Brownian motion.

II.4.4 Modelling with a Single Component:

Since the local velocity of nanofluids is the same as that of transparent heat transfer fluids, the standard heat transfer equations for fluid dynamics can be simply applied to them in one-component models. This implies that the calculations take into consideration the thermophysical characteristics of nanofluids and that all of the traditional heat transfer correlations might be applied to nanofluids. Consequently, it is thought that higher heat transmission is solely determined by improved thermal conductivity. Recently researchers adopted this strategy, which was initially used.

Previous study show comparisons between analytical and experimental results, the homogeneous flow models contradict the experimental research in order to routinely notice the enhancement of nanofluid heat transfer (29). However, an existing research focused on one-component models and asserted that the lack of pertinent theoretical studies or experimental data in the literature to investigate these issues makes the current macroscopic two-component model inappropriate for analyzing nanofluids. Furthermore, because the heat transfer process is the primary focus, the modified one-component model which takes into account some of the mechanisms is more beneficial than the two-component model. Additionally, they pointed out

that compared to conventional solid-fluid mixes, nanofluids' superior properties enable them to behave more like a fluid.

II.5 Preparation of nanofluids:

The most crucial aspect of fluid NF research is achieving a consistent distribution of nanoparticles while preserving their uniform size. The uniform dispersion of the particles, which affects the nanofluids thermophysical properties, is mostly the result of the preparation procedure. The Nanofluids are more adversely affected since they need to be made under specific circumstances within a liquid-solid mixture, including homogeneity, physical and chemical stabilities, durability, and dispersibility. The highly unequal distribution brought about by the uneven dispersion of the larger particles alters the characteristics of nanoparticles. Preparing the NF is an essential step when employing NP for heat transfer. The one-step method (bottom-up) and the two-step method (top-down) are two different approaches to producing nanofluids.

II.5.1 Single-step approach:

First, a single step is used to handle nanoparticles that could agglomerate or change composition when distributed throughout the base liquid. By converting a vapor-depositing solid solution, a direct evaporation approach usually solidifies NPs in a base fluid to produce NFs. This method eliminates the need for NP processing, including dispersion, drying, shipping, and storage. The method's drawback is that concentrated contaminants stay in the NFs, making it difficult to extract impurities from the NFs. The particles are unlikely to disperse when NPs are prepared in a single step in a uniformly distributed condition, and this method does not Yield pure metallic nano powder, making the disposal of contaminants challenging (25).

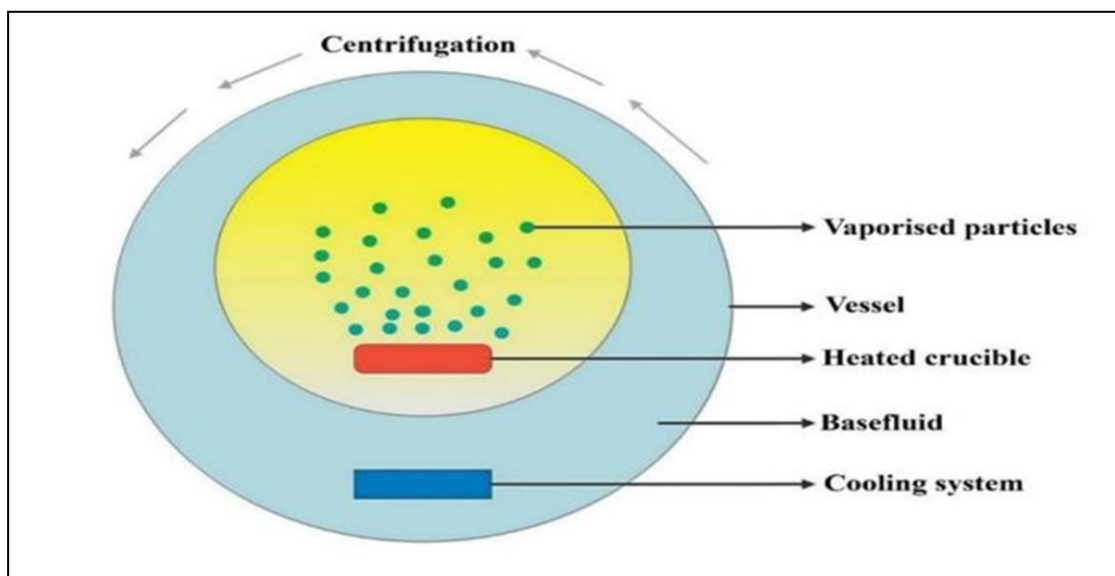


Figure. II.4 “Description of the single-stage approach (31)”

II.5.2 Two-step approach:

One popular method for preparing nanofluids is the two-stage procedure. Initially, physical and chemical processes are used to create the dry fine particles of nanoparticles, nanofibers, nanotubes, etc. Shear mixing, homogenizing ball milling, magnetic energy disturbance, and ultrasonic vibration are used to disperse nanoparticles to the base fluid. Because it is less expensive and the materials are easily accessible in the market, the two-stage method is frequently employed

According to researchers, the two-stage procedure is typically thought to be the best option for Nanofluids preparation. The two-step method's main flaw is that nanoparticles may form clusters during preparation, which prevents nanoparticles from properly synthesizing within the conventional fluid. Physical treatment techniques are the most popular way to increase the stability of nanoparticles in thermal transmission fluids.

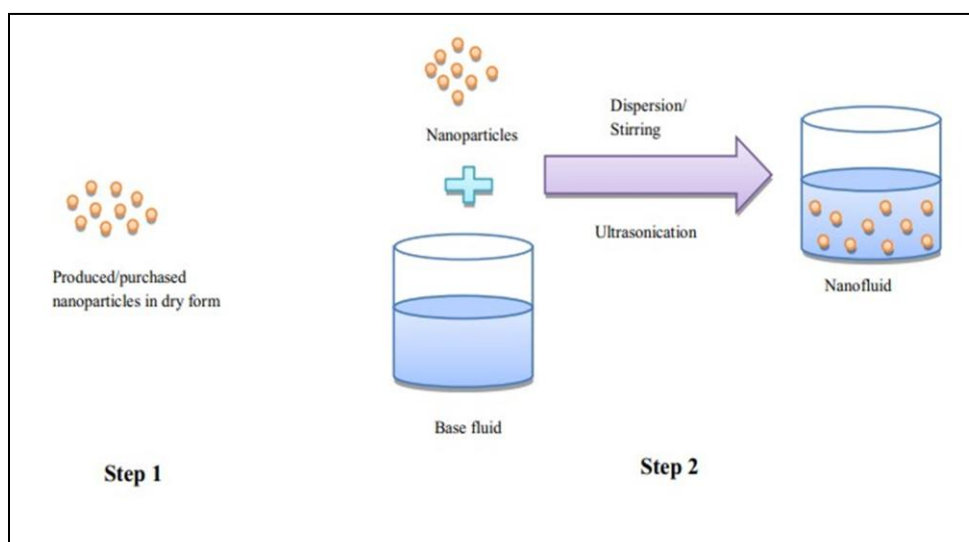


Figure. II.5: “Description of the two-step approach (32)”.

II.5.3 Some Other Methods:

To create copper nanofluids, researchers always create a continuous flow microfluidic micro-reactor. Previous researchers showed that a novel precursor transformation technique

using microwave and ultrasonic irradiation can produce Cu nanofluids with a high solid volume fraction. Another study showed that obtaining monodisperse noble metal colloids is also easy using the phase transfer method. This method allows copper nanofluids to be continuously synthesised and their microstructure properties to be varied by adjusting parameters such as reactant concentration, flow rate, and additives.

II.6 Thermophysical properties of nanofluids:

The thermal properties of the nanoparticles have a significant impact on the Nanofluids' performance. The characteristics of the base fluid, such as viscosity, pressure drop, thermal conductivity, and specific heat which are influenced by the nanoparticles. Some of the main elements that change thermophysical properties are temperature variation, ambient circumstances, basic fluid type, nanoparticle size, shape, and volume concentration. To maximize the outcomes, the right Nanofluids must be chosen while taking all factors into account. In conclusion, research on nanofluids is still developing but has expanded dramatically in recent years (33). However, the area is still growing and many questions remain unresolved and unanswered despite recent developments such as the creation of surprising thermal characteristics, novel mechanisms, and unusual models. Nanofluids are an interdisciplinary group of scientific and technical domains. Every aspect of nanofluids, from formulation to large-scale production, requires a significant quantity of work.

II.6.1 Thermal conductivity:

Thermal conductivity is the capacity of a substance to transport heat. A material's conductivity rate changes according on how well it conducts. Materials such as metals transmit heat more readily than insulating materials like glass wool. The conductor's length, cross-sectional area, chemical phase, and temperature gradient are other factors that influence the thermal conductivity rate. A nanoparticle is any particle that has a diameter of less than 100 nm.

The particles do not undergo sedimentation due to Brownian motion. As the temperature rises, NFs' thermal conductivity rises as well, and vice versa. Many industries use thermal conductivity to add or remove energy produced in the system the thermal conductivity of NFs has been the subject of numerous theoretical and experimental investigations. The characteristics of nanofluids make them perfect for industrial use. Previous research paper investigated the thermal conductivity of copper oxide/water and aluminium oxide water nanofluids. They applied

various temperature gradients and concentrations using the temperature oscillation method. According to the findings, raising the temperature and concentration of the nanofluids increased their thermal conductivity by certain percentage (34).

II.6.2 Dynamic viscosity:

According to research on nanofluids (21), one of the main features that makes them especially beneficial for industrial and engineering applications is viscosity. After this finding, a lot of research was done on nanofluids and their dynamic viscosity. The rise in the dynamic viscosity of nanofluids may be due to the addition of nanoparticles to the base fluid, which modifies other velocity field and friction force parameters to increase the performance of heat transfer systems. The thermo-physical characteristics of base fluids and nanofluids are different because of the weight of the nanoparticles they contain; nanofluids have a higher viscosity than base fluids (. The field of dynamic viscosity of nanofluids has seen a number of recent investigations. For instance certain study showed that the Newtonian behavior of the base fluid remained constant when Fe_3O_4 nanoparticles were dispersed into water and it was discovered that the nanofluid viscosity increased with decreasing temperature and increasing volume fraction.

II.6.3 Density and specific heat of nanofluids :

Another crucial thermophysical characteristic for evaluating the heat transfer efficiency is density. The density of nanofluid is determined by the solid (nanoparticles) and liquid (base fluid) volume proportions. When the solid density is higher than the fluid density, the nanofluid density usually increases as nanoparticle are added to the fluid. Few researcher computed the alumina density (Al_2O_3)/water and results show that the variation using the density equation falls between 0.015% and 0.06% and 0.25% and 2.53%.

The rate at which nanofluids are primarily influenced by the specific heat. It is the quantity of heat needed to raise one kilogram of nanofluids temperature by one degree Celsius. One of the important factor in determining thermal performance of the material is its specific heat. For conventional materials, the specific heat stays constant across a wide range of temperatures and at constant pressure.

II.7 Thermodynamic properties (Rho, Cp, K):

The dissociation of O₂ molecules, which occurs spontaneously during the adsorption process, is the catalyst's main role in the oxidation of CO. CO₂ is created when adsorbed CO combines with the "free" oxygen atoms on the surface. A thin RhO₂ surface oxide film forms on metal Rh before the bulk Rh₂O₃ with corundum structure. The presence of these thin RhO₂ surface films has been associated with an increase in CO₂ production..

The metal is also used in automotive three-way catalysts, which oxidize CO and hydrocarbons in exhaust gases and reduce NO_x. O₂ molecules are naturally separated during the adsorption process, which is the catalyst's main role in the oxidation of CO. When adsorbed CO reacts with the "free" oxygen atoms on the surface, CO₂ is produced.. An increase in CO₂ generation has been associated with thin RhO₂ surface films. An existing research employed Knudsen cell mass spectrometry to identify both RhO and RhO₂ species in the gas phase with a continuous flow of oxygen into the Knudsen cell at partial pressures varying from 1273K to 1773 K, Another researchers examined the volatility of Rh as a function of oxygen partial pressure from 1273 to 1773 K. They show that RhO₂ is the most prevalent gas species(35)

II.7.1 Combination types (Al₂O₃/TiO₂/graphene):

When employing nanoparticles to raise the thermal conductivity of traditional heat transfer fluids, the creation of nanofluids is an essential first step. Carbon nanotubes, metallic particles (Cu, Al, Fe, Au, and Ag), and non-metallic particles (Al₂O₃, CuO, Fe₃O₄, TiO₂, and SiC) have all been employed by researchers. The size, shape, and type of material of nanofluids all affect their thermal conductivity. For example, the increase in thermal conductivity of metallic nanofluids containing spherical nanoparticles is less than that of those containing cylindrical (nanorod) nanoparticles. Carbon nanotubes, non-metallic particles (Al₂O₃, CuO, Fe₃O₄, TiO₂, and SiC), and metallic particles (Cu, Al, Fe, Au, and Ag) have all been used by researchers.

The thermal conductivity of nanofluids is influenced by the size, shape, and composition of nanoparticles. For example, it was found that the thermal conductivity of nanofluids with metallic nanoparticles is higher than that of those with non-metallic (oxide) nanoparticles. As particle size decreases, nanofluids' thermal conductivities rise. Furthermore, spherical nanoparticle nanofluids exhibit a lower improvement in thermal conductivity than cylindrical (nano-rod or tube) nanoparticle nanofluids.

II.8 Applications of Nanofluids:

II.8.1 Applications in Biological and Biomedical:

Because the size of the nanoparticles is similar to that of biomolecules, nanofluids have a great deal of potential to contribute to biomedical applications like drug delivery and nanofluid-based control of biological functions. The field of sensors makes extensive use of gold nanoparticles. A DNA collector's surface can be modified with gold nanoparticles to increase its sensitivity. For instance, the performance of chemical and biological sensing will be significantly enhanced when gold nanoparticles are added to sensitive membrane preparation. Additionally, nanotechnology has made it possible to use nanoparticles to deliver medications to particular cells.

The majority of research on bio-micro-electro-mechanical systems (MEMS) was conducted in the 1990s, and more recently, there has been a significant increase in the commercialization of such strategies using technological equipment. Drug delivery systems have attempted to use a variety of nanoforms of chemical substances, such as different polymers; nanoparticles in nanofluids; and biological substances, such as albumin, gelatin, and phospholipids for vesicles. These nanodrug delivery systems can make excellent use of the nanoparticles, whose size is comparable to biomolecules and still controllable within 100 nm.

The purpose of these nano delivery systems is to either conjugate to or absorb onto the particle surface. As a result, medications can be shielded from hazardous environments, or their undesirable biopharmaceutical characteristics can be concealed and substituted with those of nanomaterial (36). Additionally, because of the enriched permeability and retention (EPR) effect, nanoparticles can accumulate preferentially at tumors, infectious sites, and inflammatory locations. These characteristics provide numerous benefits for nanodrug delivery systems.

II.8.2 Solar Industry:

Solar energy is among the greatest renewable energy sources. Heat exchangers known as solar collectors convert solar radiation energy into internal radiation energy (37). These devices absorb solar radiation, convert it to heat, and then transmit that heat to a liquid, example glazing-type solar collector which is use for water heating. This technology has been combined with recently discovered nanofluid technologies to create a new type of nanofluid-based solar collector. Study show that the efficiency increases when the volume fraction of nanoparticles dispersed in working fluids is low. In addition, they investigated nanofluid on solar collectors

using computational and experimental results using a range of nanoparticles, including carbon nanotubes, graphite, and silver. Using nanofluids as the absorption medium increased the efficiency of solar thermal collectors by 5%. Under comparable operating conditions, an absorption solar collector using nanofluid as an existing fluid performed roughly 10% better than a flat plate collector.

II.8.3 Industrial Cooling Applications:

When used as cooling media for industrial cooling processes, nanofluids seem to be more suitable and could result in significant energy savings and emission reductions. For instance, using nanofluids in place of regular cool and heating water could save trillions of Btu. Additionally, it is estimated that using nanofluids in closed-loop cooling circuits could save the U.S. electric power industry between 10 and 30 quads per year. About 5.6 million metric tons of carbon dioxide (CO₂), 8,600 metric tons of nitrogen oxides (NO_x), and 21,000 metric tons of sulphur dioxide (SO₂) would be reduced as a result. Nanofluids have the potential to cool rubber as much as possible during processing in the rubber and tire industries. The issue now is that my ability to cool the entire thing effectively limits the cooling of rubber during processing in that many industrial processes.

II.8.4 Smart Fluid:

A smart fluid is one whose characteristics can be altered by using a magnetic or electric field. It is possible to use nanofluids as smart fluids. Our lack of plentiful clean energy sources and the widespread use of battery-operated devices, including laptops, cell phones, cars, lights, etc., have highlighted the need for intelligent technological management of energy resources in this new era of energy consciousness example using solar energy under cold climate condition. In certain situations, nanofluids have been shown to be capable of performing these functions as smart fluids. Certain research demonstrated that some type of nanofluids can be easily formed either on high state, where dissipation is more effective, or a low state, where it conducts heat poorly.

II.9 Stability of nanofluids :

Nanofluid stability is the most important factor in improving the performance of any system. Nanoparticles have very small sizes and high kinetic energies due to Brownian motion. Despite their size and stability, they do not remain suspended. Gravity causes the nanoparticles to

progressively separate from the solution. Nanofluids can have poor stability due to interactions between the particles and the surrounding liquid, which hinders their commercialization (38). (a) The repulsive electric double layer, which tends to counteract both steric and electrostatic mechanisms of repulsion as well as the force of gravity.

(b) The well-known Van der Waals attraction on the particle surface, which pulls particles together to form agglomerations or clusters before gravity pulls them to the bottom.

The repulsive force of the electric double layer must be stronger than the attractive forces of the Van der Waals in order to produce a stable nanofluid. In practice, sedimentation and clustering result in two issues. The accumulation of silt that clogs solar collectors and the thermal and photo thermal properties of the nanofluids are lost. In order to reduce flow and abrade the wall tube, sediments accumulate, maintaining dispersed nanofluids depends on the stability and performance of the nanofluids. To improve stability and reduce sedimentation and nanoparticle concentrations, researchers used a variety of techniques. The long-term stability and thermal characteristics of nanofluids were supported by both chemical and physical treatments, such as the addition of surfactants and homogenization and ultra-sonication.

II.9.1 Chemical treatment for enhance nanofluid stability:

The stability of nanofluids depends on the characteristics of both the base fluid and the nanoparticles. Nanofluids are bound to base fluids by surface-active substances known as surfactants, which stop particle aggregation. Surfactant addition is a simple and cost-effective chemical process that reduces base fluid surfaces, improves nanoparticle immersion, increases stability, and inhibits the agglomeration of nanoparticles in nanofluids.

The type of base fluid used and the surface charges of NPs are the primary factors that influence the choice of surfactant and dispersant can be classified into four groups: (a) the negative charge head group of ionic surfactants (b) the neutral head group non-ionic surfactants (c) the positive charge head group of cationic surfactants (d) amphoteric surfactants of zwitterionic head groups.

In nanofluids research, a variety of surfactants are commonly used, such as polyvinylpyrrolidone, sodium dodecyl sulphate, oleic acid, hexadecyl trimethyl ammonium bromide, acrylic acid sodium salt, sodium dodecyl benzene sulfonate, and dodecyl trimethylammonium bromide (39). The sensitivity of the Nanofluids stabilizer dispersant to high temperatures is a disadvantage because it breaks the bonds between the NPs and the surfactant

and, in certain cases, can react chemically to create foams. Moreover, an excess of surfactants changes the thermophysical properties of nanofluids, making them less thermally conductive and more viscous.

II.9.2 Physical treatment for enhance nanofluid stability:

The most widely physical treatment method use for stabilizing nanofluids is probe sonication. Stabilization of a nanofluid to break up nanoparticle clusters and disperse nanoparticles into base fluids. (40)At the ultrasonic level, sound energies exceed 20 kHz. Ultrasound procedure uses different power and frequency levels for different durations. Many researchers use ultrasonic to prepare and stabilize nanofluids, the impact of ultrasonic time on the stability of water-based Al_2O_3 nanoparticle and sonication times were found to improve colloidal dispersion and reduce viscosity.

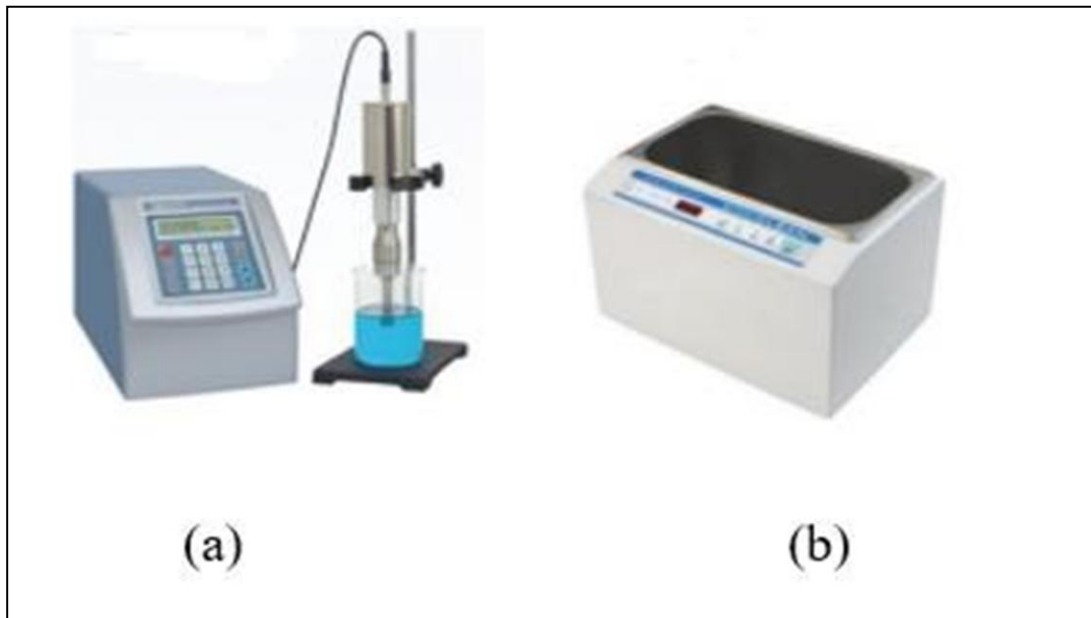


Figure II.6: “Ultrasonic types. (a) Probe Ultrasonic (b) Bath Ultrasonic ”.

II.10 Advantages of using nanofluid in the solar collectors:

Due to their many advantages over conventional fluids, nanofluids are very effective in the field of solar collectors. Regarding this issue, the following advantages of nanofluids can be measured: One of the characteristics of nanofluids is their high thermal conductivity. As a result, the suspensions' thermal conductivities and heat transfer characteristics improved, because of Brownian motion which improves the efficiency of heat transfer (41).

- The nanoparticles' small size allows them to pass through porous materials and be readily combined with fluids. Under ultrasonic vibration, it was found that the nanoparticles are uniformly distributed in the base fluid and have a tendency to flow and move quickly even inside the solid.
- The particles settled quickly and affected the fluid movement when micrometer and millimeter particles were used in solar collectors. To solve this problem, nanoparticles have been developed.
- By varying the particle concentration, a nanofluids thermal conductivity, viscosity, density, and specific heat can be customized to meet the needs of specific applications.
- The fluid can remain fluid for an extended period of time due to the high stability and Brownian motion of the nanofluids. The rate of heat transfer is accelerated by the fluid and nanoparticles' larger surface area.
- The efficiency of a solar collector is increased when the nanofluid is used in place of the base fluid. The only way to achieve high temperatures in a typical solar collector is to increase the surface area for heat collection, which leads to costly and large collectors.
- Without increasing the surface area that absorbs heat, nanofluids offer the benefit of improved heat transfer. As a result, they improve collector efficiency without requiring expensive procedures or the production of enormous heat-absorbing sheets.

II.11 Use of nanofluids in flat plate solar collector system:

Over the past few years, renewable energy sources have gained popularity in most countries due to the scarcity of energy resources. One of the renewable energy sources that has received the most attention is solar thermal energy systems for use in homes and businesses. Flat-plate collectors have been in use for so many years without substantial design modifications or a revolution in engineering principles. While there are some advantages of using a FPSC, such as its dependability, durability, and affordability, there are disadvantages as well, such as low sensitivity and efficiency under low irradiance and ambient temperature. After passing through a transparent working fluid such as water, oil, or ethylene glycol (EG), sunlight is absorbed by the FPSC and converted into thermal energy for commercial and residential uses, Hussein A K et al (4)

II.12 Computational fluid dynamics:

Heat transfer, chemical reactions, fluid flow, and other phenomena that take place inside solar collectors are all modeled using computational fluid dynamics (CFD) technology. With the

revolution in computing power brought about by computers, research on solar collectors took a new turn. Numerous researchers used simulation tools to apply numerical CFD simulations to investigate solar collectors. Numerous studies have examined flat plate solar collectors filled with nanofluids using modeling and numerical simulations. Previous research used ANSYS Fluent to study the 2D $\text{Al}_2\text{O}_3/\text{water}$ in flat plate solar collectors (42). The coefficient of heat transfer from convection to conduction, the Richardson number, and the particle volume fraction all increased as the Reynolds number increased. The heat transfer coefficient rose to certain percentage when nanofluids was added. Additionally, the simulation demonstrated that entropy is produced rapidly as Reynolds increases and the concentrations of increased nanofluid decrease.

Table II.1. “A summary of recent studies on FPSC using nanofluids”.

Base fluids	Nanoparticles	Remarks based on previous experimental studies	Citation/sources
Water	Carbon fiber -Multi-walled carbon nanotubes (MWCNT)	The collector's efficiency increased by 21.9% at a concentration of 0.1 and by 11.8% at a concentration of 0.05% at a 4 l/h flow rate.	Hussein et al. (2020)
Water	Nanoplatelets graphene	When nanoparticles were added to the fluid at a concentration of 0.1%, the collector efficiency was maximally increased by 18.2% in comparison to the base fluid(43).	Akram et al (2019)
Water	Aluminium (Al_2O_3)	(44)At a mass flow rate of 0.047 kg/s, the solar collector filled with Al_2O_3 nanofluid in 1 vol% concentration of particles with a size of 20 nm showed a maximum increase in efficiency of 24.1%.	Kim et al (2017)

Water	Copper (Cu)	At a volume fraction of 0.3%, the collector with twisted tape inserts showed 65% efficiency, compared to 58% for the collector without.	(45)Sundar et al(2020)
-------	-------------	---	------------------------

II.13 COMPARATIVE SYNTHESIS OF THE LITERATURE

Table II.2: “comparison of nanoparticles”.

Properties	Conventional fluid(WATER)	Single (Mono)	Hybrids
Heat Transfer Efficiency (FPSC Performance)	Low collector efficiency as a result of poor heat transfer	Relatively enhanced heat removal from the absorber plate	Significant enhancement in thermal efficiency and heat extraction
Stability	Very good long-term stability, no sedimentation was observed.	Fairly stable possible slow particle agglomeration over time	Good to high stability depending on hybrid composition and surfactant
Viscosity	Low, negligible flow resistance	Viscosity increased as a result of addition of nanoparticles	Viscosity increases with particle size and type and concentration of particles
Pumping Power Requirement	Low power consumption	Slight increase as a result of increased viscosity	As known, the higher pumping power is required for some arrangements.
Preparation Complexity	Simple and readily available	Moderate ,sonication and stabilization is	Difficult because multiple nanoparticles

		needed	and dispersion management
Cost	Inexpensive and readily accessible	Moderate cost due to the synthesis of the nanoparticles	Expensive due to high-tech materials (e.g. graphene, CNTs)
Industrial Application in FPSC	Widely serves as baseline working fluid	An increasing number of experiments, but still very few ones	Emerging and mostly a research-stage application

II.14 SCIENTIFIC GAP IN THE LITERATURE:

Many studies demonstrate that hybrid nanofluids do not perform better than single nanofluids because of viscosity variation, despite the fact that there are numerous studies on nanofluid and thermophysical performance on single and hybrid nanofluids but few studies on thermodynamics and experimental comparison between single and hybrid nanofluids. An existing Studies on Al_2O_3 /Water and Al_2O_3 -cu/water nanofluids show that the enhancing the performance of flat plate solar collectors are also lacking, according to the literature review. In order for FPC to be effective, this study will close the gap in the literature by examining how well it performs when hybrid nanofluid is used in place of base fluid.

The study will also look at how filling with nanofluids affects the thermodynamic properties of the FPSC. The study examine entropy generation, energy analysis, Nusselt number, and exergy destruction in this regard. The significance of this research was emphasize on the efficiency and performance of nanofluids using fpSC. Since there is limited resources to performance research on nanotechnology an existing literatures highlighted the potential of nanoparticles for use in renewable energy applications to improve energy efficiency e and enhance system improvements which can benefit this current and future research. According to the aforementioned review, no thorough analysis of the characteristics of aluminium oxide (Al_2O_3) and aluminium oxide –copper (Al_2O_3 -cu) nanoparticles was identified

II.15 Summary of literature review:

The increasing demand for energy and the continuous battle with energy generation costs are preceded by a catastrophic depletion of fossil fuel power reserves and an increase in environmental pollution. Renewable energy is a part of the modern era because it can produce more energy and is more environmentally friendly. Flat-plate solar collectors (FPSC) are widely used in many low- and medium-temperature home applications because of their popularity. However, FPSCs' ability to convert solar energy into thermal energy is limited because solar fluids on the collector's flow tubes transfer heat inefficiently. The significance of nanoparticles has received a lot of attention from scientists lately. Using nanofluids instead of traditional base fluids in FPSC has a number of benefits, including higher collector efficiency. According to the literature review, the following points will give a detailed explanation of the research gaps and the primary contributions of this study to fill them: The distinct characteristics of aluminum oxide (Al_2O_3) and aluminum oxide –copper (Al_2O_3 -Cu) nanoparticles are another reason for this investigation. According to the literature review, several previous studies have addressed the preparation of nanofluids. Lastly, to the best of the authors' knowledge, the current study is a novel endeavor that sheds light on the possibility of utilizing nanofluids to investigate the efficacy of a flat plate solar collector. Thus, this study's objective was to fill in all of the aforementioned research gaps while considering different types of nanofluids. The study also demonstrated that some nanofluids have advantageous thermal properties that can facilitate heat transfer in solar collectors. The study also describes how adding various types of nanoparticles to the fluid produces hybrid nanofluids, which outperform nanofluids and have the potential to yield incredible outcomes when applied to solar collectors. Additionally, this study can be used in future research to explore the potential of employing the designated nanofluids in renewable energy applications.

CHAPTER III: Research Methodology

III.1 Introduction:

Nanofluids, such as metal oxides, non-oxides, or mixes of these, are made by dispersing nanoparticles in common fluids like water, ethylene glycol, water-based ethylene glycol, and so forth. Because of the combination of the particles' exceptionally high surface-area-to-volume ratio and nanoscale thermal transport mechanisms like Brownian motion and interfacial phonon scattering, effective thermal conductivity, heat capacity, and convective heat transfer coefficients are measured and often significantly increased at this length scale. Since the enhanced properties reported in scientific literature have been shown in a range of experimental setups, the current challenge is to interpret laboratory results into predictive computational models of adequate engineering design. The different types of nanoparticles are varying base on strength and characteristic, For example carbon nanotubes have remarkable axial thermal conductivity; alumina is chemically stable; and copper has high absolute conductivity. If handled properly, their combination may result in synergistic enhancement that is greater than what either component can accomplish alone.

A relatively new and interesting idea is hybrid nanofluids, which are composed of two or more different types of nanoparticles co-dispersed in the same base fluid. Which indicate that alumina is chemically stable, copper has great absolute conductivity, carbon nanotubes have exceptional axial thermal conductivity, and different types of nanoparticles have varying strengths. When combined, they can produce a synergistic improvement that beyond what either element can do on its own. It is still debatable if and under what conditions this synergy actually occurs.

III.2 Simulation Procedure and Presentation of the Physical Model:

III.2.1 Architecture of the collector and domain idealisation:

The flat-plate solar collector under consideration here is a common single-glazed, non-concentrating model used for heating low-temperature industrial processes and hot water in homes. There are five primary subsystems that make up the collector in its physical form:

- (i) Two header manifolds that distribute flow evenly across the riser array.
- (ii) a selective-surface absorber plate that offers absorptance values higher than 0.93 and is often composed of roll-bonded copper or aluminum sheet with a spectrally selective covering;

CHAPTER III: Research Methodology

- (iii) The working fluid passes through a series of parallel riser tubes that are either mechanically or brazed to the absorber plate;
- (iv) A hard glass glazing cover whose spectral transmittance is adjusted to match the sun radiation's spectral distribution;
- (v) A back casing with thermal insulation to reduce conductive heat loss to the environment.

For a parametric research with many nanofluid types, volume fractions, and flow rates, modelling the whole 2D collector geometry with conjugate heat transfer and manifold flow distribution would not be practical in terms of computation time. The nanofluid approach is a basic and proven technique. As a result, the FPSC literature's representative unit cell is derived from a single riser tube with its half absorber plate width constrained by symmetry at its lateral edges. The basic mechanics of forced convection inside the tube and conduction in the absorber plate are preserved in this approximation. While bringing the computational domain's size down to a manageable level. The even flow distribution within the riser array, which is susceptible to capsuled manifold analysis, is the foundation for this approach's soundness.

III.2.2 Nanofluids Systems Studied:

In this work, we present a comparative numerical study on the thermo hydraulic performance of simple nanofluids and hybrid nanofluids. The main objective is to evaluate the influence of adding nanoparticles on the heat transfer and flow characteristics of the base fluid. For this, the results obtained with a simple nanofluid are compared to those of a hybrid fluid in order to analyze their respective effectiveness in terms of improving thermal transfer and hydrodynamic behavior.

This study thus highlights the potential advantages of hybrid nanofluids in thermal management applications.

Category I: Simple Nanofluids:

Water-AL₂O₃

Category II: Hybrid Nanofluids:

AL₂O₃-CU

III.3 Theoretical Background for Thermophysical Properties:

III.3.1 Basic Assumptions:

The assumptions on which the governing equations are based must be explicitly specified prior to writing the governing equations, because the whole mathematical model validity depends on whether they are physically reasonable in the considered parametric space:

- The flow is steady-state. Transient effects due to diurnal solar irradiance variation are ignored; the study is performed at quasi-steady operating conditions.
- The flow is laminar and incompressible. All the considered Reynolds numbers are less than 2100, so there are no turbulent fluctuations. The assumption of incompressibility is valid owing to the low Mach numbers ($Ma \ll 0.01$) involved.
- Nanofluid is treated as a single phase Newtonian fluid with effective properties. This single phase model is valid for $\phi \leq 4\%$ and particle diameters are less than about 100 nm for these conditions the inter-phase slip velocity is negligible and sedimentation time scales are very long compared to fluid residence time.
- Thermophysical properties are calculated at an average bulk temperature and are a function of the temperature alone. Viscosity-temperature dependence is especially important for some nanofluid and a sensitivity analysis with respect to this assumption. Viscous dissipation is not taken into account. The Brinkman number ($Br \approx 10^{-7}$ to 10^{-5} for the velocities under consideration) states that frictional heating is much smaller than the heat of the wall.
- The absorber plate is treated as an isotropic homogeneous material and its properties do not vary with temperature. The selective coating is modelled implicitly by means of the absorptance factor α_a at the boundary surface.

III.3.2 Mathematical Modeling

In the present study, the heat transfer from the absorber to working fluid was investigated by considering the working fluid to have steady-state laminar flow. The mathematical details, such as the governing equations and equations describing the nanofluid heat properties, is outlined in this chapter. Simulations were performed on fluent(46).

III.3.2.1 Governing Equations for Single-Phase Fluid Flow:

A working fluid to which solid nanoparticles have been added is generally considered as a two-phase fluid; however previous studies stated that in some conditions, the nanofluid can be assumed as a homogeneous single-phase fluid since the nanoparticles are less than 100nm and

CHAPTER III: Research Methodology

fluidized (43). Under the assumption that there is no slip between phases and that the phases are in thermal equilibrium, the governing equations for incompressible laminar flow

Continuity:

The classical divergence form represents mass conservation for a constant, incompressible flow field:

$$\nabla \cdot (\rho_{nx} \vec{V}) = 0 \quad (\text{III.1})$$

V and ρ_{nx} are the fluid velocity and density of the nanofluid, respectively and it is expanded in Cartesian coordinates (x, y, z) with velocity components (u, v, w) , reduces to the familiar solenoidal constraint:

$$\partial u / \partial x + \partial v / \partial y + \partial w / \partial z = 0 \quad (\text{III.2})$$

Momentum (Navier–Stokes):

The momentum equations describe the balance between inertial, pressure, and viscous forces within the fluid. For the incompressible, constant-property regime adopted here, the vector form is:

$$\rho_{nx} (\vec{V} \cdot \nabla) \vec{V} = -\nabla P + \mu_{nx} \nabla^2 \vec{V} + \rho_{nx} \vec{g} \quad [\text{buoyancy retained for natural convection sensitivity}] \quad (\text{III.3})$$

P is the thermodynamic pressure, μ_{nx} is the nano fluid dynamic viscosity, and g the acceleration due to gravity vector. The buoyancy term is kept in the formulation (allowing for mixed convection in inclined collector configurations) but it is not operative in the base line horizontal cases.

Energy equation — Fluid Domain:

Thermal energy conservation in fluid, accounting for viscous dissipation and internal heat generation are negligible, results for:

$$\rho_{nx} c_{p, nx} (\vec{V} \cdot \nabla T) = \nabla \cdot (k_{nx} \nabla T) \quad (\text{III.4})$$

$c_{p, nx}$ and k_{nx} are the specific heat and thermal conductivity of the nanofluid, T denotes the temperature. The convective transport of enthalpy by the mean flow is on the left-hand side, and the molecular (conductive) diffusion is on the right-hand side. It is this interaction between the flow field (Equations III.1–III.3) and the temperature field (that renders nanofluid heat transfer a

CHAPTER III: Research Methodology

fully nonlinear problem: the velocity profile controls convection, but the temperature profile can also influence the velocity field (via buoyancy).

Energy: Solid Absorber Plate:

In the solid plate, which implies $\sigma = 0$, the energy equation reduces to heat conduction in steady state with a surface source term:

$$\nabla \cdot (k_s \nabla T_s) + \dot{s}''_{\text{elt}} = 0 \quad [\text{applied at outer plate surface only}] \quad (\text{III.5})$$

The volumetric heat source $\dot{s}''_{\text{elt}}$ equals zero everywhere except at the plate's outside surface where it stands for the net absorbed solar flux: $\dot{s}''_{\text{elt}} = \tau^g \alpha_a I_s^o$. The fluid and solid phases are coupled in energy at their mutual interface via conjugate boundary conditions.

III.3.3 Thermophysical Property Correlations of water and water base nanofluid:

The addition of nanoparticles influences the physical properties of a fluid, such as the density, specific heat, thermal conductivity, and dynamic viscosity. Produced a well-dispersed colloidal suspension. Research show that the reliable results of a single-phase nanofluid simulation strongly depend on the accuracy of the mixing-law correlations that were applied in the calculation of effective properties. The correlations considered in this work have been chosen according to three criteria:

- (i) proven agreement with experimental data within the range of parameters considered in this work,
- (ii) acceptance in the FPSC nanofluid literature to allow direct comparison, and (iii) possibility of analytical solution within the iterative numerical solver.

Effective Density:

Density is the mass of a substance in a given volume and it is expressed in kg/m^3 . Previous studies shown that the effective density of nanofluid is calculated from the density of the constituents by a volume-weighted linear superposition produced a well-dispersed colloidal suspension (47).

$$\rho_{\text{nx}} = (1 - \varphi) \rho_x + \varphi \rho_{\text{np}} \quad (\text{III.6})$$

This result is derived by applying the conservation of mass to the mixture and is exact assuming incompressibility for two species of particles with volume fractions φ_1 and φ_2 in hybrid nanofluids:

$$\rho_{\text{nx}}^{\text{H}} = (1 - \varphi^{\text{H}}) \rho_{\text{xx}} + \varphi_1 \rho_{\text{np1}} + \varphi_2 \rho_{\text{np2}}, \quad \varphi^{\text{H}} = \varphi_1 + \varphi_2 \quad (\text{III.7})$$

Specific Heat Capacity nanofluid:

Specific heat capacity is the quantity of heat required to raise the temperature of one kilogram of a substance by one-degree Kelvin and it has units of J/ kg.K. The volumetric heat capacity of the nanofluid mixture is:

$$(\rho c_p)_{nx} = (1 - \varphi)(\rho c_p)_x + \varphi(\rho c_p)_{np} \dots\dots\dots(III.8)$$

The importance of specific heat capacity is also emphasized in solar collector applications where the desired temperature of the collector outlet is higher. The specific heat capacity at pressure constant (without the density weighting) does not fulfill a straightforward mixing rule; it is the quantity ρc_p that is additive. The equation (III.8) through by the effective density from (III.6) to obtain $c_{p/nx}$.

Effective Thermal Conductivity nanofluid:

Thermal conductivity is the property that is most strongly affected by the addition of nanoparticles and the one that is most determined by modelling. The Hamilton–Crosser model, which is an extension of the classical Maxwell effective medium theory for non-spherical particles by considering an empirical shape factor n , is used for single nanofluids:

$$k_{nx} / k_{xx} = [k_{np} + (n - 1)k_{xx} - (n - 1)\varphi(k_{xx} - k_{np})] / [k_{np} + (n - 1)k_{xx} + \varphi(k_{xx} - k_{np})] \dots\dots\dots(III.9)$$

where n is the particle shape factor ($n = 3$ for spheres, $n = 6$ for cylinders, in line with the MWCNT system). The thermal conductivity of the nanofluid can be calculated at all the evacuated temperatures by using the Maxwell equation.

$$k_{nx}^H / k_{xx} = [\varphi_1 k_{np1} / \varphi^H + \varphi_2 k_{np2} / \varphi^H + 2k_{xx} + 2\varphi^H(\varphi_1 k_{np1} / \varphi^H + \varphi_2 k_{np2} / \varphi^H - k_{xx})] / [\varphi_1 k_{np1} / \varphi^H + \varphi_2 k_{np2} / \varphi^H + 2k_{xx} - \varphi^H(\varphi_1 k_{np1} / \varphi^H + \varphi_2 k_{np2} / \varphi^H - k_{xx})] \dots\dots\dots(III.10)$$

Effective Dynamic Viscosity of nanofluid:

Viscosity is the thermophysical property that directly affects the pumping power and therefore its accurate prediction is inevitable for any energy analysis. The Brinkman (1952) model, which is by far the most validated correlation for dilute nanofluid suspensions, The Einstein model is valid for low volume concentrations ϕ is less than 0.02 and since high concentrated volume were considered in the simulation in the recent study of the model (48)

$$\mu_{nx} = \mu_{xx} \cdot (1 - \phi)^{-2.5} \quad (3.11)$$

It is important to keep in mind that the Brinkman model was derived for solid spheres at low concentrations and it underestimates systematically the viscosity for nonspherical or clustered particles at $\phi > 3\%$. The impact of underestimating this on total collector efficiency is quantified. In the case of hybrid nanofluids, the overall volume fraction ϕ^H substitutes ϕ in Eq. (III.11).

The complete thermophysical property data for nanoparticles and base fluids used in computing the effective properties are tabulated in Table III.1.

Table III.1: Thermophysical properties of base fluids and nanoparticles at 25°C. (MWCNT axial conductivity; effective suspension value substantially lower due to contact resistance and orientation effects.

Materials	k ($W\ m^{-1}\ K^{-1}$)	ρ ($kg\ m^{-3}$)	c_p ($J\ kg^{-1}\ K^{-1}$)	μ ($mPa\cdot s$)
Water (25°C)	0.613	10^3	4.182	0.890
Al_2O_3	40	3970	765	–
Cu	410	8933	385	–
MWCNT	3000	2100	711	–
SiO_2	1.4	2220	745	–
Ethylene Glycol (25°C)	0.258	1113	2415	16.10
CuO	33	6310	686	–
TiO_2	8.9	4250	535	–

III.3.4 Pressure Drop and Pumping Power of Nanofluid:

The forced convection in the flat plate solar collector (FPSC) pipe required a mechanical pump to push it. The inlet and outlet pressures were measured in fluent, and the pressure difference between them was the pressure drop. The following equation was used to relate the pressure drop to the calculated pumping power.

$$\text{Pumping power} = (\dot{m} / \rho) \times \Delta P = \Delta P \times V = \rho \cdot g \cdot V \cdot h / \eta_p \dots \dots (III.12)$$

Where $\dot{m}$ is the mass flow rate, ρ is the density, ΔP is the pressure drop, V is the volume flow rate, g is the gravity, h is the differential height, and η_p is the pump efficiency.

III.3.5 Efficiency of FPSC :

Q is the amount of solar radiation received by the FPSC. In this research, a constant heat flux was set to be the heat source of the solar collector.

$$Q_{rec} = q''A \dots\dots\dots (III.13)$$

q'' is the constant solar heat flux and A is the surface area of the absorber plate. The working fluid in the tube extracts some heat when it flows through the absorber plate:

$$Q_{abs} = m \times CP \times (T_{out} - T_{in}) \quad (III.14)$$

The efficiency equation η of the solar collectors:

$$\eta = m \times CP \times (T_{out} - T_{in}) / q''A \quad \dots\dots\dots (III.15)$$

III.4 Boundary Conditions:

The boundary conditions comprised inlet, outlet, wall, constant pressure, axisymmetric, symmetric, periodic conditions and the accuracy of any CFD modeling is always dependent on how realistic its boundary conditions are. Five different types of boundaries for the FPSC domain are distinguished and established with careful consideration of both the physics being represented and the numerical treatment.

Inlet:

In this boundary condition, the flow rate or velocity of the fluid is defined. In the simulation, the density of the nanofluid varied with the temperature, and this would have rendered the results temperature dependent. In the simulation, the density of the nanofluid varied with the temperature, and this would have rendered the results temperature dependent. T .

Velocity = 0.5m/s and Temperature = 300K.

Outlet:

Atmospheric pressure. $P = 101325 \text{ Pa}$.

Top Upper:

Heat flux. $Q = 750 \text{ W/m}^2$.

Bottom Lower:

Temperature = 350K.

III.5 Principle of finite volume method:

Analytical methods seem to be incapable of solving the conservation equations. Therefore, the application of numerical techniques such the finite difference, finite volume, and finite element approaches turns out to be essential. For conservation equations, the most popular approach is the finite volume method (F.V.M.). In order to solve them, partial differential equations must be converted into algebraic equations. This requires the following four steps (49):

- 1- Perform a mesh of the study domain: A mesh is a succession of control volumes linked together with nodes placed at the center of each volume.
- 2- Integrate the partial differential equations over each control volume.
- 3- Choice of the scheme used: Choose the variation profile of five between two adjacent nodes for its evaluation at the interface.
- 5- Establish "n" algebraic equations to solve for "n" nodes.
- 6- Use one of the methods for solving nominally linear algebraic equations (e.g., T.D.M.A, Gauss-Seidel) to solve the system of equations.

III.6 Advantages of the finite volume method:

- 1-Very "physical" approach: flow balance
- 2-Adapts to any geometry
- 3-Multiple schemes for solving hyperbolic nonlinear terms
- 4-Conservative (by its formulation)
- 4-The foundation of all general-purpose codes in Fluid Mechanics: Fluent, Star-CD, CFX, Fire....

III.7 Mesh concept:

Fluent" handles several types of very complex meshes that are generally imported directly from other mesh generation software "GAMBIT.

The computational domain is divided into a finite and direct number of control volumes, which is referred to as mesh generation. The operation consists of defining a certain number of nodes by drawing a grid on the domain (50).

CHAPTER III: Research Methodology

III .8 Presentation of the FLUENT software:

III .8 .1 Introduction:

The Gambit software is a 2D/3D mesher; a pre-processor that allows meshing geometry domains of a CFD (Computational Fluid Dynamics) problem. It generates mesh files for Fluent. Fluent is a software that allows solving and simulating fluid mechanics and heat transfer problems using the finite volume method((51).

Gambit combines three functions:

- definition of the problem geometry.
- meshing and its verification.
- definition of boundaries (Types of boundary conditions) and definitions of calculation domains.

III.9 Presentation of Gambit:

III.9.1 Starting Gambit:

The path to the Gambit application is as follows:

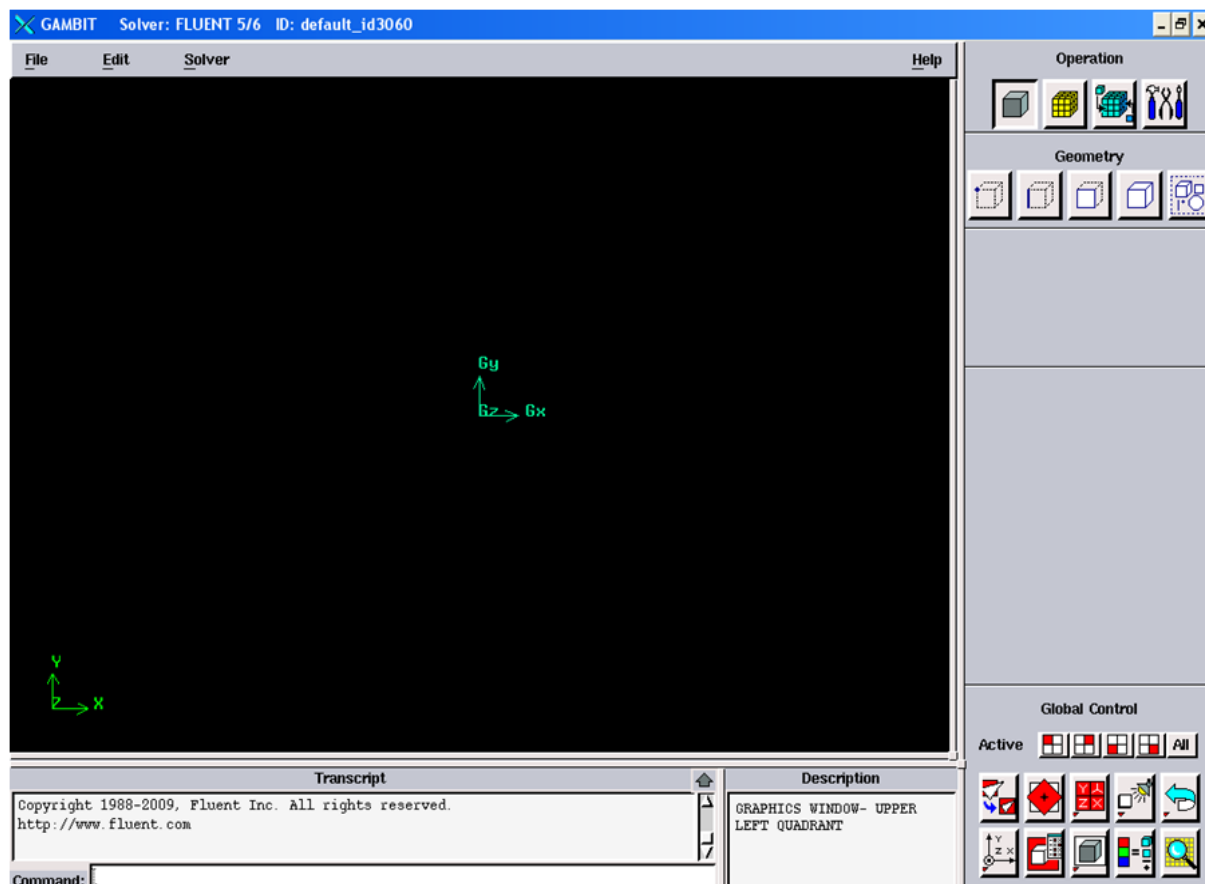


figure III.1: "Launching Gambit".

III.9.2 Geometry Construction:

The purpose of constructing the geometry is to define the calculation domains that will be faces in a 2D problem and volumes in a 3D problem.

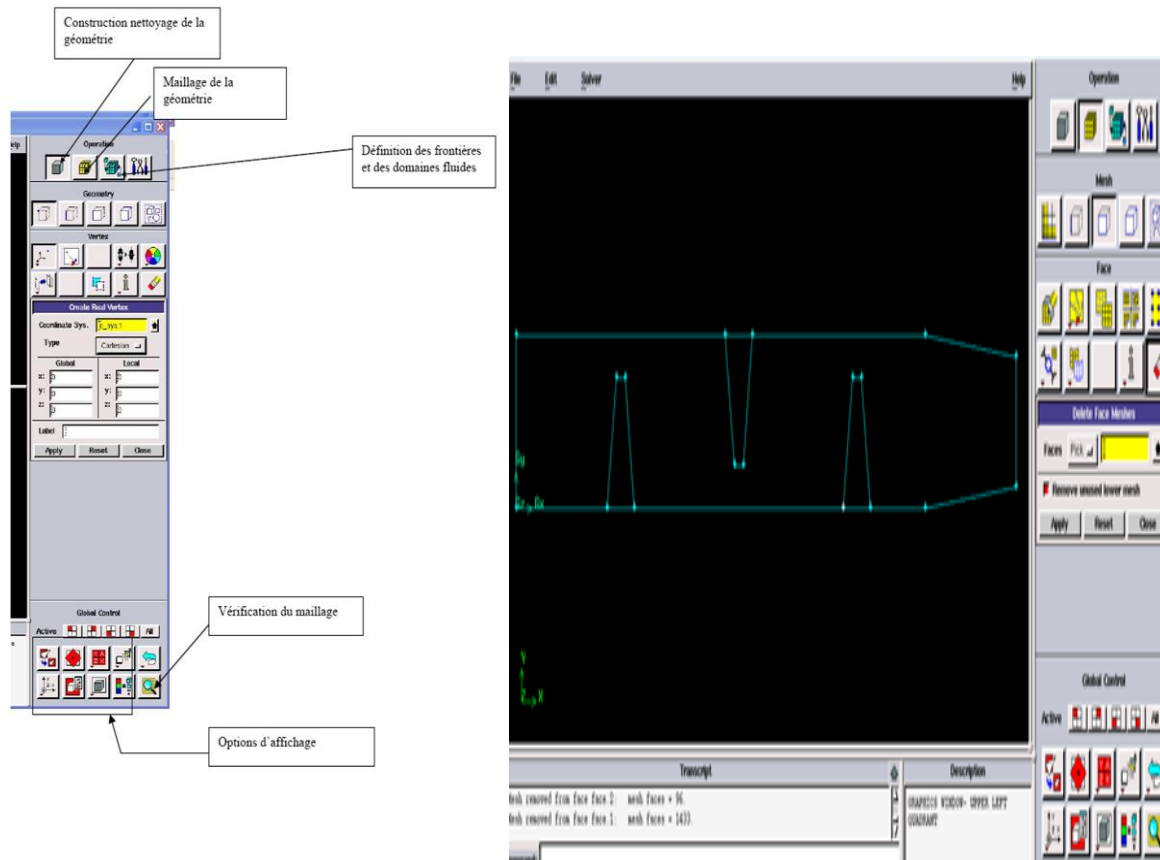


Figure III.2: "The operations to construct a geometry".

III.9.3. Mesh:

The generation of the mesh (2D or 3D) is a very important phase in a CFD analysis, given the influence of its parameters on the calculated solution.

This menu allows for meshing, in a particular line of the geometry that is, placing the nodes with specific conditions (using a ratio to modify the mesh weighting, applying different mesh shapes).

III.9.3.1 Structured mesh (quadra/hexa):

It is much easier to generate it using a multi-block geometry, it has the following advantages:

- Economical in the number of elements, it presents a lower number of cells compared to an equivalent unstructured mesh.
- Reduces the risk of numerical errors because the flow is aligned with the mesh.

The disadvantages are:

- Difficult to generate in the case of a complex geometry.
- Difficult to achieve good mesh quality for certain complex geometries.

III.9.3.2 Unstructured mesh (triang):

The elements of this type of mesh are generated arbitrarily without any constraints on their arrangement.

Its advantages:

- The mesh Can be generated on a complex geometry while maintaining good element quality.
- The algorithms for generating this type of mesh (triangular) are highly automated.

The disadvantages are:

- Very demanding in terms of the number of cells compared to structured meshing.
- Generates numerical errors (false diffusion) that can be more significant compared to structured meshing.

III.9.3.3 Hybrid mesh:

Mesh generated by a mixture of elements of different types, triangular or quadrilateral in 2D, tetrahedral, prismatic, or pyramidal in 3D.

Its advantages:

- Combines the advantages of structured meshing and those of unstructured meshing.

For our study, the mesh of the computational domain is given by Figure III.3’.

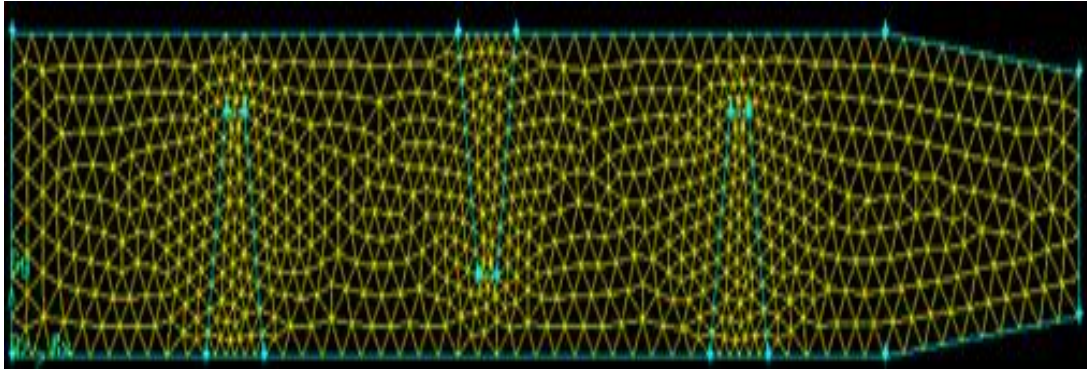


Figure III.3 "The framework of our study".

III.9.4 Definition of Boundaries:

Select the solver type "FLUENT5/6" from the "Solver" menu, then define the boundaries.

III.9.5 Mesh Export:

The mesh can then be exported to a file for reading with FLUENT.

File → Export → Mesh

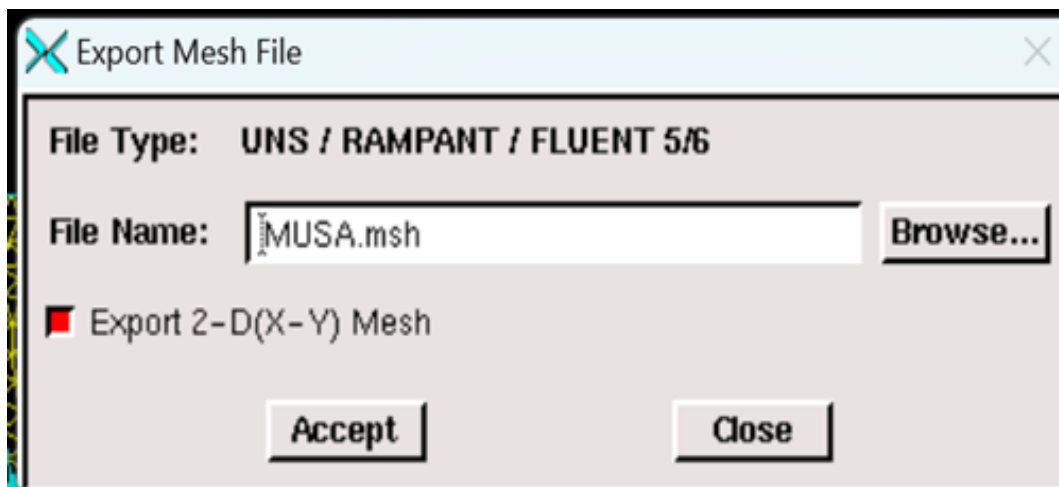


Figure III.4 "Mesh Export".

Give a name to the file and select the "2DD" mesh, then save the Gambit file:

File → Save As

III.10 Presentation of Fluent:

III .10.1 Importing the Geometry:

To start the simulation, you need to import the file and generated the mesh in Gambit.

File → Read → Case

III .10.2 Verification of the imported mesh:

Grid → Check

This allows checking if the imported mesh does not contain errors or negative volumes.

III .10.3 Scale Verification:

Grid → Scale

You must always check that the displayed dimensions correspond to the physical dimensions of the problem.

III .10.4 Choice of Solver:

Define → Models → Solver...

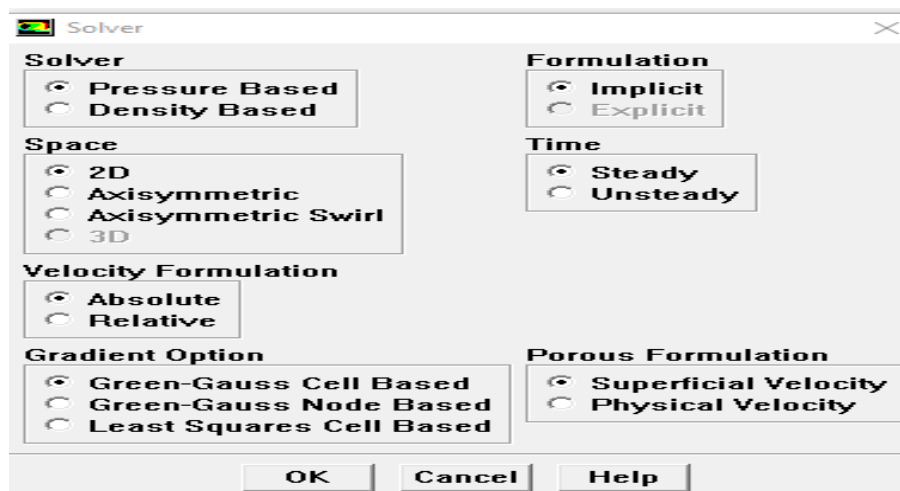


Figure III.5 "Solver Selection".

- **Segregated Solver:** is the most appropriate for incompressible flows (Fans, pumps)
- **Coupled Solvers**

The coupled implicit" and "coupled explicit" solvers, are rather reserved for high-speed compressible flows. This is also where the flow regime is chosen; steady or unsteady.

III .10.5 The energy equation:

Define → **Models** → **Energy...**

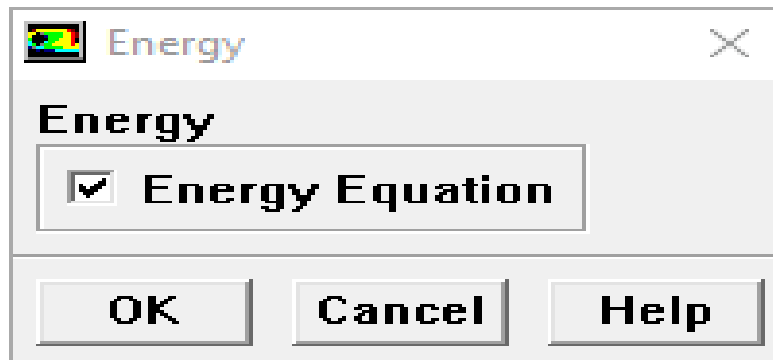


Figure III.6 “Energy Equation”.

IV.10.6 Choice of Turbulence Model:

Define → **Models** → **Viscous**

Fluent offers different models for turbulent flow. Among which are inviscid, laminar, turbulentf flow.

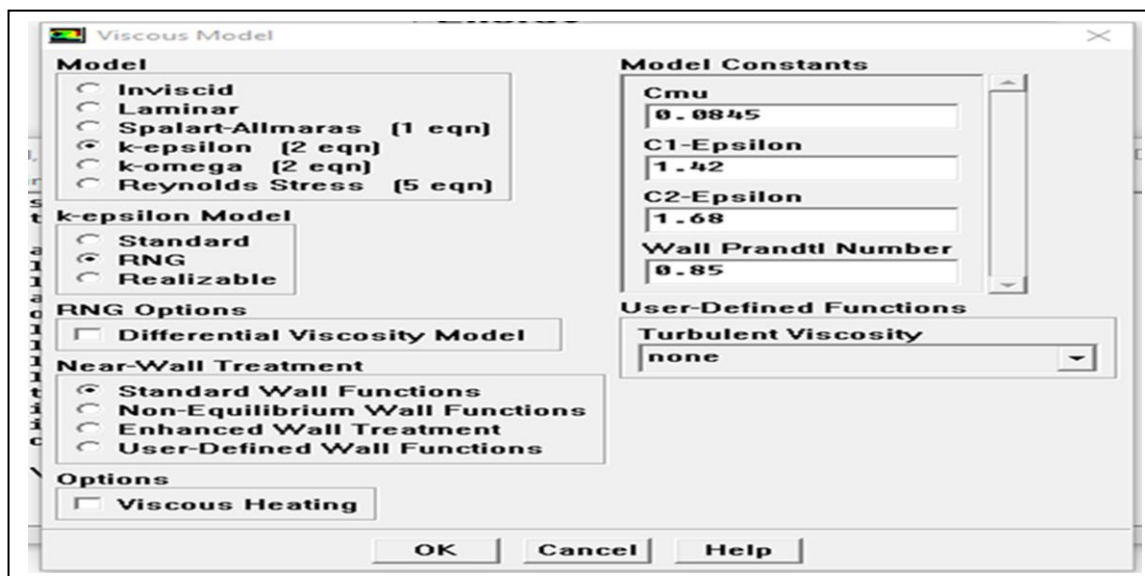


Figure III.7: “Turbulence Model”.

III.10.7 Definition of fluid characteristics:

Define → Materials

The characteristics of the fluids (Nanofluids) are presented in the following figures, Figure 8.

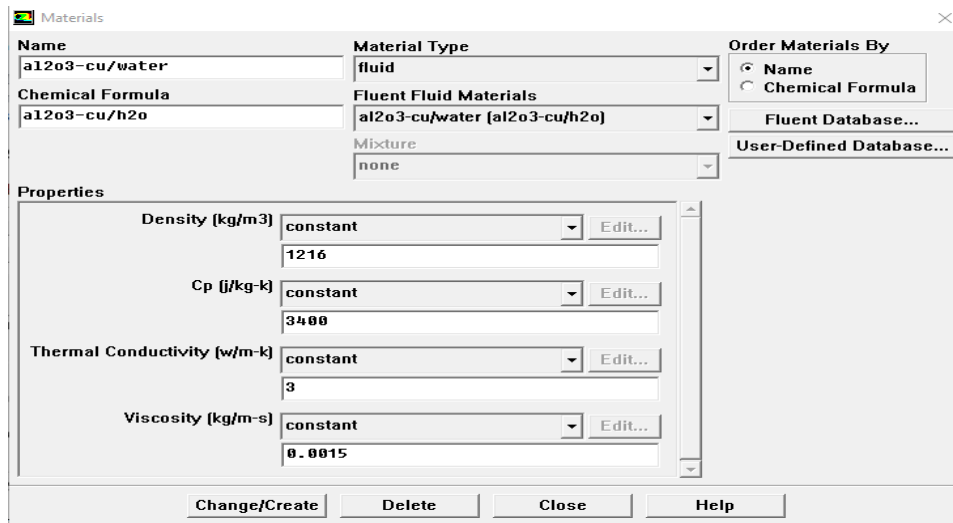


Figure III.8 “Definition of fluid characteristic

III .10.8 Operating conditions :

Define → Operating conditions

Before choosing the boundary conditions, one must first select the value of the reference pressure "operating conditions.

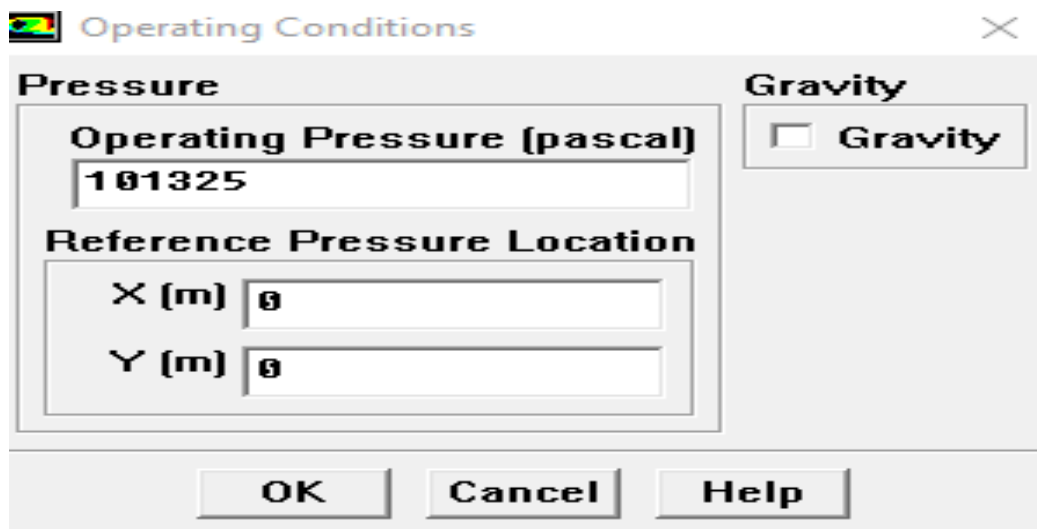


Figure III.9: “Choice of Reference Pressure”.

III.10.9 Boundary Conditions:

Define —→ Boundary Conditions

The boundary condition values must be set.

Velocity inlet

Velocity Inlet

Zone Name:

Momentum | Thermal | Radiation | Species | DPM | Multiphase | UDS

Velocity Specification Method:

Reference Frame:

Velocity Magnitude (m/s):

Turbulence

Specification Method:

Turbulent Kinetic Energy (m2/s2):

Turbulent Dissipation Rate (m2/s3):

OK Cancel Help

Figure III.10: “Fluid inlet velocity

Wall:

The boundary conditions at the domain

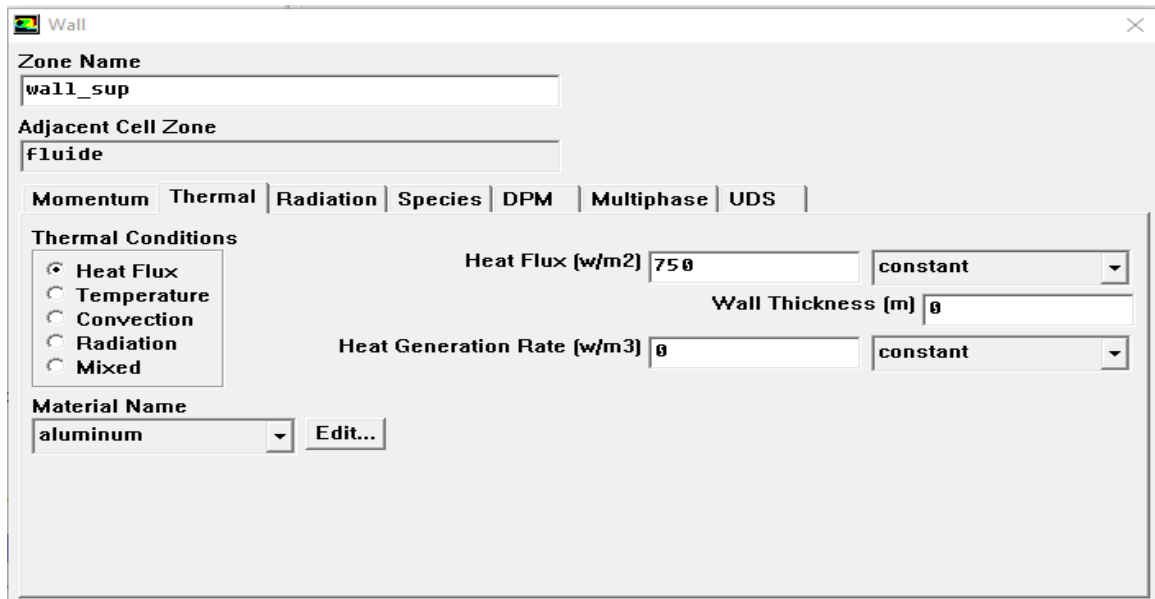


Figure III.11: "Boundary Conditions at the Border".

Pressure Outlet :

Pressure Outlet requires introducing the relative static pressure (or manometric pressure) at the outlet.

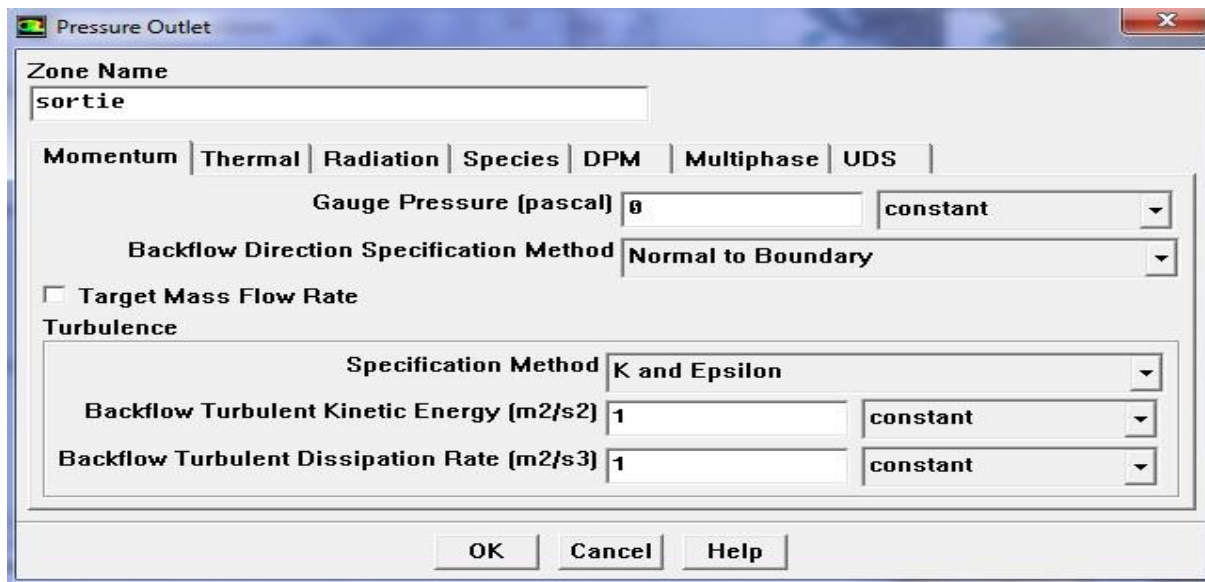


Figure III.21 “Pressure Outlet”.

III.10.10 Choice of order of equations and the algorithm:

Solve —> Controls —> Solution...

This allows specifying the order of the equations to be solved, as well as the algorithm.

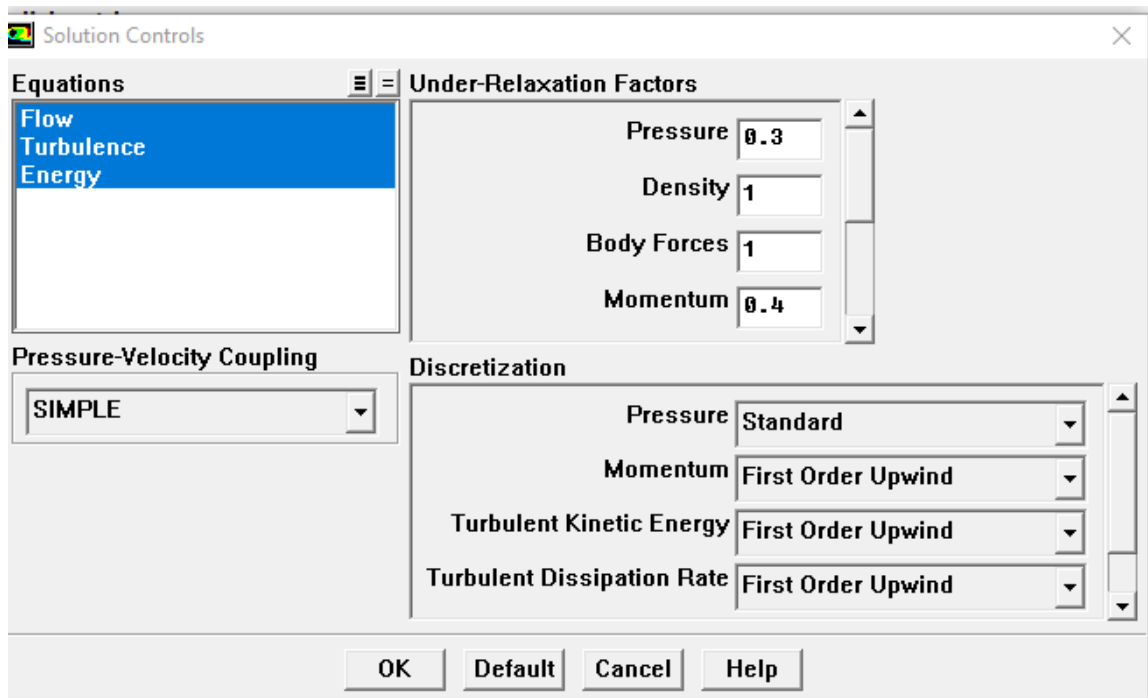


Figure III.13 “Choice of order of equations and the algorithm”.

III.10.11 Initialisation:

Solve → Initialize → Initialize...

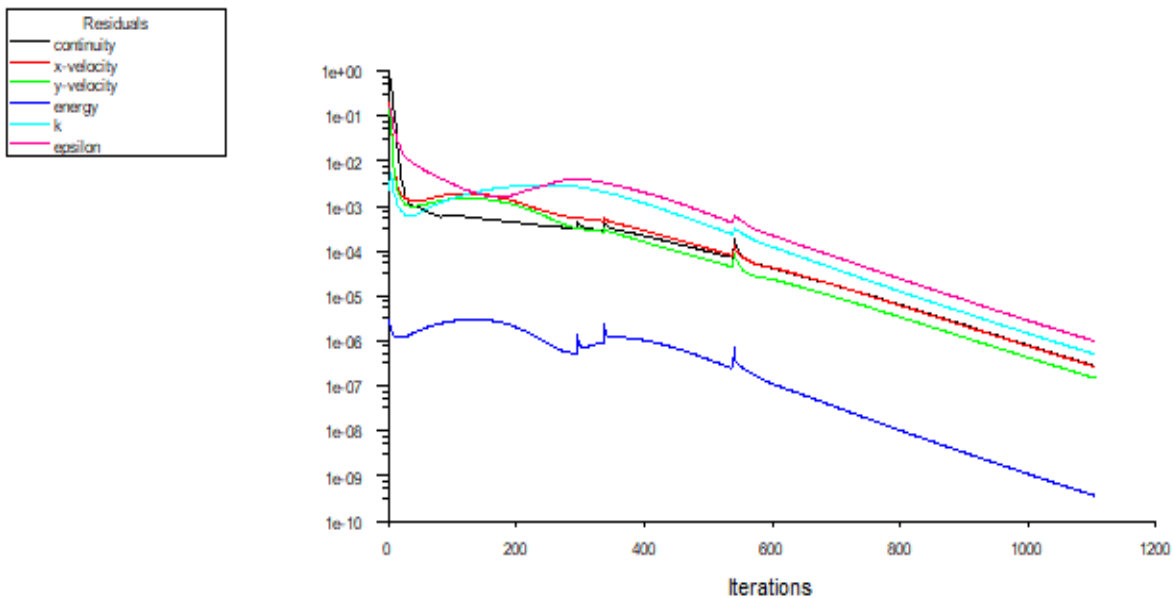
This function allows the calculation to be initialised.

III.10.12 Initialisation of calcul

Solve → Monitors → Residual

This is about choosing the criteria that must be verified for the simulation calculations to stop.

To display the convergence on the screen during the calculations in the form of a graph, you need to activate the Plot option. It is possible to disable certain simulation stop criteria by unchecking the convergence box.



Scaled Residuals

Jun 04, 2026
FLUENT 6.3 (2d, dp, pbrs, rngke)

Figure III.14 “Residual Graph”

III .10.13 Launching the calculation:

Solve —> Iterate To start the calculations, you must first choose the number of iterations.

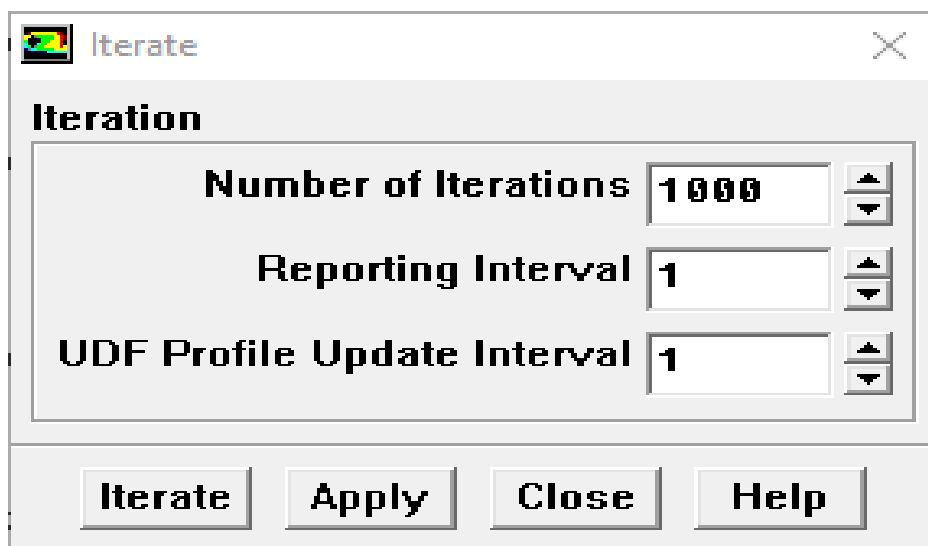


Figure III.15 “Iteration of the solution”.

CHAPTER III: Research Methodology

Conclusion:

This chapter has presented the basic methodology for numerical analysis of single and hybrid nanofluids in flat plate solar collector. The physical domain is introduced and described as a conjugate fluid-solid domain including only a single riser tube and its associated absorber plate segment, a simplification that maintains the crucial physics while enabling the parametric range sought in this work.

CHAPTER IV: Results and discussion

IV.1 Introduction:

The numerical simulations were carried out using the FLUENT 6.3 software, while the geometry of the study domain and the mesh were generated using the GAMBIT 2.4 preprocessor. The results obtained allow for the analysis of the hydrodynamic and thermal behavior of the flow in the studied channel. The interpretation mainly focuses on the streamlines, temperature distributions, velocity contours, and total pressure contours for the two considered configurations: the simple nanofluid and the hybrid nanofluid. This analysis aims to highlight the influence of the fluid's nature on the flow characteristics and the thermal performance of the system.

IV.2 The Mesh :

The mesh used in the simulation is a triangular mesh of the type used for paving for both configuration”.

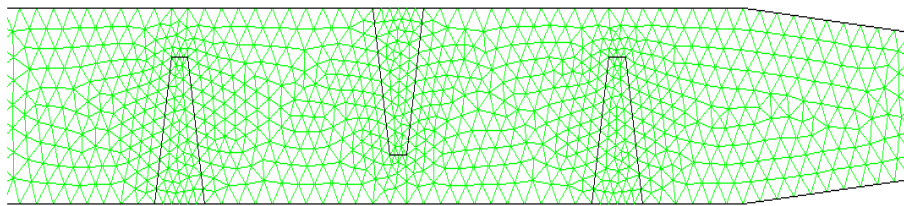


Figure IV.1 “Mesh of the geometries”

IV.3. Streamlines:

The following figures, Figure IV.2, illustrate the contours of the streamlines in the two configurations of our physical model.

The graphs illustrate the formation of recirculation zones (vortices) between the obstacles.

Red/yellow zones: Represent the highest values of the stream function, indicating the main flow at the center of the channel.

Blue zones: Indicate low or negative values, corresponding to recirculation or stagnation areas behind obstacles.

For the flow structure, both fluids exhibit similar flow patterns, suggesting that the addition of copper nanoparticles (hybrid) does not radically alter the macroscopic structure of the vortices compared to the simple nanofluid. Left (ranging from 0 to 1.00e-01) allows for the quantification of the local mass flow rate.

CHAPTER IV: Results and discussion

The streamlines of the hybrid nanofluid reveal a more homogeneous circulation and slightly less pronounced recirculation zones than those of the single nanofluid, indicating a better redistribution of the flow in the channel.

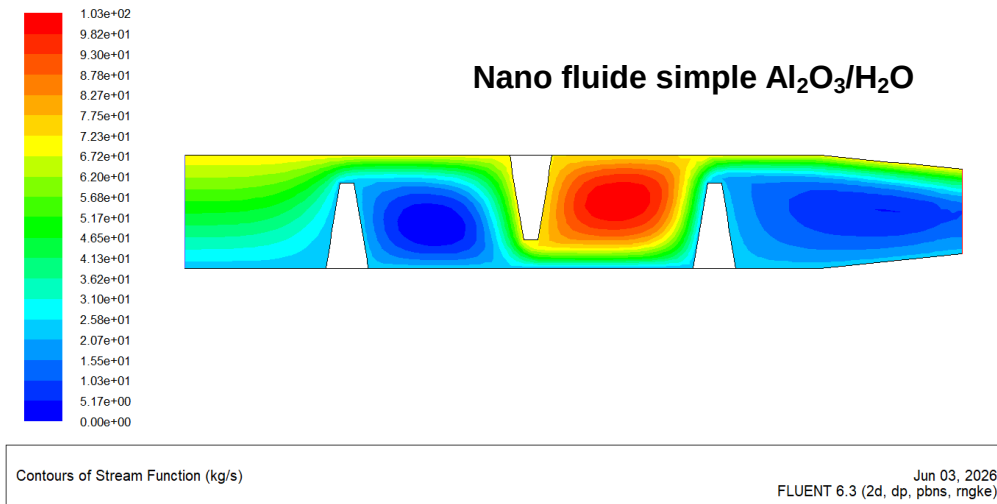


Figure. IV.2 “Streamlines for a single nanofluid”.

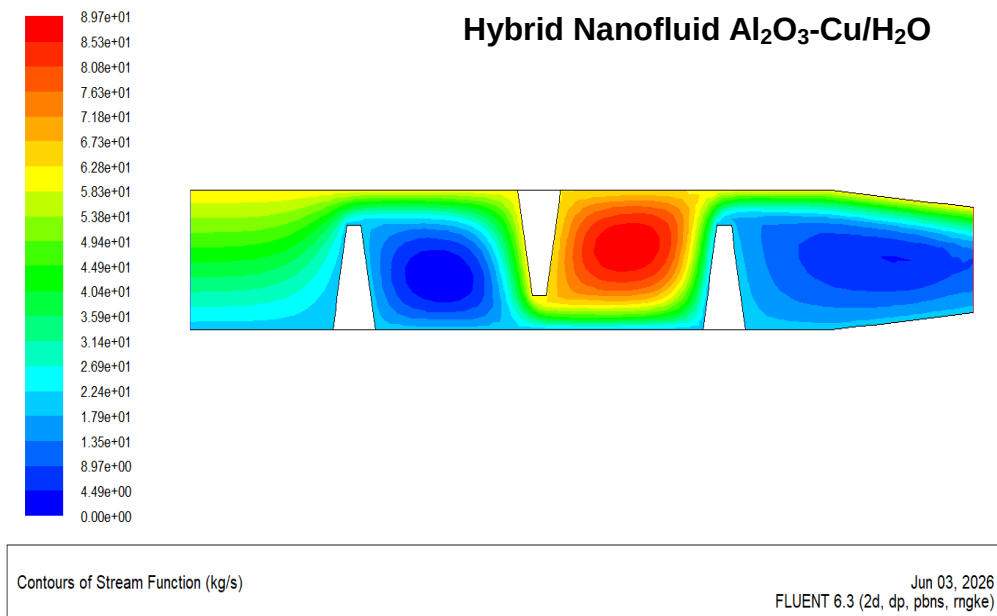


Figure. IV.3 “Streamlines for a hybrid nanofluid”.

CHAPTER IV: Results and discussion

IV.4 Velocities Distribution:

The following figures Figure and Figure show the evolution of the velocity contours in the channel. The first configuration corresponds to the Al_2O_3 nanofluid, while the second corresponds to the hybrid nanofluid.

For the analysis of the Al_2O_3 nanofluid, the maximum speed reaches approximately **2.96 m/s**, the fluid acceleration appears mainly in the narrowed passages between the obstacles, low-velocity

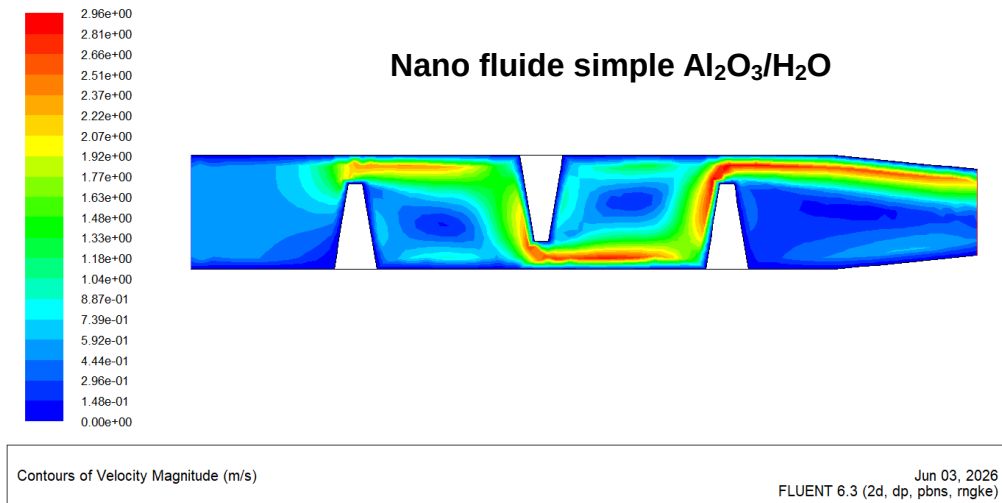


Figure IV.4 “Velocity distribution for a single nanofluid”

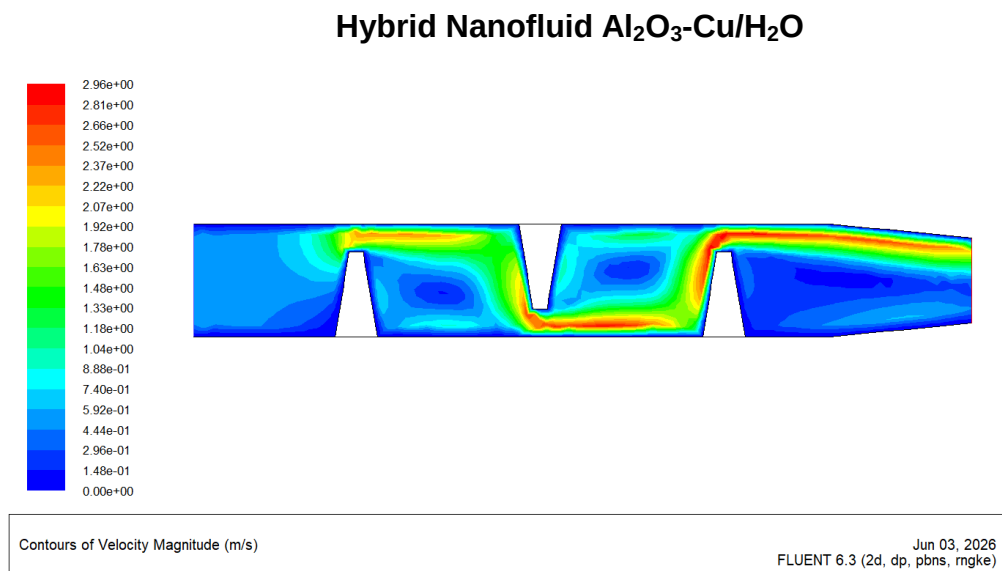


Figure IV.5 “Velocity distribution for a hybrid nanofluid”

CHAPTER IV: Results and discussion

The Zones develop behind the obstacles indicating the presence of recirculation zones. The velocity distribution is relatively homogeneous in the upstream part of the channel. For the analysis of the hybrid nanofluid, The maximum velocity remains practically identical ($\approx 2.96 \text{ m/s}$). The low-speed regions behind the obstacles are slightly reduced. The velocity distribution is uniform in the downstream part of the channel. The hybrid nanofluid seems to reduce dead zones behind obstacles and promote better flow redistribution.

The figures present the velocity distribution for the single nanofluid $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ and the hybrid nanofluid $\text{Al}_2\text{O}_3\text{--Cu}/\text{H}_2\text{O}$ along different lines in the flow domain.

IV.4.1 Single nanofluid ($\text{Al}_2\text{O}_3/\text{H}_2\text{O}$):

The velocity generally varies between **0 and 2.7 m/s**.

The majority of the points are between **0.4 and 0.9 m/s**, indicating a relatively stable flow. Velocity peaks appear at certain positions, indicating a local acceleration of the fluid. The velocity profile remains generally uniform across the entire domain.

IV.4.2 Hybrid nanofluid ($\text{Al}_2\text{O}_3\text{--Cu}/\text{H}_2\text{O}$):

The maximum velocity also reaches approximately **2.6 to 2.7 m/s**.

Slightly larger velocity fluctuations are observed compared to the single nanofluid. The addition of copper nanoparticles slightly modifies the velocity distribution due to changes in density and viscosity.

Despite these variations, the flow remains stable.

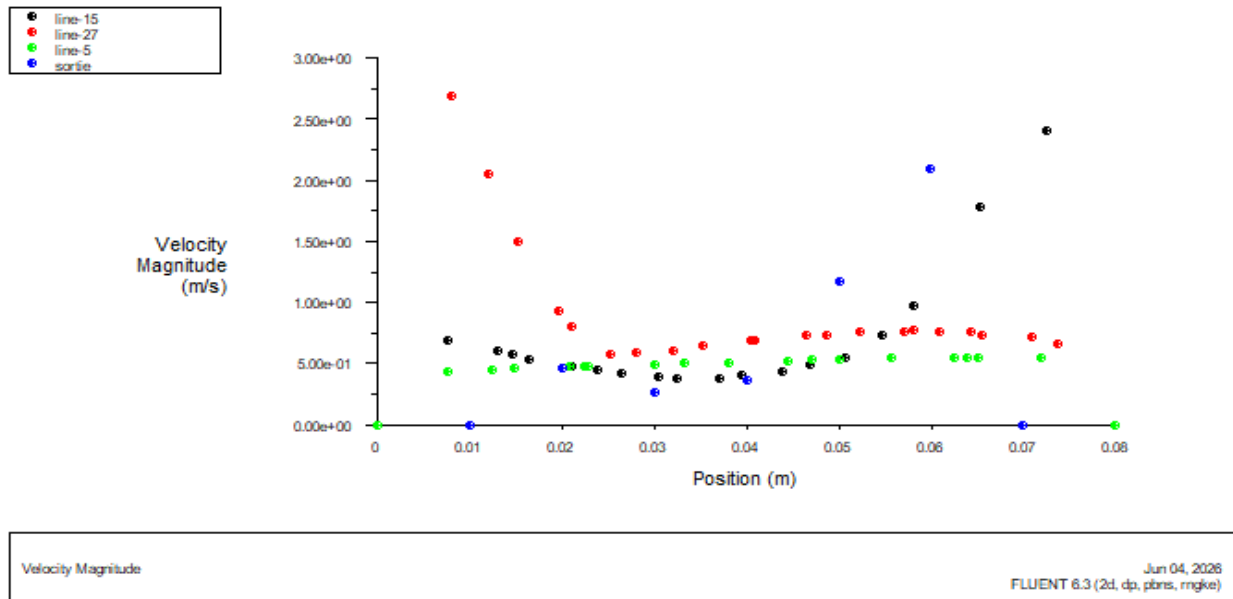
IV.4.3 General comparison:

The two nanofluids exhibit similar maximum velocities.

The hybrid nanofluid shows a slightly more dispersed velocity distribution than the single nanofluid.

The addition of copper potentially improves thermal performance while maintaining satisfactory hydrodynamic behavior.

Single Nanofluid $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$



Hybrid Nanofluid $\text{Al}_2\text{O}_3\text{-Cu}/\text{H}_2\text{O}$

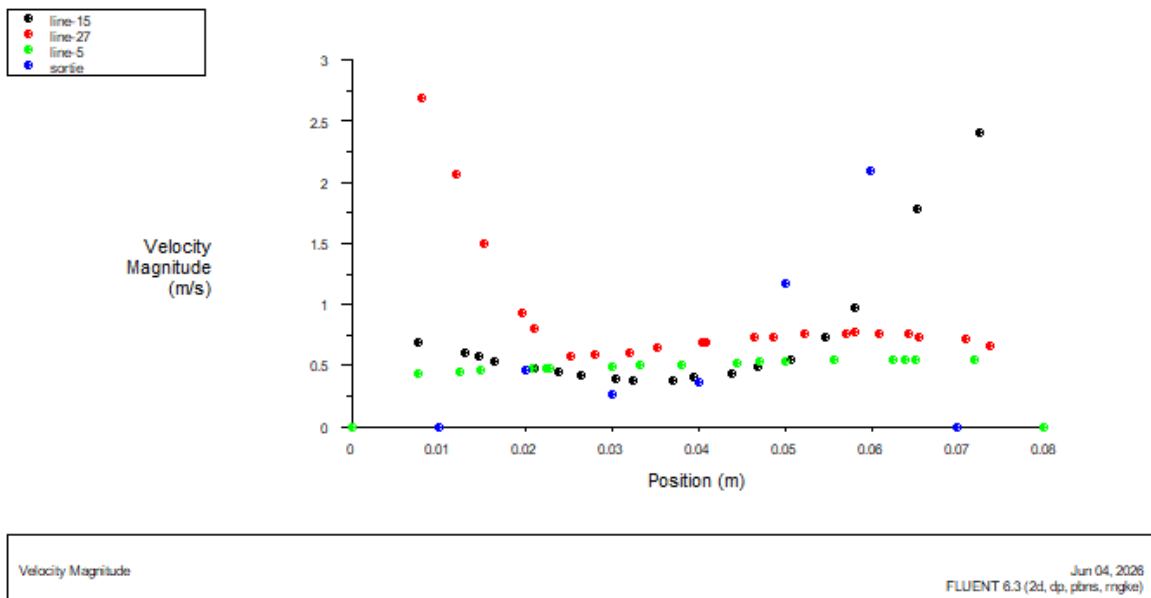


Figure IV.6 “Velocity profiles for the two configurations at different sections at positions $x=50\text{mm}$, $x=150\text{mm}$, $x=270\text{mm}$, and $x=600\text{mm}$ ”.

CHAPTER IV: Results and discussion

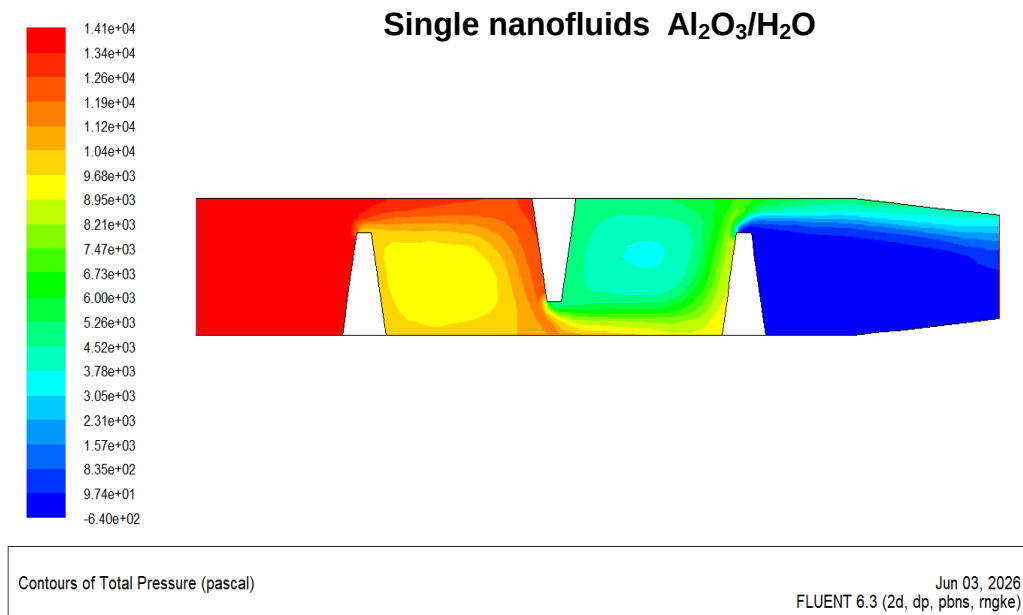
IV.5 Distribution of the total pressure of the total pressure:

The following figures figure and figure show the evolution of the total pressure for the two configurations.

The pressure contours show that the total pressure is maximum at the entrance of the channel and gradually decreases towards the outlet. This decrease is due to the pressure losses caused by the friction between the fluid and the walls, as well as by the presence of obstacles that disrupt the flow.

The total pressure shows negative values. It varies from -6.4×10^2 for the single nanofluid figure to -7.4×10^2 for the hybrid nanofluid figure, which shows that the total pressure is lower at the outlet in the case of the hybrid nanofluid.

However, the analysis of the average total pressure shows a higher value for the hybrid nanofluid compared to the simple nanofluid. This indicates that, despite a more pronounced local drop at the outlet, the overall pressure distribution in the domain remains higher for the hybrid case.



:Figure. IV.7 “ Total pressure for single nanofluid”

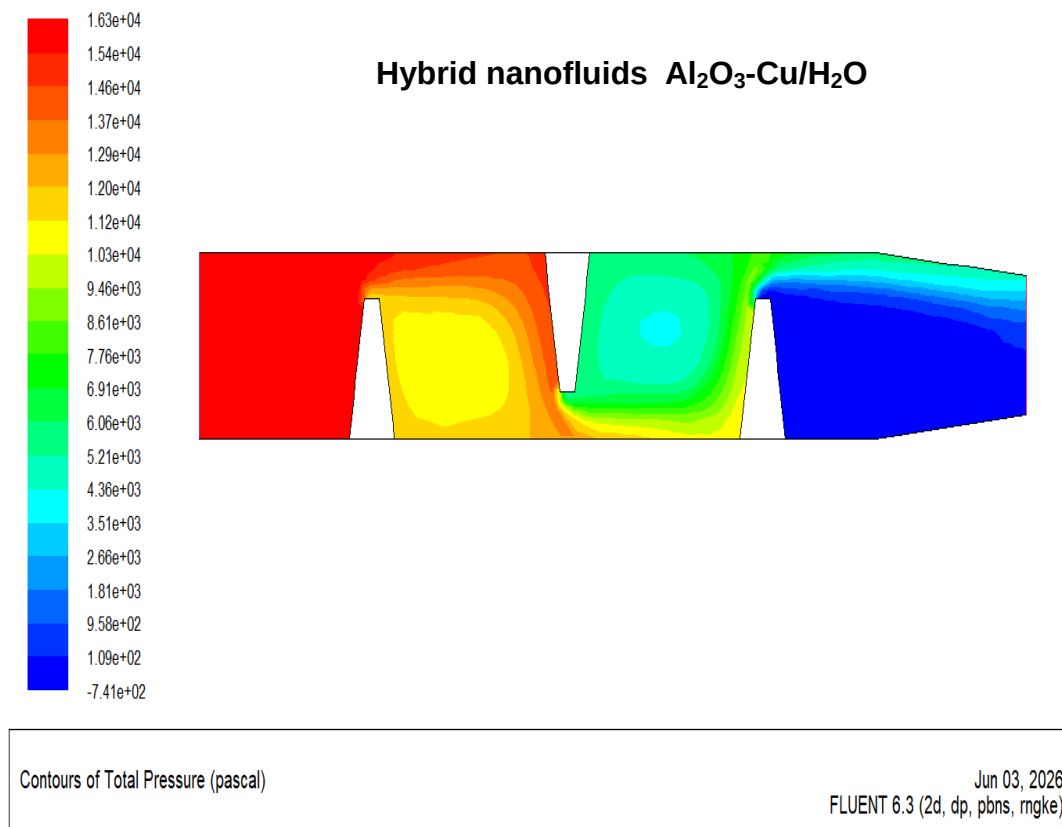


Figure IV.8 "Total pressure for hybrid nanofluid".

IV.6 Temperature Distribution:

The following figures, Figure 9 and Figure 10, present the temperature contour for the two configurations (single nanofluid and hybrid nanofluid). The temperature is important around the obstacles.

The temperature profiles for the two configurations are presented in Figures 11 and 12. For the hybrid nanofluid The peak of the temperature distribution is higher compared to the simple nanofluid.

Its profiles also show that the temperature is highest at the section $x=270$ mm and $y=80$ mm.

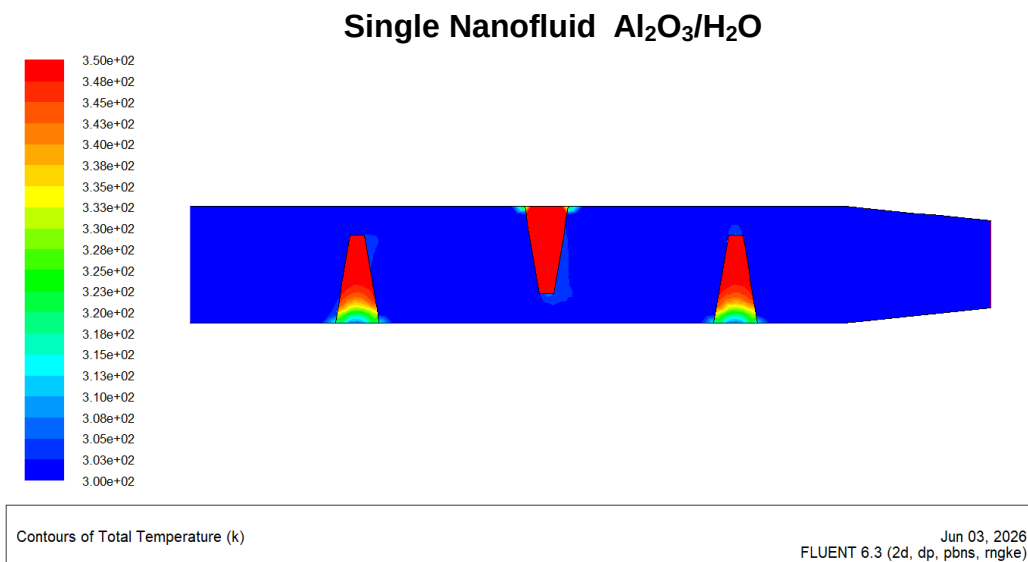


Figure IV.9 “Total Temperature for single nanofluid”

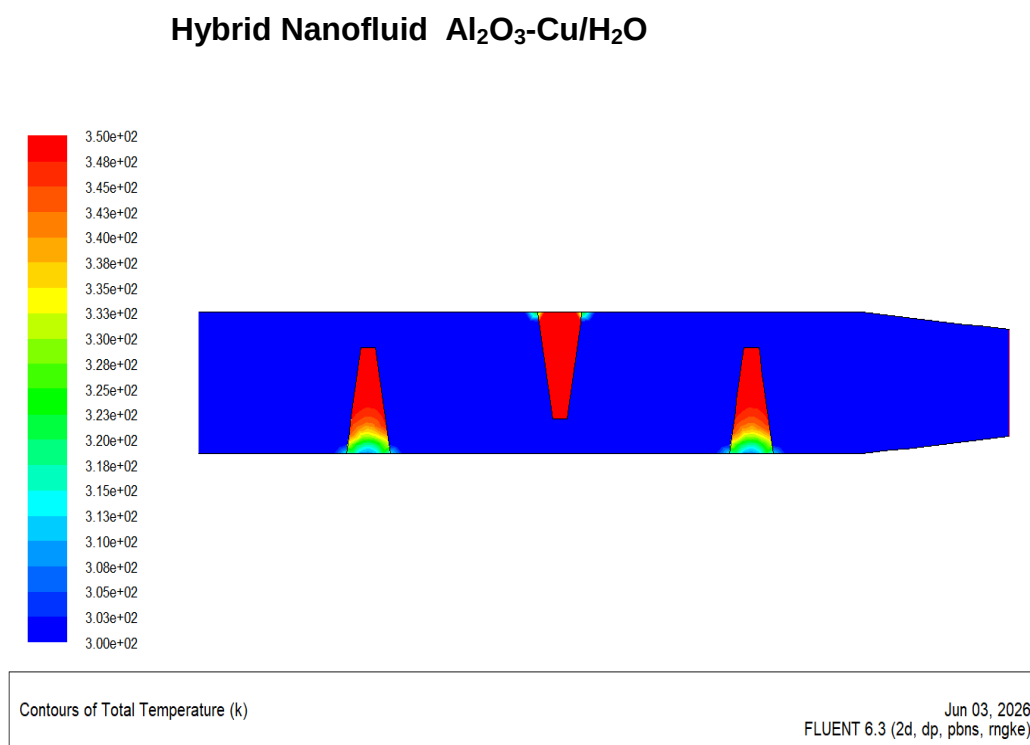
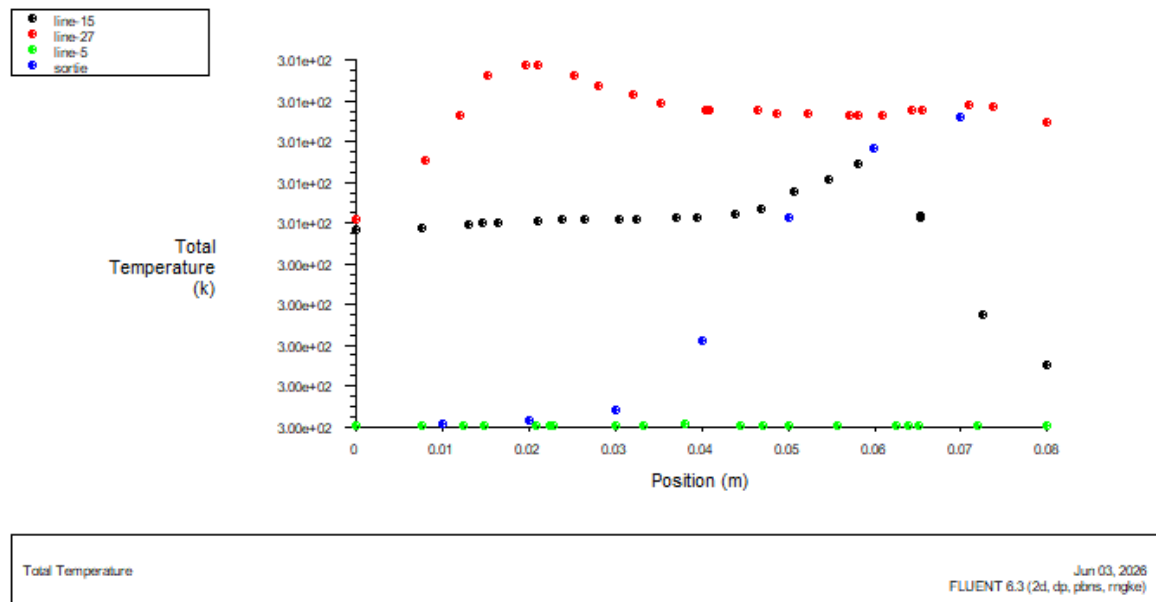


Figure. IV.10 “Total Temperature for hybrid nanofluid”

Single Nanofluid $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$



Hybrid Nanofluid $\text{Al}_2\text{O}_3\text{-Cu}/\text{H}_2\text{O}$

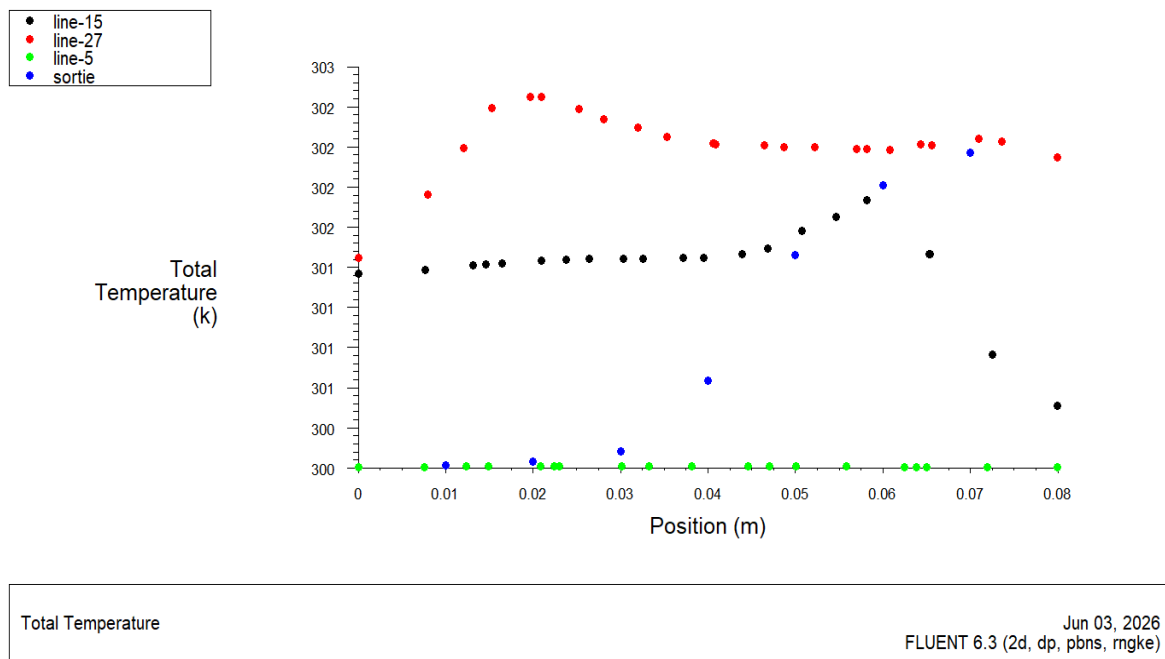


Figure IV.11 “Profil of Temperature for the two configuration at different sections at the position $x=50\text{mm}$, $x=150\text{mm}$, $x=270\text{mm}$ et $x=600\text{mm}$ “

CHAPTER IV: Results and discussion

The following table, Table IV.1, presents the average values of velocity, total pressure, and temperature for the two configurations.

The hybrid nanofluid exhibits a slightly higher velocity (**0.9831 m/s**) than the simple nanofluid (**0.9829 m/s**), indicating a marginal improvement in fluid flow.

The total pressure increases significantly, from **7025.37 Pa** for the simple nanofluid to **8095.11 Pa** for the hybrid nanofluid, suggesting a greater momentum transfer.

The total temperature also increases from **300.42 K** to 301.09, highlighting a better thermal transfer performance of the hybrid nanofluid.

Table IV.1 "Comparison of the results of velocity, total pressure, and temperature".

Nanoparticles	Velocity (m/s)	Total pressure (pa)	Temperature total
Single Nano fluide	0.9829256	7025.37	300.4229
Hybrid nano	0.9830785	8095.113	301.0922

Conclusion:

The results show that the $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ and $\text{Al}_2\text{O}_3\text{--Cu}/\text{H}_2\text{O}$ nanofluids exhibit similar velocity profiles and stable flow. The incorporation of copper nanoparticles slightly influences the velocity distribution, without causing any significant disturbance to the flow. This improvement in flow and heat transfer characteristics makes the hybrid nanofluid particularly interesting for thermal management applications.

Chapter 5 CONCLUSION: AND RECOMMENDATION

General conclusion

The analysis of the numerical results highlights the influence of the hybrid nanofluid on the hydrodynamic and thermal characteristics of the flow in the studied channel. The streamlines show that both configurations exhibit similar flow structures, characterised by the presence of recirculation zones behind the obstacles. However, the hybrid nanofluid promotes a more homogeneous circulation and slightly reduces the recirculation zones, thereby improving the redistribution of the flow.

The study of the velocity contours reveals that both fluids exhibit comparable maximum velocities, on the order of **2.96 m/s**. Nevertheless, the hybrid nanofluid leads to a more uniform velocity distribution and a reduction in the low-velocity zones located downstream of the obstacles.

Regarding the total pressure, the results show a gradual decrease from the inlet to the outlet of the channel due to the pressure losses induced by friction and the presence of obstacles. Although the local total pressure is lower at the outlet in the case of the hybrid nanofluid, the average total pressure is higher (**8095.11 Pa** compared to **7025.37 Pa** for the simple nanofluid), indicating a different overall distribution of energy in the flow.

The thermal analysis shows that the highest temperatures are observed near the obstacles. The hybrid nanofluid exhibits higher temperatures than the simple nanofluid, with an average temperature of **301.09 K** compared to **300.42 K**. This increase highlights an improvement in the thermal performance and heat transfer capacity of the hybrid nanofluid. In summary, the use of the hybrid nanofluid slightly improves the hydrodynamic characteristics of the flow while enhancing the thermal performance of the system. These results show that the hybrid nanofluid constitutes an interesting alternative to the simple nanofluid for applications requiring an improvement in thermal transfer.

Recommendation

The following are recommendations for further research on single and hybrid nanofluids: Water is the base fluid that is most frequently used with various forms of nanoparticles. Nanoparticles are the most prevalent and widely utilized types of nanoparticles used to undertake numerical and experimental investigations. The behavior of novel nanoparticles and base fluids requires further study. The majority of stability enhancement investigations are challenged by the high level of Nanofluid instability. Therefore, technical commercialization is still required for nanofluid stability investigations. The economic and environmental effects of using nanofluids due to insufficient research funding and laboratories. Since FPSCs are still in the early stages of development, many researchers are thinking about the techno-economic and environmental studies required to evaluate their viability in flat plate solar collectors.

REFERENCE

1. Beckman, W.A. , Duffie, J.A., and McGowan, J. (1985): Solar Engineering of Thermal Processes, American Journal of Physics. Doi:10.1119/1.14178
2. Mussard, M. (2017): Solar energy under cold climatic conditions: A review, Renewable and Sustainable Energy Reviews, 74 (December 2016), pp. 733–745. Doi:10.1016/j.rser.2017.03.009
3. review, Renewable and Sustainable Energy Reviews, 82(October 2017), pp. 3179–3190. Doi: 10.1016/j.rser.2017.10.025.
4. Hussein, A.K. (2016): Applications of nanotechnology to improve the performance of solar collectors – Recent advances and overview, Renewable and Sustainable Energy Reviews, 62, pp. 767–792. Doi:10.1016/j.rser.2016.04.050
5. 67.S. U. S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, in developments and applications of non-Newtonian flows, D. A. Siginer, and H. P. Wang, eds., ASME, FED- 231/MD- 66, 99-105, 1995
6. S. U. S. Choi, Nanofluids: From vision to reality through research. J. Heat Transf. 131(3), 033106, 2009
7. Amirtham, V.A. and Devendiran, D.K. (2016): A review on preparation, characterization, properties and applications of nanofluids, Renewable and Sustainable Energy Reviews, 60, pp. 21–40. doi:10.1016/j.rser.2016.01.055
8. Ali, H.M. and Babar, H. (2019): Towards hybrid nanofluids: Preparation, thermophysical properties, applications, and challenges, Journal of Molecular Liquids, 281, pp. 598–633. doi:10.1016/j.molliq.2019.02.102
9. Subudhi, S and Raj, P. (2018): A review of studies using nanofluids in flat-plate and direct absorption solar collectors, Renewable and Sustainable Energy Reviews, 84 (September 2016), pp. 54–74. doi:10.1016/j.rser.2017.10.012
10. Kalogirou, S. A., 2004. Solar Energy Engineering: Processes and Systems. Academic Press.
11. Gouri, D., Garg, H. P, & Bandyopadhyay, B. (1983). The temperature dependence of the overall heatloss coefficient for flat plate collectors. Energy, 8(6), 451-459.
12. S A Klein, (1975). Calculations of flat-plate collector loss coefficient. Solar Energy Journal, 17, 79-81.
13. Mullick, S. C. and Akhtar, A. (2007). Computations of glass-cover temperatures and top heat loss coefficient of flat-plate solar collectors with double glazing. Energy Journal, 32, 1067-1074.
14. Norton, B and Ekechukwu, O. V. (1999). Review of solar energy drying systems I: an overview of drying principles and theory. Energy conservation and Management, 40, 593-613.

15. Ho, C. D., Yeh, H. M., Cheng, T. W., Chen, T. C., & Wang, R. C. (2009). The influence of recycle on the performance of baffled double pass plate solar air heater with internal fins attached. *Applied Energy*, 86, 1470-1478.
16. Bilgili, E. , Alta, D., Erketin, C., & Yalozid, O. (2010). Experimental investigation of three different solar air heaters: energy and exergy analyses. *Applied Energy*, 87, 2953-2973.
17. Papaioannou, J and Francey, J. L. A.,. (1985). Wind-related heat losses of a flat-plate collector. *Solar Energy Journal*, 35(1), 15-19.
18. Ebadi, H., Gorjian, S., Calise, F., Shukla, A. and Ingraio, C. (2020)a: A review on recent advancements in performance enhancement techniques for low-temperature solar collectors, *Energy Conversion and Management*, 222 (August), p. 113246. doi:10.1016/j.enconman.2020.113246
19. Azmi, W.H., Jamar, A., Majid, Z.A.A., Norhafana, M. and Razak, A.A. (2016): A review of water heating system for solar energy applications, *International Communications in Heat and Mass Transfer*, 76, pp. 178–187. doi:10.1016/j.icheatmasstransfer.2016.05.028
20. M S Hossain, et al. (2011): Review on solar water heater collector and thermal energy performance of circulating pipe, *Renewable and Sustainable Energy Reviews*, 15(8), pp. 3801–3812. doi:10.1016/j.rser.2011.06.008.
21. Víg, P. , Ajeena, Ahmed M. and Farkas, I.(2024): Characterization, rheological behaviour, and dynamic viscosity of ZrO₂-SiC(50–50)/DW hybrid nanofluid under different temperatures and solid volume fractions: An experimental study and proposing a new correlation, *Powder Technology*, 431(October 2023), p. 119069. Doi:10.1016/j.powtec.2023.119069.
22. Hotel, H. C., & Woertz, B. (1942). Performance of flat-plate solar heat collectors. *Trans ASME*, 64, 91.
23. D. Wen and Y. Ding, Effect of particle migration on heat transfer in suspensions of nanoparticles flowing through minichannels. *Microfluid Nanofluid.* 1, 183-189, 2005.
24. A K Jain, and Jain, S., 2012. *Solar Thermal Energy Systems: Design and Performance Analysis*. New Delhi: PHI Learning.
25. S. U. S. Choi , Y. Wenhua , S. K. Das , and T. Pradeep, *Nonofluids: science and technology*, John Wiley and Sons, 2007.
26. S. U. S. Choi, S. Li , W. Yu , J. A. Eastman, and L. J. Thomson, Anomalous Increased effective thermal conductivities of ethylene glycol based nanofluids containing copper nanoparticles. *Appl. Phys. Lett.* 78, 718-720, 2001.
27. Brunetti, I. Borgia, A. Sgamellotti, A. , S. Padovani, C. Sada, P. Mazzoldi, B. Giulivi, F. D'Acapito and G. Battaglin, Copper in glazes of renaissance luster

- pottery: nanoparticles, ions, and local environment. J. Appl. Phys. 93(12), 10058-10063, 2003.
28. Víg, P. , Ajeena, A.M. and Farkas, I.(2023), A comparative experimental investigation of dynamic viscosity of ZrO₂/DW and SiC/DW nanofluids: Characterization, rheological behavior, and development of new correlation, Heliyon, 9(10) p. E21113. Doi:10.1016/j.heliyon.2023.e21113.
 29. J. Buongiorno, Convective transport in nanofluids, J. Heat Transf., 128, 240-250, 2006.
 30. murty, b.s. wagener, m., and guenther, b. (1997): preparation of metal nano suspensions by high-pressure dc-sputtering on running liquids, materials research society symposium – proceedings, 457, pp. 149–154. doi:10.1557/proc-457-149.
 31. Ali, N., Teixeira, J.A. Almurtaji, Sand Addali, A. (2020): On the role of nanofluids in thermal-hydraulic performance of heat exchangers-a review, Nanomaterials, 10(4). doi:10.3390/nano10040734
 32. Gupta, M. and Arora, N. (2021): Thermo-hydraulic performance of nanofluids in enhanced tubes - a review, Heat and Mass Transfer/Waerme- und Stoffuebertragung, 57(3), pp. 377– 404. doi:10.1007/s00231-020-02958-y
 33. Kabelac, S. and Eggers, J.R. (2016): Nanofluids revisited, Applied Thermal Engineering, 106, pp. 1114–1126. doi:10.1016/j.applthermaleng.2016.06.100.
 34. N. Putra, S. K. Das, P. Thiesen and W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluids. J. Heat Transf., 125(4), 567-574, 2003.
 35. Hamidi, A.A Amrollahi, A.,. and Rashidi, A.M. (2008): The effects of temperature, volume fraction and vibration time on the thermo-physical properties of a carbon nanotube suspension (carbon nanofluid), Nanotechnology, 19(31). doi:10.1088/09574484/19/31/315701.
 36. Rahman, M.M. Uddin, M.J and Alam, S. (2016) Fundamentals of Nanofluids : Evolution, Applications and New Theory, International Journal of Biomathematics and Systems Biology, 2(1), pp. 1–31.
 37. Erickson, P., Shukla, R., Sumathy, K., and Gong, J. (2013): Recent advances in the solar water heating systems: A review, Renewable and Sustainable Energy Reviews, 19, pp. 173–190. doi:10.1016/j.rser.2012.10.048
 38. Sachdeva, A. , Choudhary, S., and Kumar, P. (2020): Investigation of the stability of MgO nanofluid and its effect on the thermal performance of flat plate solar collector, Renewable Energy, 147, pp. 1801–1814. doi:10.1016/j.renene.2019.09.126.
 39. Li, C.H. and Peterson, G.P. (2007): The effect of particle size on the effective thermal conductivity of Al₂O₃-water nanofluids, Journal of Applied Physics, 101(4). doi:10.1063/1.2436472

40. Noroozi, M., Radiman, S., & Zakaria, A. (2014). Influence of Sonication on the Stability and Thermal Properties of Al₂O₃ Nanofluids. *Journal of Nanomaterials*, 2014, 1–10.
41. Hassan, Y. M., Noordin, N. H., Guan, B. H., & Chuan, L. K. (2025). Enhancing Zinc Oxide Nanofluid Stability: Technical Insight on Surfactant Selection. *Journal of Surfactants and Detergents*, 29(1), 59
42. Saidur, R., Leong, K. Y., & Mohammed, H. A. (2011). A review on applications and challenges of nanofluids. *Renewable and Sustainable Energy Reviews*, 15(3), 1646-1668.
43. N Akram, et al. (2019): An experimental investigation on the performance of a flat-plate solar collector using eco-friendly treated graphene nanoplatelets–water nanofluids, *Journal of Thermal Analysis and Calorimetry*, 138(1), pp. 609–621. doi:10.1007/s10973-01908153-4
44. Kim, J , Kim, H. and Cho, H. (2017): Experimental study on performance improvement of U-tube solar collector depending on nanoparticle size and concentration of Al₂O₃ nanofluid, *Energy*, 118, pp. 1304–1312. doi:10.1016/j.energy.2016.11.009
45. Misganaw, A.H., Singh, M.K., Sundar, L.S., Pereira, A.M.B. and Sousa, A.C.M. (2020): Efficiency, energy and economic analysis of twisted tape inserts in a thermosyphon solar flat plate collector with Cu nanofluids, *Renewable Energy Focus*, 35(December), pp. 10–31. doi:10.1016/j.ref.2020.06.004
46. Samira Gharekhani , Mohammad Reza Safaei, A.J., Ali Kianifar, , Akeel Shebeeb Kherbeet, Marjan Goodarzi and Mahidzal Dahari, *Mathematical Modeling for Nanofluids Simulation: A Review of the Latest Works*. 2016.
47. Kianifar, A., Mahian, O., Kalogirou, S. A., Pop, I., & Wongwises, S. (2013). A review of the applications of nanofluids in solar energy. *International Journal of Heat and Mass Transfer*, 57(2), 582–594. <https://doi.org/10.1016/j.ijheatmasstransfer.2012.10.037>
48. M.M Tawfik , (2017): Experimental studies of nanofluid thermal conductivity enhancement and applications: A review, *Renewable and Sustainable Energy Reviews*, 75 (January 2015), pp. 1239–1253. doi:10.1016/j.rser.2016.11.111
49. Mohammed Hemmat Esfe, M. et al. (2015): Modeling of thermal conductivity of ZnO-EG using experimental data and ANN methods, *International Communications in Heat and Mass Transfer*, 63, pp. 35–40. doi:10.1016/j.icheatmasstransfer.2015.01.001
50. Andre Bakker. Lecture 7 - Meshing. *Applied Computational Fluid Dynamics 2002*; Available from: <http://www.bakker.org/dartmouth06/engs150/07-mesh.pdf>.
51. M. Lightstone, K. Khanafer, K. Vafai, Buoyancy-driven heat transfer enhancement in a two dimensional enclosure utilizing nanofluids, *Int. J. Heat Mass Transf.* 46 (2003) 3639–3653. doi:10.1016/S0017-9310(03)00156-X.

52. M. Alim & Nasrin, R. Finite Element Simulation of Forced Convection in a Flat Plate Solar Collector: Influence of Nanofluid with Double Nanoparticles. *Journal of Applied Fluid Mechanics*, 2014. 7(3).