THESIS REPORT

Specialty: ENERGY ENGINEERING

By:

Raghad ADNAN ALAZAWI

Born on : 12/09/1990 in Baghdad, IRAQ

A parametric study of heat transfer enhancement in solar receiver using internal fins

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Pr. Hacen Dhahri	**Chair**
Pr. Daoued Mihoubi	**Examiner**
Pr. Saloua Marzouk Khairallah	**Examiner**
Pr. Mohamed Naceur Borjini	**Member**
Mc. Ramla Gheith	**Supervisor**
Dr. Ahlem Houcine	**Invited Member**

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Abstract:

This study details the thermal performance of parabolic collectors (PTCs) when using an absorber tube with longitudinal fins inside. The basic idea of the study is to understand how to improve heat transfer inside a 12-fin tube, adopting Syltherm-800 as the thermal fluid. To achieve this, advanced numerical models based on finite volume simulation (CFD) were used to analyze the fluid and heat behavior inside the tube under different operating conditions.

A wide range of engineering and operational variables were tested, such as changing the fin thickness between 1–6 mm and its length between 2–20 mm, in addition to changing the volumetric flow rate from 50 to 250 liters/minute and inlet temperature 300-600 k. This diversity aims to understand the relationship between the shapes of the fins, the way the fluid flows, and the amount of heat the system can absorb. The results were studied in terms of thermal flux, pressure drop inside the tube, and the overall thermal efficiency of the solar collector.

For the results not to remain limited to the theoretical aspect only, the research used the Experiment Design Methodology (DoE) to identify the variables that most influence performance. This method helped reveal the true effect of each factor, whether it was fin thickness, length, or flow rate. The results showed that the best thermal performance is recorded at a thickness of 6 mm and a length of 20 mm, with a flow rate of 50 liters/minute, as this group provides the highest thermal efficiency with an acceptable pressure drop.

Dedications

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(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ) يونس (الآية 10)

فـالله الفضـل ولـه الحمـد مـا كنـت لاخـتم مسيرتي هـذه لـولا فضـل الله فالحمـد لله عنـد البـدء وعنـد الخـتـام الحمـد لله مـا انتهـى درب ولا خـتم جهـد ولا تـم سـعي الا بفضـلـه الحمـد لله علـى التمـام والكمال وعلى لذه الانجاز

اهدي تخرجي الـى مـن حبهم يعلـو فـوق كـل حـب الـى مـن انـاروا لـي طريـق العلم وسـاندوني ووفروا لي سبل السعادة والنجاح

الـى مـن كـان لـي عمـودي الفقري الـذي سـاندي بكـل حـب فـي ضـعفي الـذي اخـرج اجمـل مـا فـي داخلـي للوصـول الـى طموحـاتي الـى مـن انتظـر هـذه اللحظـات ليفخـر بـي الـى العزيـز الـذي حملت اسمه فخـرا يـردد اسمي عاليا في عنان السماء حامـلا شرف لقلبه وبكل اعتزاز انا لهذا الرجـل ابنـه الـى مـن كللـه الله بالهيبـة والوقـار يا مـن افتقدتـه ولا زال قلبـي يـرتعش لـذكره الـى مـن فـارقني بجسده وروحـه مـا زالـت ترفرف فـي سـماء حيـاتي .... الـى تلـك الـروح الطـاهرة والـدي العزيز المحامي

(عدنان حميد العزاوي)

الـى نـور عينـي وضـوء دربـي ومهجـة حيـاتي الـى التـي وهبتنـي الحيـاة والامـل واحتضـنني قلبهـا قبل يدها وسهلت لي الشدائد بدعائها الى المضحية من أجلي ..... **امي الحبيبة**

الـى ضـلعي الثـابـت وامـان ايـامي ملهـم نجـاحي الـى مـن سـاندني ووقـف بجـانبي وقـدم لـي الـدعم لمواصلة طريقي الى من وهبني الحياة والحب الى خيرة ايامي وصفوتها ..... **زوجي فهد**

الـى مـن شـددت بهـم ازري واشـركتهم فـي امـري واسـتقمت بـدعمهم واهتـديت بنصـحهم حتى اكتمل الحلم لاصحاب المواقف النبيلة والارواح السامية اخواتي ..... **(رشا .. رنا .. رؤى)**

الـى مـن تسـعد العـين بـرؤيتهم ويطـرب القلـب بنجـواهم وتهـدأ نفسـي بلقيـاهم ويبتسـم الثغـر بمحياهم بناتي .... **(ميار .. درة)**

الى القلوب النقية التي تمنح حياتي فرحاً الى من كانوا الدافع والامل لي صغاري ....

(يسر .. هيا .. حسن .. ذو الفقار .. عبدالله)

الـى اخـواني الـذين لـم تلـدهم امـي مـن كـانوا لـي عونـا وسـندا لاكمـل مسـيرتي .... **(عمار..محمد..بشير)**

الـى رفقـاء دربـي الـذين امـدوني بـالقوة دائمـا وكـانوا موضـع الاتكـاء فـي كـل عثـراتي مـن كـانوا لي سندا وسهلوا عليه طريقي .... صديقاتي واصدقائي

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Acknowledgment

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Nomenclature

A_a	Outer surface area (m)
A_c	Collector aperture (m)
C_p	Specific heat capacity of the working fluid (J/kg.K)
D_{ia}	Absorber inner diameter (m)
D_{ig}	Glass inner diameter (m)
D_{oa}	Absorber outer diameter (m)
D_{og}	Glass outer diameter (m)
f	Friction coefficient (-)
f_c	Focal length (m)
h	Heat transfer coefficient(W/m².k)
I	Solar radiation (W/m²)
k	Thermal conductivity (W/m.K)
L	Parabola length (m)
L_{fin}	Length of fin (m)
$\dot{m}$	Mass flow rate (kg/s)
Q_u	Useful heat (W)
Re	Reynolds number (-)
S_{fin}	Spacing between fins (m)
T	Temperature (K)
T_{in}	Inlet temperature (K)
T_{out}	Outlet temperature (K)
u	HTF velocity (m/s²)
VFR	Volume Flow Rate (L/min)
W_c	Parabola width (m)
W_{fin}	Thickness of fin (m)
α	Absorptivity (-)
ΔP	Pressure drop (Pa)
η	efficiency (-)
λ_{fin}	Fin pitch ratio (-)

μ	Dynamic viscosity of the working fluid (kg/m.s)
ρ_f	Density (kg/m^3)
ρ_m	Reflectivity (-)
τ_g	Transmissivity (-)
N_u	Nusselt number
p_r	Prandtl number
θ_{rim}	Rim angle (°)

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GENERAL INTRODUCTION

General introduction

The world is seeing a major change in the way it deals with energy dependence on fossil fuels is no longer the same as before, due to their environmental problems, high cost and instability. As factories expand and the need for clean and stable thermal energy increases, it has become necessary to turn to dependable sources for a long time. Here, solar thermal energy appears as an important solution, because it provides high heat that can be used directly in industry or in electricity production.

Among the various solar technologies, parabolic collectors (PTCs) are among the most common systems, because they are competent of producing high heat, can be easily connected to traditional systems, and most importantly, allow heat to be stored for long periods. However, the performance of these collectors depends largely on the receiver tube through which the heat-conducting fluid passes. It is this part that essentially determines the amount of energy that can be obtained.

The receiver tube is the element through which thermal energy is transferred to the liquid, and any defect in its performance is directly reflected in the efficiency of the entire system. The problem facing these pipes is that heat transfer within them depends on several factors, such as the shape of the pipe's inner surface, the nature of the fluid, and its flow rate. Often, even with high solar heat availability, it is not fully exploited due to limited heat transfer within the tube.

For this reason, several attempts have emerged to improve this important part of the system. One common solution was to add internal fins that help increase the heat-conducting surface area, which results in better heat distribution and reduces the static layer that forms near the wall. These fins improve mixing within the liquid and thus increase heat transfer efficiency. But at the same time, increasing the number or size of fins increases the resistance inside the tube, which causes a higher pressure drop and makes the pump consume more energy to push the fluid.

On the other hand, many studies have turned to developing the liquid itself using what are known as nanofluids. They are traditional liquids to which very small nanoparticles are added in order to improve their thermal properties. These particles significantly increase the thermal conductivity of the liquid, making heat transfer faster and more efficient. However, the use of nanofluids requires a delicate balance, as increased particle concentration may cause increased viscosity or lead to fluid stability problems.

As studies progressed, it became clear that improving just one element whether the shape of the tube or the liquid does not give the optimal solution. These elements are interconnected, and a

change in one directly affects the performance of the other. Therefore, it has become necessary to treat internal engineering, the fluid used, and operating conditions as integrated elements that must be studied together and not each one separately. When these factors are studied together, it becomes possible to achieve a design that achieves the highest performance without causing unnecessary operational losses.

To understand this collector interaction between variables, this research relies on numerical simulation (CFD). This method helps us understand how the fluid moves inside the tube, how heat is distributed, and where areas of turbulence or high resistance to flow may appear. They also help evaluate the effect of fins and nanofluids in a detailed way that is difficult to achieve in practical experiments alone.

At the same time, the design of experiments (DoE) methodology is used to organize the study of variables in a scientific way that helps identify the most important influencing factors and know how they interact with each other. This approach provides a strong basis for building a predictive model that can be used to develop more efficient real systems.

By combining internal fins and nanofluids, and analyzing performance using CFD and DoE, this research provides an integrated view aimed at arriving at the best future tube design, so that it provides the highest possible heat transfer efficiency without a high increase in hydraulic losses. This type of development is an essential step to enhance the role of solar thermal energy in the future, especially with the great global trend towards using clean and reliable energy sources that can meet the needs of industry and modern energy.

CHAPTER I:
STATE OF THE ART AND
CONTEXTUALIZATION

Chapter I

State of the Art and Contextualization

1.1 Introduction

In today's world, energy is the fundamental pillar of human civilization, economic development, and the well being of society. It is the indispensable driver of all modern activities, from manufacturing and agricultural production to transportation, digital communications, and home amenities. Countries' progress and technological development are closely linked to their ability to produce energy and ensure security of supply. Therefore, countries with larger and more stable energy resources often achieve higher levels of economic and social development **[1].**

Globally, energy is produced from a wide range of resources that are essentially classified into two main categories: renewable and non-renewable as shown in Figure (1-1). For more than a century, non-renewable sources, primarily fossil fuels such as coal, crude oil and natural gas, have dominated the global energy landscape, meeting the bulk of the world's energy needs. This historical dependence came about due to its high energy density, the well-established infrastructure associated with it, and its economic cost, which was previously considered low and uncompetitive **[1].** However, the widespread burning of these limited resources has had serious and increasing consequences. It leads to the emission of huge amounts of greenhouse gases, most notably carbon dioxide (CO_2), in addition to other harmful pollutants such as sulfur oxides (SOx) and nitrogen oxides (NOx). This has resulted in three major global challenges: accelerating climate change seen in extreme weather events, deteriorating air quality that directly affects human health, and the acidification of natural ecosystems **[2].** Additional concerns also arise, including thermal pollution of water bodies resulting from power plant cooling systems, in addition to long-term environmental and security challenges associated with radioactive waste resulting from nuclear power plants, which in turn is a non-renewable source of energy.
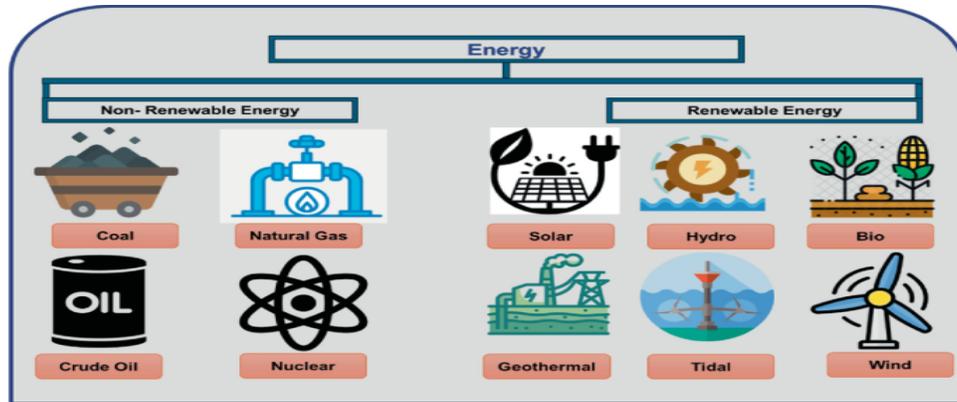
Figure 10-1 Classification of Energy Sources[1]

This emergency environmental reality has prompted the world to seriously move towards renewable energy. These sources depend on natural processes that are constantly renewed, and in most of their forms, they are directly or indirectly due to the sun, as shown in Figure (1-2). They include solar, wind, hydroelectric, biomass, biofuels, geothermal, as well as Ocean Energy. The real power of these resources lies in their ability to offer almost unlimited clean and sustainable energy. Its operation also emits almost no net greenhouse gas emissions, which makes it a key focus in global plans to address climate change under international agreements such as the Paris Agreement, and in building a circular and sustainable economy **[3].**
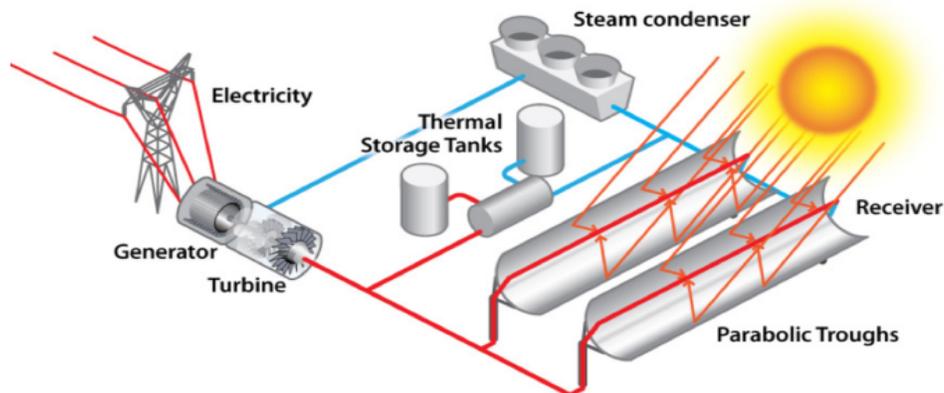
Figure 1-2 Schematic of Parabolic Trough Solar Power System[3]

Even the economic equation has now changed in favor of renewable energy. After fossil fuels had the advantage in terms of cost, over the past ten years, the cost of producing electricity from large-scale solar power plants and wind turbines on land has decreased significantly, to the point that it has become the most competitive option for new electricity generation in most countries of the

World **[3].** This transformation has been made even stronger by stringent climate policies, pledges of sustainability by global companies, and rapid and non-stop technical development.

Within the renewable energy system, solar energy is emerging as the main option due to its high prevalence and enormous ability to meet global demand. They can be used in two main ways: the first are photovoltaic systems that convert sunlight directly into electricity, and the second are solar thermal systems as shown in Figure (1-3). Thermal systems are of particular importance because they help to cope with the problem of energy availability when needed. In this area, concentrated solar energy (CSP) systems are of great importance because they include in their design a thermal energy storage system (TES). This storage allows electricity to be generated even after sunset, which enhances the stability of electrical networks and complements the volatile nature of solar PV and wind energy **[4].**
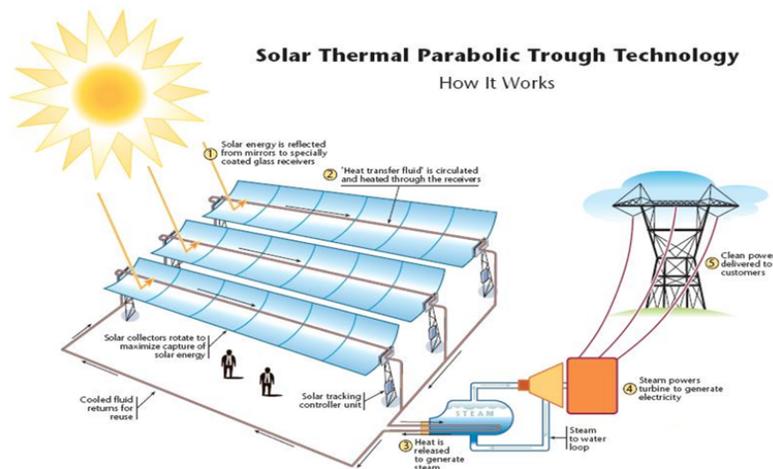
Figure 1-3 Operation Principle of Solar Thermal Parabolic Trough System[4]

Since it is the most advanced and widespread technology in the field of concentrated solar energy, parabola collectors (PTC) occupy a pivotal position in this segment. Such systems are based on the principle of geometric focusing, in which a long mirror with a parabola shape collects direct sunlight and focuses it on a receiving tube running along the axis, shown in Figure (1-4)

Inside this tube, heat is absorbed by a liquid intended for Energy Transfer most often synthetic oil or molten salt. The resulting heat can be used immediately to power a conventional electric turbine or stored for later use when needed. This flexibility gives PTC systems an important ability to bridge the gap between when solar energy is available and when demand is high, making it an essential element in building a more stable and low carbon electricity grid **[4].**
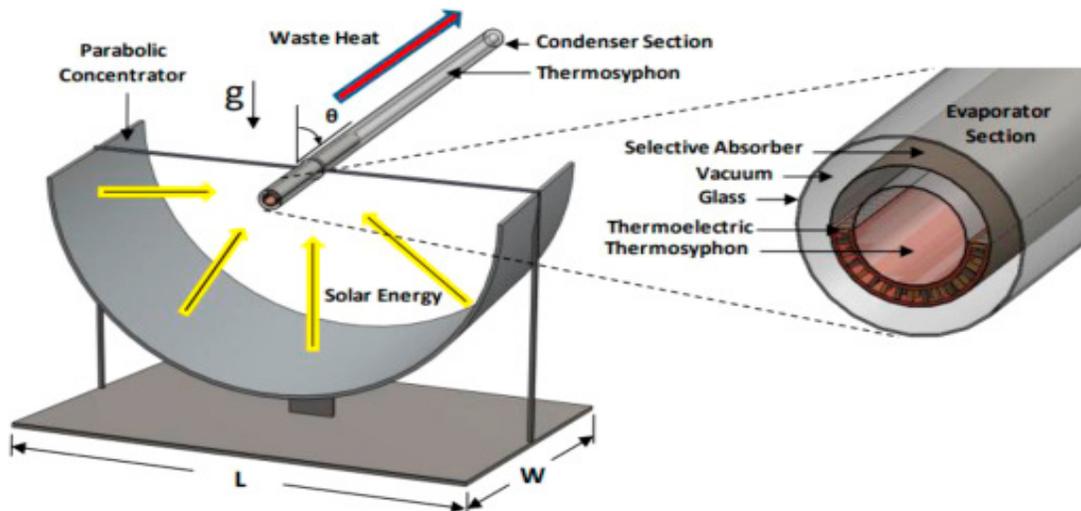
Figure 01-4 Structure and Working Principle of a Parabolic Trough Collector[4]

For this reason, the continuous work on improving the efficiency of Parabola systems and reducing their cost is not just a theoretical research effort, but an essential step that supports the global transition towards clean energy. This development carries a direct impact on energy security, support for economic growth, Environmental Protection. In the framework of raising the thermal performance of Parabola complexes (PTCs), researchers have increasingly focused on modifying the internal shape of the absorption tube. Among the most important of these methods is the use of internal fins to enhance heat transfer. But this improvement comes with a clear challenge: increased hydraulic losses. To deal with this delicate balancing act, the role of experimental design methodology (DOE) is emerging as a necessary tool. They make it possible to study important engineering factors such as fin height, thickness and number along with operating conditions, primarily the Reynolds number. Through a rigorously planned matrix of experiments or simulations, often using the response surface methodology (RSM), a robust model can be built that is able to predict the effect of each factor on its own and the effect of the interaction of various factors on performance indicators, such as the Nusselt number (Nu) and the coefficient of friction (f). The ultimate goal is to achieve the highest possible Thermo-hydraulic performance (η), while minimizing the impact of pumping requirements. This data-driven scientific approach provides an effective and practical way to develop receptor designs in PTC systems, rather than relying on traditional methods based on trial and error [5].

Although this study relies on pure Syltherm-800 as the main heat transfer fluid, one of the most important development paths in improving the performance of Parabola complexes (PTC) is the use of nanofluids, as shown in Figure 1-5. Nanofluids are liquids that are improved by adding nanoparticles-such as metal oxides or various forms of carbon that are suspended inside a base liquid. These liquids take advantage of the properties of nanoparticles to visibly improve their thermal properties. The addition of particles with high thermal conductivity addresses one of the biggest weaknesses of conventional heat transfer fluids: their low thermal conductivity. This improvement is directly reflected in the performance of the system, as it increases the heat transfer coefficient and the number of Nusselt, which enhances the thermal efficiency of the receiver. Several studies indicate that nanofluids can achieve much better thermal performance than conventional liquids, which makes them a key technology for the next generation of high flow solar thermal systems. At the same time, the adoption of Syltherm-800 in this study allows to provide a baseline on which future research can be built **[6].**

Figure 01-5 Nanofluid-Enhanced Heat Transfer in Parabolic Trough Collectors[6]

1.2 Overview of Solar Energy and Renewable Technologies

Solar energy today has become a natural part of our lives because it is simple, available, and does not require complex equipment. The idea is very straightforward: we harness sunlight and turn it into energy to power homes and factories. They are used in two main ways; the first is through photovoltaic (PV) panels that produce electricity directly from light, and the second is through concentrated solar systems (CSP) that collect the sun's heat and convert it into steam that drives turbines **[7].** In recent years, developments have accelerated significantly; panels have become cheaper and more efficient, which has encouraged countries, institutions, and people to install them. A strong example of development is that the efficiency of multi-junction cells has reached more than 47% in the laboratory, a figure that reflects the speed of progress in this sector **[8].**

Globally, solar installed capacity increased by about 29% in 2024, making it one of the fastest growing renewable energy sources, especially after falling prices and expanding government support **[9].**

However, there are still problems that need to be solved. Solar energy production varies depending on time and weather, and this creates pressure on the electricity grid if efficient storage solutions are available. For this reason, we observe extensive investments in batteries and smart grids to adjust oscillation and improve stability **[10].** Combining solar energy with other sources such as wind and biomass makes the system stronger and more stable, because it relies on only one source **[11].** Solar energy is no longer just rooftop panels but has become a key component of an integrated energy system that helps the world gradually transform into a cleaner, more sustainable future.

1.3 Solar Thermal Technologies: Principles and Development

Although photovoltaic (PV) technologies usually receive the most attention when talking about solar energy, solar thermal technologies are no less important and even provide a widely used path for converting solar radiation into thermal energy. Instead of converting light directly into electricity, solar thermal systems collect the sun's energy in the form of heat that can be exploited in a wide range of applications, from heating water in homes to powering large power plants or supporting industrial processes. This section reviews the basic principles of this technology, the diversity of its systems, and the most prominent developments that have shaped this fast-growing and constantly changing field **[12].**

1.3.1 Fundamental Principles and Technological Spectrum

All solar thermal technologies are based on a simple but basic idea: converting sunlight into heat and it happens according to the principles of thermodynamics. Collector roofs-usually designed in a dark color, with high absorbency and low emissivity capture solar radiation and raise their temperature. Then this heat is transferred to the working fluid, be it water, air, thermal oil or even molten salt. This heat can be used directly or stored for later utilization **[13].**

Solar thermal technologies are usually classified according to the range of temperatures they produce, because it is this factor that determines the type of applications in which they can be used.

- Low-temperature systems (<100°C): This category includes systems that do not depend on the concentration of sunlight. The most widespread examples are flat collectors and vacuum tube collectors, widely used in water heating of houses, swimming pool heating, light heating

applications of buildings. Such systems are characterized by simplicity, reliability and low cost, which is why they are so widespread around the world.

- Medium to high temperature systems (100°C – 400°C): In this range light focusing techniques are used to reach higher temperatures. Parabolic trough collectors (PTCs) are one of the most mature and widespread technologies in concentrated solar power (CSP) plants. They are also becoming increasingly important in industrial heat applications, such as providing steam to manufacturing processes, the food industry, and chemical processes sectors that are a key focus of industrial emissions reduction efforts.

- High temperature systems (>400°C): Such systems need very precise focusing of light. One of the most striking examples is the solar tower, where large mirrors (heliostats) direct sunlight to a receiver located on top of a tower, and temperatures reach more than 560°C. Parabolic dish systems, on the other hand, concentrate sunlight at one point and achieve higher temperatures, often working with a Stirling engine to produce electricity directly and with modular capacities that can be increased as needed **[14].**

1.4 Classification of Solar Collectors

Solar collectors are devices that capture sunlight and convert it into heat that can be used by heating a special fluid. Depending on whether the system uses a visual focus and depending on the required temperature level and nature of use, complexes are usually divided into two types: non-concentrated and concentrated collectors. Each type features a different design form and offers performance that suits the needs of specific applications **[15].**

1.4.1 Non-Concentrating Collectors

These collectors receive direct and diffuse sunlight together without using mirrors or lenses to focus it, as shown in Figure (1-7). Because it does not depend on any concentration process, the area of the surface that absorbs light is the same as that of the surface that is exposed to sunlight.

<u>1.4.1.1 Flat Plate Collectors (FPCs):</u>

These collectors are among the most used types of water heating for homes and in building-related applications. It consists of a flat absorption plate usually coated with a selective surface inside an insulated box and covered with a transparent layer. At low and medium temperatures, which usually reach around 100–150°C, these Collectors operate very efficiently and are an economical and reliable option.

1.4.1.2 Evacuated Tube Collectors (ETCs):

In this type of collector, the absorbent surface is placed inside a vacuum tube or between two concentric tubes, reducing heat losses due to load and conduction as shown in figure (1-6). The presence of a vacuum provides effective thermal insulation and helps improve performance, especially in cold climates or when there is diffuse solar radiation. As a result, higher temperatures can be achieved with lower losses. Recent research indicates continued interest in using this technology in broader home and industrial applications **[16].**

(a)   *(b)*
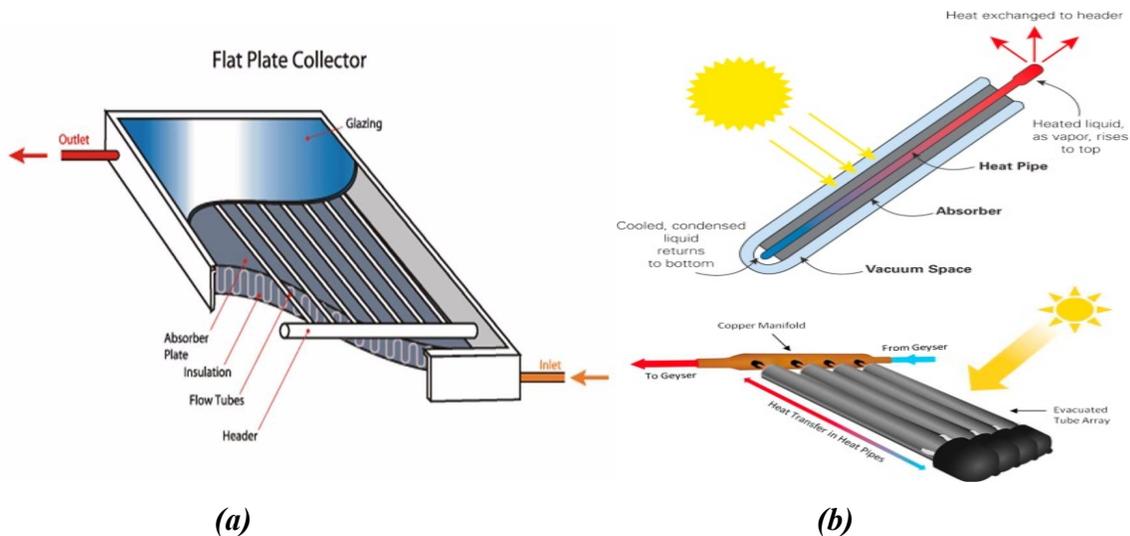
Figure 1-6 Comparison of Non-Concentrating Solar Thermal Collectors: (a) Flat Plate (b) Evacuated Tube Collectors [16]

1.4.2 Concentrating Collectors

Concentrated solar collectors are one of the most important modern technologies in the field of thermal energy, because they depend on collecting direct solar radiation (DNI) and directing it towards a small area with the aim of increasing the amount of heat captured and raising the efficiency of converting it into useful energy **[17].** The rapid development in this field is based on improving the optical design of mirrors, developing sun tracking systems, in addition to integrating thermal storage technologies with molten salts This helped these systems operate for longer periods even when direct sunlight is absent.

These collectors are usually classified into four basic types, which differ from each other in terms of the design method, the temperatures they reach, the level of efficiency, and the cost of implementation and operation of the system.

1.4.2.1 Parabolic Trough Collectors

These collectors operate using long mirrors of an equivalent shape to collect sunlight and point it toward a receiver tube that runs along the focal length as shown in the figure (1-7). It is considered one of the most widely used solar energy technologies, due to its proven performance and ease of operation. It achieves stable thermal efficiency within a range of 400–550 °C, featuring a simple design and a single-axis tracking system, which reduces mechanical complexity and reduces operating and maintenance costs **[18].**
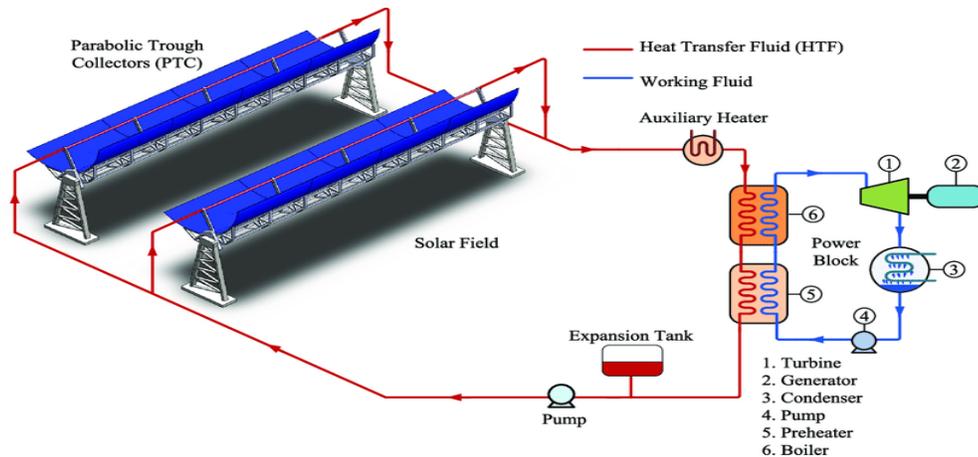
Figure 01-7 Simplified schematics of parabolic trough collector [18]

1.4.2.2 Linear Fresnel Reflectors

Linear Fresnel collectors use rows of flat or semi-flat mirrors to collect sunlight and point it toward a fixed tube at the top as shown in the figure (1-8). The idea here is simpler than parabolic blocks, so it's less expensive to build and maintain. continuous development in mirror arrangement and improved tracking systems have contributed to higher light concentration efficiency, making this type very suitable for industrial applications requiring average temperatures between 150 and 350°C **[17].**
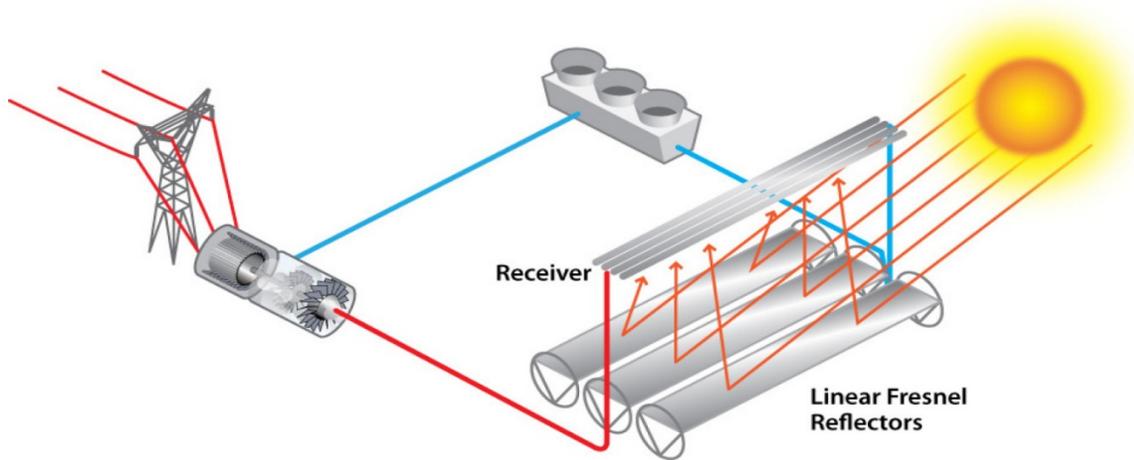
Figure 01-8 Simplified schematics of Linear Fresnel Reflectors [17]

1.4.2.3 Parabolic Dish Collectors

Equivalent plate systems are capable of concentrating sunlight higher than any other CSP technology, and this intense focus allows power to be directed directly to the Stirling engine for high efficiency in electricity production as shown in the figure (1-9). The performance of these systems is very strong, but their main problem lies in their high cost and the need to accurately track the sun in two directions, making their operation more complicated **[19].**
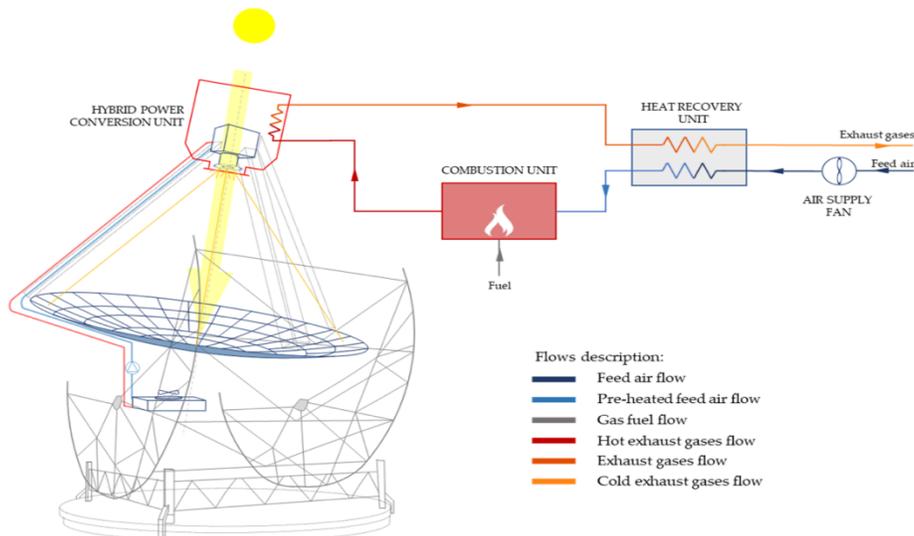
Figure 01-9 Simplified schematics of Parabolic Dish Collectors [19]

1.4.2.4 Solar tower collectors

In the central Future Tower system, thousands of moving mirrors track the sun and reflect its light towards a future located at the top of a tall tower as shown in the figure (1-10). This method generates very high temperatures, up to 600–800 °C, which allows advanced power systems to operate with high efficiency. This species has gained considerable attention in recent years because it can be easily combined with molten salt tanks, giving the plant the ability to produce electricity even after sunset for a long time, where it is almost continuous throughout the day **[16].**
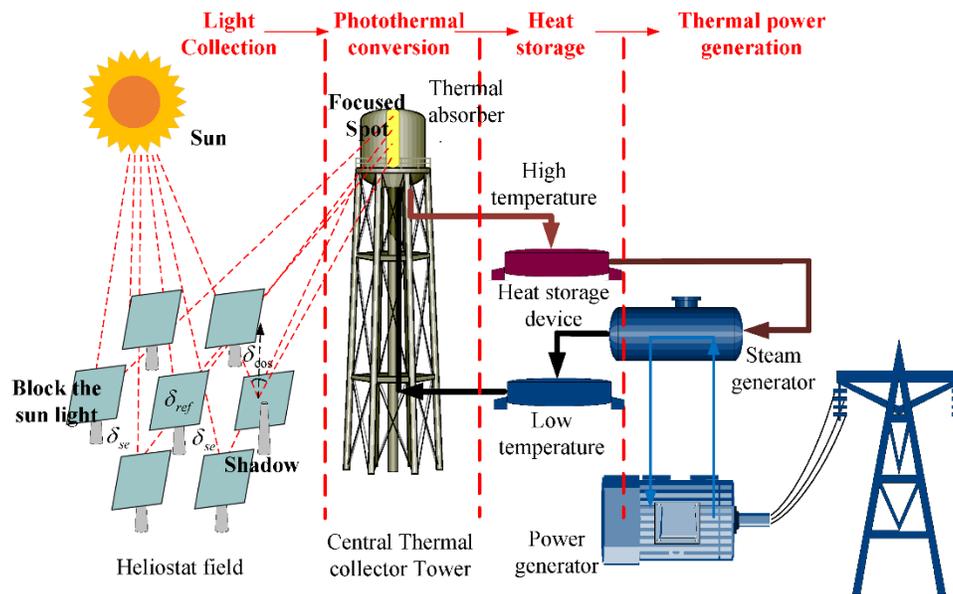
Figure 01-10 Simplified schematics of solar tower collector [16]

When choosing the right type of complex, the decision often depends on what the application actually needs. If the required temperature is average, the equivalent cutting pools are usually most appropriate. In large projects that require high power and stable operation, tower systems offer the best performance. If the goal is to achieve the highest possible efficiency even if the cost is higher, the equivalent dish is the best option. In contrast, the Fresnel complexes remain an economical and simple solution for industrial applications operating in a medium temperature range.

1.5 Parabolic Trough Solar Collectors (PTSC): Concept and Components

1.5.1 Conceptual Foundation and Operating Principle

PTSCs are one of the most mature and reliable concentrated solar energy technologies, because they adopt a simple but effective idea: to use long parabolic mirrors to collect and focus sunlight on a single line. These mirrors rely on a well-known geometric feature of parabolic pieces, their

ability to reflect any parallel rays toward the focal line. To ensure that light remains focused, mirrors move as the sun moves on one axis often north-south.

On this focal line is the receiver tube, known as the heat collection element (HCE), which passes through the heat transfer fluid. With the concentration of radiation, the temperature of the fluid inside the tube rises to a high level, possibly between 300 and 550 °C, thanks to a concentration ratio that is usually 70 to 100 times that of natural radiation. The hot liquid is then transferred to the power production unit to generate high-pressure steam, which powers the Rankine cycle turbines to produce electricity [20].

1.5.2 Critical Components and Technological Advancements

The performance of the solar parabolic collector system, as well as its operational life and economic feasibility, depends on the quality of its main components. In recent years, researchers have directed their efforts towards small improvements in every part of the system, but they are significant and clearly reflective of the efficiency of the system.

1.5.2.1 Parabolic Reflectors (Mirrors)

Mirrors in parabolic cutting complexes collect sunlight and focus it on the receiving tube. They are usually made of low-iron glass and coated with a silver layer on the back with a protective layer, to ensure high reflectivity exceeding 93.5% and good environmental tolerance. In recent years, several research trends have emerged aimed at developing these reflectors, including:

- Advanced Reflective Films:

Lightweight polymer films are being produced as an alternative to traditional glass mirrors. These films are easier to install and less prone to breakage and may help reduce structure costs. But researchers are still studying how well they can maintain their reflexivity and durability for long periods [7]. Anti-dirt coatings:

Waterproof and anti-static ultra-expulsion coatings are being developed to reduce the adhesion of dust and dirt to the surface of mirrors. This technique reduces the need for frequent cleaning and reduces water consumption, and helps maintain the effectiveness of the optical reflector for as long as possible [8]

1.5.2.2 Heat Collection Element (HCE)

The heat collection element (HCE) is the part about which the whole system is working, responsible for receiving and transmitting heat. This element is made of a metal tube usually made

of stainless steel and is placed inside a glass casing discharged from the air to reduce heat losses caused by load and conduction.

- Selective coatings:

The metal tube is covered with a special layer that is designed to attract maximum solar radiation (with absorption above 0.95) and at the same time reduce heat loss (with heat emission below 0.10 at 400°C). Recent research is developing more advanced coatings based on multiple layers of ceramics and nitride materials that can withstand higher temperatures without losing their efficiency **[12].**

- Vacuum preservation and absorption materials:

Having a good vacuum inside the glass casing is an essential step to prevent unwanted heat transfer. To achieve this, non-evaporative absorbers (NEGs) are used to capture any gases or small particles that leak over time. Recent research is also improving the way glass is bonded to metal and using more effective absorbents, with the aim of extending the life of this element over 30 years of operation **[8].**

1.5.2.3 Heat Transfer Fluid (HTF) and Thermal Storage Integration

The choice of heat transfer fluid (HTF) plays an essential role in determining the operating temperature of the system and its ability to store thermal energy.

- Synthetic oils:

Thermal oils such as a mixture of biphenyls and biphenyls have been widely used in concentrated solar systems because they offer good performance within a medium thermal range and have been available on the market for many years. But as the use of these systems expanded and the operating requirements increased, the disadvantages of this type of oil began to become apparent. These oils cannot maintain stability at temperatures above about 400°C, and as the temperature rises, they begin to break down chemically and form products that affect their performance and increase the need for replacement and maintenance. In addition, these oils have flammability, which imposes severe safety restrictions and complicates operation in power plants **[6].**

- Melted salts:

Recent years have seen a significant shift towards the use of molten salts as a direct heat transfer fluid. The most famous of these is the solar salt consisting of 60% sodium nitrate and 40% potassium nitrate. This type allows to operate at temperatures up to 550°C and gives the system

higher thermal efficiency. The most important feature is the possibility of using the same liquid in thermal storage, which simplifies design and reduces operational cost **[10]**. Alternative liquids: New liquids, known as nano fluid, are currently being studied, which are liquids containing suspended nanoparticles such as graphite or metals. The idea of these fluids is to improve thermal conductivity and increase heat transfer performance. However, challenges remain regarding their long-term stability and high cost **[10].**

1.5.2.4 Support Structure and Solar Tracking System

The support structure and sun tracking system are the basis on which the performance of equivalent cutting complexes is based. The function of the support structure is simple on the surface but very important: keep the mirrors stationary and accurate in place no matter how the weather changes or the wind intensifies. irregular winds may generate higher loads than expected, making the structure design a critical factor, because any slight deviation in the mirror angle directly reflects on the amount of focused light and the effectiveness of the system **[11].**

The sun tracking system is the part that ensures that mirrors "catch up" the sun momentarily. In parabolic collectors, a single axis tracking system is usually used, which is enough to keep the mirror in the best position throughout the day and at a lower cost tracking accuracy could increase the amount of energy captured by 20% to 35% compared to fixed systems, showing that tracking is not just an addition, but an essential component of system success.

When the structure is strong and the tracking is accurate, the complex operates with higher stability, fewer thermal losses, and the operating system life increases, increasing its long-term economic efficiency **[12].**

1.6 Applications of Parabolic Trough Solar Collectors

Parabolic collectors are now used in more than one field, and in a simpler way than previously presented. The basic idea is that it collects the sun's heat and converts it into energy that can be used, whether to generate electricity or to operate various industrial processes.

1-In large power plants, these collectors are used with thermal storage systems based on molten salts. This storage allows the station to generate electricity even after no sun, such as in the evening. Recent studies indicate that raising the operating temperature and using modern cycles such as the supercritical carbon dioxide cycle helps improve performance and reduce cost **[10].**

In industry, they are used to provide the medium heat required in food, pharmaceutical, textile and metal factories. This reduces factories' reliance on conventional fuels and lowers emissions, especially with the development in solar field design **[3].**

In desalination, the heat of these collectors can be used to power systems such as MED and TVC, helping to provide a stable heat source for the plant, especially in areas that rely on desalination as the main source of water **[13].**

There are also hybrid uses, in which collectors are combined with conventional power plants to improve efficiency and reduce fuel consumption. Study results indicate that this combination gives good results in places with strong sun **[14].**

The heat of these collectors is also used in heating networks or in the operation of absorption cooling systems, which helps reduce emissions in buildings and large facilities **[15].**

Even in the oil sector, there are applications that rely on collectors to generate steam that is used to improve oil extraction, especially in fields with strong sun **[16].**

In general, parabolic collectors have become a flexible solution that can be used to generate electricity, heat industrial processes, desalination, and even some oil applications, with a noticeable development in research that helps raise their efficiency and reduce their cost.

1.7 Optimization Strategies for Parabolic Trough Solar Collectors

Improving the performance of parabolic collectors relies on a range of methods aimed at increasing heat transfer, reducing losses, and improving long-term operating stability. In general, these methods can be divided into three main categories: passive methods, active methods, and hybrid methods that combine the two, as recent reviews in this field have shown **[17].**

1.7.1 Active Enhancement Techniques

Active methods rely on adding external energy to move the fluid or influence its flow. These methods may involve moving the receiver tube, creating pulses in the fluid flow, or applying electric or magnetic fields. Although these methods achieve strong test results, their use in large solar fields remains limited due to complexity, cost, and difficulty of maintenance, as indicated by a comprehensive analysis of active technologies **[18].** Recent studies have also shown that heat transfer can be improved through innovative internal inserts, but it also increases design and mechanical requirements **[19].**

1.7.2 Passive Enhancement Techniques

Passive methods rely on modifying the shape of the receiver tube or changing the inner surface without adding any moving parts as shown in figure (1-12). The idea of these methods is simple but effective, as they help mix the liquid better and reduce the thermal layer that reduces heat transfer. Examples include using twisted strips inside the tube or adding internal cavities and ripples, methods that have been shown to increase system efficiency without consuming additional energy, according to experimental results and documented numerical modeling **[20].**
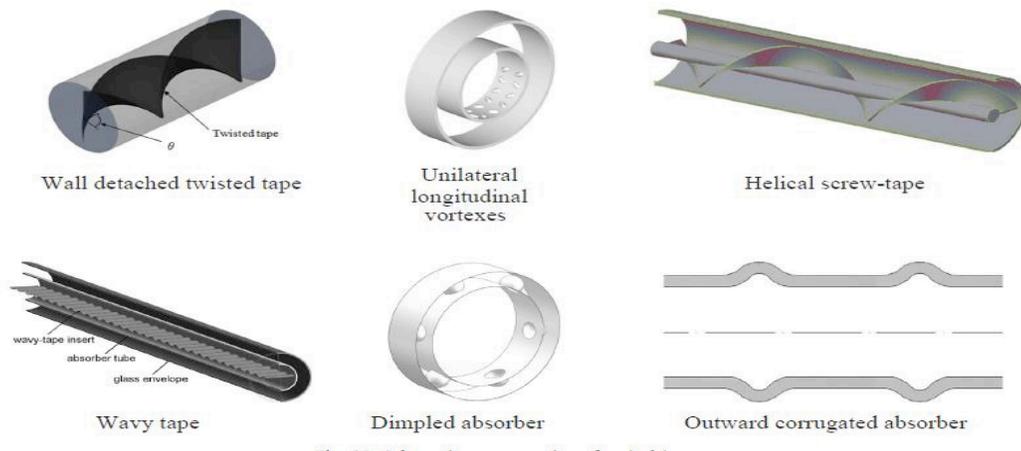
Figure 1-11 Passive Heat Transfer Enhancement Techniques in Parabolic Trough Collector Absorber Tubes [20]

1.7.3 Hybrid Enhancement Techniques

Hybrid methods, which are a combination of passive and active, such as combining improved internal surfaces and using nanofluids that have a higher heat transfer capacity. This type of method has demonstrated the highest levels of performance in many studies, especially when mechanical enhancers are combined with highly thermally conductive nanofluids **[7].** However, this type of technology needs a careful balance to ensure that the thermal benefit does not come at the expense of increased pressure or difficulty of operation.

In general, the current focus of research is towards passive and hybrid approaches because they achieve the best balance between efficiency, cost, and reliability in large-scale solar power plants

1.8 Research Gaps and Objectives of the Study

Despite the significant development achieved by parabolic complexes in recent years, there are fundamental points that still need deeper study. Specifically, there is still a clear lack of research that combines modifying the design of the future tube with the development of fluids used for heat transfer at the same time. Most studies have focused on only one aspect either improving the shape

of the tube by adding internal fins, or improving the properties of conventional fluids without considering the effect of combining the two factors within an integrated analytical methodology such as experimental design (DoE), what is known so far is that the inner fins actually help increase heat transfer because they increase the surface area and create turbulence within the fluid stream. But in contrast, this improvement usually comes with an increase in hydraulic loss and an increase in the capacity required to pump fluid. On the other hand, nanofluids which contain very fine particles such as Al_2O_3, CuO, and TiO_2 have proven in several studies to significantly improve thermal conductivity and heat transfer coefficient. However, the relationship between fin shape, number, thickness, and nanoparticle concentration in a liquid remains unclear, especially when trying to evaluate performance under realistic operating conditions, Studies that combined the two aspects were limited. For example [13] tested hybrid nanofluids inside finned tubes using Syltherm-800 and found a significant improvement in heat transfer. [14][15] studies have also shown The shape of the fin and the way its edges are rotated have a direct effect on the Nusselt number. In turn,[12]. It was found that using hybrid nanofluids with twisted strips inside the tube may increase the efficiency of the collector by up to 44.3%. Despite these results, there is still a lack of a comprehensive model that combines engineering design, fluid properties, and operational parameters within a single analysis that combines numerical and statistical modeling.

Therefore, this research seeks to bridge this gap by integrating numerical simulation (CFD) with experimental design (DoE) with the aim of analyzing and improving the thermal and hydraulic performance of receiver tubes with internal fins powered by nanofluids.

1.9 Conclusion

In this chapter, the theoretical basis on which the research is based is explained, and why parabolic complexes are important within the global transition towards renewable energy is explained. We reviewed the working idea of PTC, its basic components, the factors that affect its performance, along with different ways to improve heat transfer.

Despite the significant development in these technologies, there is still a clear gap in research, especially regarding combining improved future tube design with the use of nanofluids within one integrated framework. This gap is what drives this research to use numerical simulation and experimental design to achieve more accurate understanding and develop better performance.

CHAPTER II:
LITERATURE REVIEW ON HEAT TRANSFER ENHANCEMENT IN PTC RECEIVERS

Chapter II:
Literature Review on Heat Transfer Enhancement in PTC

2.1 Introduction

This chapter provides a clear reading of studies on methods for improving heat transfer in parabolic solar collectors (PTCs). The basic idea is to understand what affects the performance of these complexes, and what methods have been developed to increase their efficiency in practical and applicable ways. The chapter begins with a simplified explanation of how heat is transferred within the collector, then humanly and understandably reviews the most important passive methods of improvement, such as adding internal fins to the tube, using twisted bands, creating spiral vortices within the fluid, or modifying the shape of the tube itself. The pros and cons of each method are also explained through a comparison that shows the strength of each technology, the pressure loss it causes, and the balance the system needs between thermal performance and hydraulic resistance. This review is not just a list of information, but rather a prelude to the next chapter, which will take the topic a step further, focusing on improving the performance of finned tubes using nanofluids, in a systematic manner based on experimental design (DoE) to achieve the best possible performance.

2.2 Heat Transfer Characteristics in Parabolic Trough Collector (PTC) Receivers

The absorber tube is the true core of the parabolic solar collector; it is the element that receives the concentrated solar radiation and converts it into heat that is later transferred to the heat transfer fluid. The higher the tube's ability to absorb heat and distribute it evenly, the more efficient the system is and the fewer losses resulting from radiation and convection, in addition to reducing energy consumption and mechanical problems resulting from high temperatures. The distribution of radiation on the tube surface is usually heterogeneous, resulting in large temperature differences and the emergence of thermal stresses that may reduce the life of the tube and the efficiency of the system [1] [2]. Inside the tube, factors such as the speed of the fluid, its viscosity, its thermal conductivity, and the shape of the inner surface control the effectiveness of heat transfer. Therefore, choosing a suitable heat transfer fluid is an essential step before embarking on any further engineering improvements. Recent research focuses on enhancing heat transfer inside the tube by improving fluid movement and breaking the static thermal layer. The most prominent

methods include adding internal fins, using nanofluids, and designing internal surfaces with improved shapes to raise the efficiency of heat transfer and improve the performance of the solar system as a whole **[3].**

Tables (2.1) and (2.2) provide an overview of previous studies and a comparison of the main heat-transfer fluids used in parabolic trough collectors (PTCs). Table (2.1) summarizes research published between 2016 and 2025 and shows that synthetic oils such as Dowtherm Q and Therminol VP-1 generally offer better thermal performance than water, especially at high operating temperatures. Water is mainly used in low-temperature applications and shows lower efficiency. Several studies also focus on Syltherm-800, which shows stable behavior and good heat-transfer performance under certain conditions, although its efficiency depends strongly on the operating point and system design. Overall, the literature suggests that Therminol VP-1 and Dowtherm Q tend to provide higher efficiency, while Syltherm-800 shows reliable performance and low vapor pressure.

Table 2-1 Previous studies on (HTF) used in parabolic trough collectors

Reference	Year	(HTF)	Technique	Outcomes
[4]	2020	Water and Therminol VP-1	Numerical	The results showed higher heat transfer and efficiency of Therminol VP-1 by 15-20% compared to water under the same conditions.
[5]	2025	Water	Experimental	The results show an efficiency ranging between 11% and 15% for domestic water heating.
[6]	2022	Water	Experimental + Numerical	Increasing the flow rates raised the efficiency of the collector and reduced the outlet fluid temperature, thus confirming the accuracy and validity of the simulation model used.
[7]	2020	Dowtherm Q, Therminol VP-1, Syltherm-800	Numerical	The thermal performance of the Dowtherm Q and VP-1 were similar, and both were more efficient than the Syltherm-800 under the same conditions.
[8]	2018	Water	Numerical + Experimental	There is a good match between the simulated and measured results.
[9]	2016	Dowtherm Q, Syltherm-800, Therminol VP-1	Numerical	The efficiency of Dowtherm Q and Therminol VP-1 were higher than Syltherm-800 in most temperature ranges.
[10]	2023	Syltherm-800 and Therminol VP-1	Numerical	Heat transfer in the Syltherm-800 was better compared to the Therminol VP-1 under some operating conditions.
[11]	2023	Syltherm-800	Numerical	The results showed that the improvement in heat transfer reached 21%.
[12]	2024	Syltherm-800	Numerical	The results showed that the performance of the Syltherm-800 was moderate, and that achieving efficiency depended largely on improving the engineering design.
[13]	2022	Syltherm-800	Numerical	The relationship between viscosity and temperature is constant, reflecting stable and reliable performance in medium-temperature solar collectors.

Table (2-2) compares the thermophysical properties of water, Syltherm-800, Therminol VP-1, and Dowtherm Q. Water has the highest thermal conductivity and specific heat capacity, but its operating temperature is limited, and its vapor pressure increases significantly at high temperature. In contrast, the three synthetic oils can reach temperatures up to 360–400°C, with Syltherm-800 showing very low vapor pressure and excellent pumping efficiency at low temperatures. Therminol VP-1 and Dowtherm Q have similar properties, especially in terms of thermal conductivity and maximum operating temperature. These differences explain why synthetic oils are preferred for high-temperature solar applications, while water remains suitable for low-temperature or domestic thermal systems.

Table 2-2 Thermophysical properties of water, Syltherm-800, Therminol VP-1, and DowthermQ.

Property	Water	Syltherm-800	Therminol VP-1	Dowtherm Q
Thermal Conductivity (W/m·K)	~0.6	~0.15	~0.12	~0.12
Specific Heat Capacity (kJ/kg·K)	~4.18	~1.6	~1.5	~1.7
Max Operating Temperature (°C)	~100 –150 (pressurized)	Up to 400°C	Up to 400°C	Up to 360°C
Vapor Pressure at 300°C	High	Very Low	Moderate	Moderate
Pumping efficiency at Low Temperature	Poor below 0°C	Excellent (–40°C)	Poor below 12°C	Good (–35°C)

2.3 Passive enchantement techniques in absorber tubes

Passive heat transfer technologies are one of the simplest and most effective ways to improve the performance of solar collectors without any additional energy consumption. The idea is simply to change the shape of the absorbent tube or add small internal parts that change the movement of the liquid inside it, thus improving heat distribution and increasing the efficiency of its transfer. These methods are reliable and can operate for long periods with constant efficiency, which is why they are a practical option in large solar systems. Recent research has focused on several forms of these technologies, such as tubes with internal fins, twisted strips, spiral turbulence generators, and

corrugated surfaces each of which offers a special way to improve heat transfer and raise the efficiency of the solar collector.

2.3.1. Internally Finned Absorber Tubes

The internal fins increase the heat-conducting surface area, causing the sublayer near the wall to rupture and forming small vortices that further enhance heat transfer. The thermal performance of this type of tube is highly influenced by geometric factors such as fin height, thickness, angle, and number, in addition to the flow pattern of the fluid and its thermo-physical properties **[14].**

Ranjbar et al. [15] The researcher analyzed the behavior by numerical study using computational fluid dynamics (CFD) of an absorber tube equipped with segmented longitudinal fins. The researcher divided the absorber tube into two sections with fins and two sections without fins in order to reduce flow resistance while maintaining thermal optimisation. The results showed an increase in the Nusselt number by 38% with a decrease in pressure by 12% in the segmented fins compared to the continuous fins, indicating that fin segmentation is a method that can achieve better heat transfer efficiency with minimal hydraulic effects. **Darwish et al. [16]** conducted a numerical study of a tube with V-shaped longitudinal fins, using several fin angles. The results showed that a 45-degree angle performed best in terms of flow stability and vortex mixing efficiency within the tube. The results also showed an increase in the Nusselt number by 42% and an increase in efficiency by17% compared to a smooth tube, confirming the effect of V-shaped longitudinal fins in improving the efficiency of solar collectors. **Heidari et al. [17]** improve the heat dissipation along the inner wall of the absorber tube, conducted this by an experimental study of a tube with hybrid radial longitudinal fins combining axial and radial orientations. The results showed a 33% improvement in the Nusselt number and a 9.2% improvement in overall thermal efficiency compared to conventional longitudinal fins, indicating a more homogeneous heat distribution and improved fluid mixing within the tube.

Ahmed et al. [18] improve the heat dissipation along the inner wall of the absorber tube, researchers conducted this by an experimental study of a tube with hybrid radial longitudinal fins combining axial and radial orientations. The results showed a 33% improvement in the Nusselt number and a 9.2% improvement in overall thermal efficiency compared to conventional longitudinal fins, indicating a more homogeneous heat distribution and improved fluid mixing within the tube. **Bensalem et al. [19]** conducted a numerical study of an absorber tube with integrated split longitudinal fins. These splits generated vortices that intensified the tearing of the

boundary layer. The results showed an increase in the Nusselt number of 45-55% with a slight increase in the coefficient of friction, demonstrating the effect of the split fins on parabolic collectors. **Li et al. [20]**Used computational fluid dynamics and artificial neural networks, to developed a hybrid model to simulate thin longitudinal fins inside parabolic absorption tubes, the use of an artificial neural network reduced computation time while maintaining high prediction accuracy. The results showed an improvement in thermal performance of up to 25 % at the Reynolds number$2*10^{4}$, and the hybrid model showed a deviation of less than 3% from full computational fluid dynamics simulations, confirming its reliability in design optimization. A numerical experimental study was conducted by researchers on a parabolic junction absorber tube with internal longitudinal fins. The results showed a 30-60% increase in the Nusselt number compared to smooth tubes **[21]. Limboonruang et al. [22]** conducted a numerical study using computational fluid dynamics to improve fin spacing and shape. The results showed an increase in thermal efficiency and a more uniform wall temperature distribution. The results of the study conducted by researchers showed that increasing the height of the fins and decreasing their inclination lead to higher convection coefficients and, at the same time, a decrease in pressure .Their reduced-order model achieved high predictive accuracy (R² > 0.99) for complex fin geometries**[23].**The study results Conducted by researchers showed that changing the fin edge from sharp to rounded improves heat transfer performance. The study also indicated that a fin radius of 4 mm raises the overall improvement index by approximately 10.74% **[24]**.to understand the impact of the internal surface designs within the absorber tube, researchers conducted a numerical study. The results showed that the spatial location and orientation of these surfaces significantly affect heat transfer. The study also demonstrated an improvement in Nusselt's number and thermal efficiency compared to other designs **[25]**.

2.3.2 Twisted Tape Inserts

Due to their geometric simplicity and strong ability to generate vortices, Twisted tape (TT) are among the most researched passive technologies. This technique can generate secondary flow and continuous turbulence in the boundary layer because of forcing the fluid to move within a helical path, thus enhancing the exchange of convection energy between the core and the wall **[26].**

Anand et al. [27] used Twisted-tape fins. The results showed a significant improvement in convection performance as a result of combining the modified fin geometry with the twisted tape. The results also showed a significant improvement in Nusselt number and thermal efficiency

compared to smooth tubes. The results of the experimental study conducted by the researchers in two-pipe exchangers using double twisted tape showed an improvement in the Nusselt number of up to 185% with a 36% increase in pressure drop[28].The results obtained by the researchers during the study showed that inserting TT into the absorber tubes can increase the Nusselt number by 50-150% and can triple the friction factor[29].Through experimental studies conducted by researchers, flow tests at torsion ratios showed a consistent relationship between vortex intensity and coefficient of friction, providing a design basis for parabolic trough receivers[30]. **Chammam et al.[31]** conducted a numerical study using computational fluid dynamics of a absorber tube containing a twisted-tape inserts. The results showed a significant improvement in the Nusselt number. **Khan et al. [32]** conducted a numerical study comparing the thermal efficiency of an absorption tube equipped with twisted Tape and longitudinal fins to a smooth main tube. The results showed that the recorded thermal efficiency was 72.26%, 27.10%, and 72.09%, respectively, indicating the superior thermal performance of the twisted tape compared to the other types under the same conditions. A study conducted by researchers on the thermo-hydraulic behavior of alternating clockwise and counterclockwise twisted tapes showed that the twist angle plays an important role in improving heat transfer, and the results also indicated a suitable increase in pressure drop[33].Through an experimental study conducted by researchers to evaluate the exergy–energy evaluation of single and double twisted-tape inserts in a parabolic trough complex operating at a Reynolds number ranging between 1×10^3 and 9×10^3, the results showed an increase in the Nusselt number of up to 372% and an increase in thermal efficiency of up to 14%, while friction losses increased by approximately 1.6 times[34].**Stanek et al. [35]** Researchers conducted an An experimental- numerical study to analyze modifications of segmented twisted-tape retrofits for low-concentration PTCs with twist ratios TR=1, 2, and 4 were tested. The results showed that ratio TR=1 provides the highest heat transfer at moderate temperatures, while TR= 2 is optimal at higher temperatures and moderate flow rates. **Naif et al. [36]** studied experimentally an absorption tube with perforated twisted-tape inserts with mass-flow rates of 0.02–0.04 kg/s (Re ≈ 2000–4000) using water. The results showed an increase in thermal efficiency by 4.5%, an increase in Nusselt number by 5.4%, and an increase in the coefficient of friction by 6% compared to a smooth tube. **Abidi et al [37]** conducted a numerical evaluation of the perforated twisted tape absorber tube. The study results showed an increase in heat transfer coefficients of up to 40% with an acceptable pressure drop. The results of the experimental study, as well as the use of

computational fluid dynamics for a absorber tube with twisted conical-strip inserts, showed an increase in the performance evaluation criterion (PEC) by 30-45%compared to smooth tubes[38]. In this study, researchers used an absorber tube with twisted-tape inserts was studied by Their results showed an enhancement in the Nusselt number by 44% and an increase in friction by 62%, as well as an evaluation criterion (PEC ≈ 1.22) for maximum performance without excessive losses [39].

2.3.3 Helical and Spiral Inserts

Spiral and helical inserts produce a more consistent and quieter rotational motion than twisted tapes inserts. This reduces fluid stagnation zones and increases mixing within the tube. Their mechanical strength makes them a practical and longer-lasting choice in parabolic trough collectors [40].The results of the study conducted by the researchers on helical-finned absorption tubes showed that these fins help distribute heat more evenly and delay the separation of the layer near the wall, making them a good option for improving parabolic trough collectors[41].The results of the study conducted by the researchers on helical-finned absorption tubes showed that these fins help distribute heat more evenly and delay the separation of the layer near the wall, making them a good option for improving parabolic trough collectors[42]. In this study, researchers used helical finned geometric shapes on parabolic trough absorber pipes, and their results showed an improvement in the Nusselt number by55% and in the overall thermal performance coefficient by 47% [43]. In this study, researchers combined experimental measurements with computational fluid dynamics of corrugated helical absorber tubes. Their results showed that corrugation reduces the Reynolds critical number for turbulence initiation and increases the Nusselt number by 70-80% [44]. **Zaboli et al.[45]** studied numerically, using computational fluid dynamics, the thermal performance evaluation of inner helical axial finned absorber tubes. The results showed an improvement in thermal performance by 23.1% compared to smooth tubes, due to the increased surface area exposed to the fins. **Oveepsa et al.[46]** conducted the a numerical study to compare the thermal performance of straight and helical absorber tubes using different heat transfer media, the results showed that the spiral tubes with a higher number of turns significantly enhanced convection heat transfer, in addition to improving the overall collector efficiency. **Ali et al. [47]** conducted a numerical analysis of micro-helical finned absorber tubes to evaluate their thermal

behavior in parabolic trough collectors. Their results showed a significant improvement in thermal performance with a marked decrease in entropy generation, indicating an improvement in energy efficiency. **Hou et al.[48]** conducted a study to improve the geometry of helical-finned absorber tubes in parabolic trough collectors. The studies focused on the effects of fin inclination, helical angles, and fin height. Their study showed improved heat transfer at the angles35 and 45 while maintaining pressure losses within acceptable limits. An improvement in the Nusselt number by 30% was observed compared to smooth tubes and by 12-15 % compared to unoptimized helical tubes, along with a significant increase in pressure drop by 8-10%.**Saini et al. [49]** Using computational fluid dynamics, researchers conducted a numerical study of a helical-finned absorber tube to compare it with a smooth tube at various flow rates and 50–250 L/min and temperatures from 303–603 K. The results showed a thermal enhancement factor (TEF) up to 1.48, with an overall efficiency gain of about 2% at low flow rates. The pressure drop ranged between 165–313 Pa, increasing proportionally with Reynolds number. For heating domestic water, researchers conducted a study comparing helical, cylindrical, and sinusoidal absorber tubes. Their results showed the thermal efficiency of helical absorbents by 32% compared 24% to cylindrical absorbents **[50]**. **Pourfallah et al.   [51]** Using computational fluid dynamics, researchers conducted a numerical study of 4 and 7 and 10 -blades helical absorber tubes using different heat transfer media. The results showed that the 10-blades helical tube design exhibited a higher heat transfer coefficient 12.25% compared to the smooth tube. **Parlamış et al.[52]** conducted an experimental study of a parabolic trough helical tube solar collector, the results of which showed higher overall efficiency and thermal energy than a smooth tube under all test conditions.

Roohi et al. [53] conducted a study of a absorber tube equipped with helical spiral bands using computational fluid dynamics. The results showed an increase in the Nusselt number100-139% compared to smooth tubes.

2.3.4 Corrugated and Dimpled Geometries

Corrugated and modified surfaces enhance convection heat transfer because they create successive expansion and contraction zones that cause the fluid to circulate locally and repeatedly re-adhere to the wall. Since these changes are inherent to the pipe wall itself and not added components, they provide greater durability and reduce the risk of contamination **[54].** An experimental study was conducted on copper dimpled tubes, both alone and combined with twisted-tape inserts. The result showed that dimpled surface alone increased Nu moderately, while the combined configuration

achieved substantially higher thermal performance with a reasonable friction penalty[55].[56]conducted a numerical study on corrugated tubes carrying water-based nanofluids, demonstrating that the pitch-to-depth ratio governs both Nu and ΔP; an optimal configuration yielded high heat-transfer rates with minimal hydraulic loss. **Zhai et al. [57]** conducted a study on corrugated pipes and the result showed that deeper corrugations and shorter pitch significantly enhanced convection compared with smooth surfaces. **Wongcharee et al .[58]** The researchers conducted a study on corrugated tubes fitted with twisted tapes, the result showed that the enhancement in Nu and overall efficiency due to the interaction of swirl and textured wall effects. **Renas et al. [59]** The researchers conducted a study on porous and surface-textured parabolic trough receivers, the result showed that the incorporation of micro-dimples and corrugated structures intensified secondary fluid motions near the wall region, thereby improving collector efficiency by up to 20% compared to conventional smooth absorbers. The results of the numerical study conducted by the researchers on parabolic trough collector absorbers with various modified geometries showed that **reducing** corrugation diameter effectively minimized thermal resistance while maximizing the absorber surface's heat transfer capability, leading to enhanced thermal performance **[60]**. Through the numerical study conducted by the researchers on **central corrugated insert** placed inside a parabolic trough absorber tube. Their configuration consisted of a wavy or corrugated inner surface centrally aligned with the flow path. They result showed that the corrugated insert achieved a 1.3 to 2.6 times increase in the convective heat transfer coefficient compared to a smooth tube, depending on corrugation geometry and flow conditions**[61]**.The results of the study conducted by the researchers on dimpled, protrusion, and spiral absorber tube geometries under identical flow and boundary conditions showed that The dimpled tube configuration delivered superior convective performance, with a 60–70% increase in heat transfer coefficient relative to standard designs. The researchers also found that for moderate Reynolds numbers, the dimpled geometry struck a better balance between enhanced mixing and pressure losses than protrusions or spiral shapes, making it a favorable option for receiver optimization **[62]**.

Munusamy et al. [63] conducted an experimental study on a parabolic trough solar collector equipped with a copper dimpled absorber tube to evaluate its thermal–hydraulic performance. The experimental results showed that the dimpled tube improved the thermal efficiency of the collector by approximately 31.25% compared with a smooth tube, while the increase in friction factor

remained negligible (about 0.23%). These findings confirm that dimpled geometries can effectively enhance convective heat transfer with minimal hydraulic penalties, making them practical for high-efficiency solar receiver applications. The results of the study conducted on a corrugated circular absorber with internal dimples that designed to intensify the heat exchange between the absorber wall and the heat-transfer fluid Increase in outlet temperature by nearly 8 K and the overall thermal performance improved significantly compared to a conventional smooth absorber. The study demonstrated that hybrid corrugated–dimpled surfaces are among the most promising geometries for future parabolic trough receiver designs [64].

The Table (2-3) below provides overview of previous studies that have investigated heat-transfer enhancement techniques in parabolic trough collector (PTC) receiver tubes. The reviewed works cover a wide range of flow-insert mechanisms (such as twisted tapes, wire coils, helical screws, porous structures, and perforated plates) as well as internally modified absorber geometries (including finned, corrugated, and dimpled surfaces)

Table 02-3 Literature studies with internally modified absorber and flow inserts in PTCs

Reference	Insert configuration	(HTF)	Performance improvement	Method
[65]	Twisted tape with louvered edges	Behran oil	110% increase in h, $\Delta P \approx 300$ Pa	CFD
[66]	Plain twisted strip	Water	$\eta \approx 10\%$, h ×4	Model
[67]	Wall-detached twisted tape	Syltherm 800	η_{th} +27%, h +269%, ΔP +600 Pa	CFD
[68]	Wavy-tape insert	Syltherm 800	h +210%, ΔP +300 Pa	CFD
[69]	Conventional twist	Molten salt	h +190%, ΔP +150 Pa	CFD
[70]	Serrated tape	Therminol-VP1	η +5%, h +350%	Model
[71]	Wire-coil insert	Water	h +330%, ΔP +2200 Pa	Model
[72]	Wire coil	Water	h +240%, ΔP +2000 Pa	CFD + EXP
[73]	Helical screw tape	Dowtherm A	$h \approx 1000\%$, high friction	CFD
[74]	Dual twisted tapes	Water/steam		CFD
[75]	Wire coil	Air (pressurized)	h +100%, ΔP +200 Pa	Model
[76]	Multi-fin array	Air	η +15%	Model
[77]	Metal foam	Water	η +3%, ΔP +2000 Pa	EXP
[78]	Metal foam	Water/steam	h +600%, ΔP +1500 Pa	CFD
[79]	Porous discs	Water	η +6%	EXP
[80]	Porous discs	Steam	h +350%, ΔP +10 000 Pa	CFD
[81]	Dual fins (rectangular & triangular)	Dowtherm A + nanofluid	h +68%, ΔP +60 Pa	CFD
[82]	Longitudinal vortex generator	Syltherm 800	h +60%, ΔP +150 Pa	CFD
[83]	Longitudinal fins	Air, CO_2, He, Syltherm 800	η +1.3–7%, h +130–500%, ΔP 8–50 Pa	CFD

[84]	Helical fins	Syltherm 800	η +3–4.5%, ΔP +50 Pa	CFD
[85]	Converging-diverging absorber	Thermal oil	η +4.55%, h +15%, ΔP +75 Pa	CFD
[86]	Dimpled surface	Therminol-VP1	h +35%, ΔP +5 Pa	CFD
[87]	Dimpled + protruded surface	Therminol-VP1	h +60–70%, ΔP +70 Pa	CFD
[88]	Dimpled absorber	Air (pressurized)	η 0.8%, h +25%, negligible ΔP	Model

2.4 Comparative Assessment of Enhancement Techniques

2.4.1 Impact on Heat Transfer Coefficient

All the passive techniques studied above achieved improved convection heat transfer performance compared to smooth tubes. Longitudinal fins showed an increase in Nusselt number of approximately 20-30% **[45][47]** due to boundary-layer thinning and increased exchange area Helical and spiral fins **[41][42][48]**. It generated secondary swirling motion that improved temperature uniformity and boosted overall thermal performance by roughly 25–35 %. Twisted-tape technique **[32][27][39]** produced the highest enhancement levels, reaching 40–70 % above the baseline because of strong swirl intensity and improved internal mixing. Corrugated and dimpled surfaces **[61][59][60][63]** delivered 20–60 % improvements while maintaining acceptable hydraulic characteristics. In summary, all these technologies enhanced convective performance, but twisted tape and spiral designs generated the strongest local turbulence effects.

2.4.2 Pressure Drop and Pumping Power Penalties

Increased flow resistance means increased pipe turbulence. As shown in the studies above, Twisted-tape inserts showed the highest pressure drop, reaching 1.5 to 2 times that of smooth tube **[33][32].** The spiral and helical fins showed moderate hydraulic losses of approximately 8-15% But it is still within a controllable range during continuous operation **[42][48].** Studies have also shown a 10-20% increase in pressure in the longitudinal fins, depending on the fin's height and angle of inclination **[40].** As for the corrugated and modified tubes, the increases were minimal within this technology, as the friction coefficient remained below 1.3 and its impact on pumping power was very limited **[64][54].** From the above, the hydraulic penalty depends more on swirl intensity than on surface modification itself.

2.4.3 Trade-Off between Thermal Efficiency and Hydraulic Performance

The main objective of the optimization is to achieve a balance between improving heat transfer and hydraulic stability Twisted-tape inserts have been shown to maximize convection but may reduce system efficiency at high Reynolds numbers due to excessive pumping requirements **[39].** Helical and spiral inserts provide a better equilibrium, maintaining the performance-evaluation criterion (PEC > 1) while limiting frictional losses **[48] [41].** The overall efficiency remained constant with no hydraulic losses in the Internally and corrugated fin **[40][64].** In general, hybrid approaches that combine optimized geometry with nanofluid working media **[59][27]** achieve 10–

20 % higher thermal efficiency while keeping pressure-drop increases below 15 %, ensuring a sustainable operating balance for modern parabolic-trough collectors.

The table (2-4) illustrates a comparison of passive heat transfer techniques in parabolic trough solar collector absorber tubes.

Table 02-4 Comparison of Heat-Transfer Enhancement Methods in PTC Absorber Tubes

Enhancement Technique	Enhancement Mechanism	Heat-Transfer Increase (%)	Pressure-Drop Increase (%)	Overall Thermal Efficiency	Advantages	Limitations	Reference
Longitudinal fins	Increase surface area and reduce boundary-layer thickness	30–50 %	20–30 %	Moderate–High	Stable enhancement, simple to manufacture	Limited performance at high flow rates	**[40]**
Twisted-tape inserts	Generate strong swirl and enhance fluid mixing	150–370 %	130–250 % of smooth tube	High	Highest convective heat-transfer rate	High pumping-power requirement	**[39]**
Helical/spiral fins	Produce continuous swirl flow and uniform temperature distribution	25–55 %	8–15 %	Moderate–High	Good thermal–hydraulic balance	Complex manufacturing	**[48][41]**
Corrugated or dimpled tubes	Induce localized turbulence and enhance fluid–surface interaction	45–80 %	≤ 30 %	High–Stable	Excellent trade-off between heat transfer and pressure drop	Limited large-scale implementation	**[64][54]**

2.5 Conclusion

This chapter reviews a range of previous studies that explain why Syltherm-800 as are chosen as a heat transfer fluid because this fluid has high thermal stability, chemical resistance, and ability to operate across a wide temperature range (-40 °C to 400 °C), making it suitable for various environmental and operational conditions without degradation of its properties. The chapter also discussed the reason for selecting longitudinal fins inside the absorber tube, as they are among the most efficient geometries for increasing the heat-exchange surface area and enhancing convective heat transfer without causing a significant rise in pressure drop. Furthermore, to achieve additional enhancement in thermal performance, nanoparticles were introduced into the Syltherm-800 base fluid, aiming to increase its effective thermal conductivity and convective heat-transfer coefficient.

CHAPTER III:

NUMERICAL MODELING AND DESIGN OF EXPERIMENTS FOR HEAT TRANSFER ENHANCEMENT IN PTSCS

Chapter III:

Numerical Modeling and Design of Experiments for Heat Transfer Enhancement in PTSCs

3.1 Introduction

This chapter presents a numerical analysis of a parabolic trough solar collector (PTSC) with an internally finned absorber tube to enhance heat transfer efficiency. The work combines computational fluid dynamics (CFD) and experimental design (DoE) method to evaluate the influence of geometrical and operational parameters on the collector's thermal performance.

The aim of the study is to enhance thermal efficiency while minimizing pressure drop by determining the optimal fin configuration and operating conditions. The chapter also focuses on governing equations and boundary conditions and validate the simulation outcomes against reference data.

3.2 Physical Model of the Parabolic Trough Collector (PTC)

3.2.1 Description of the System and Components

Figure (1) shows a simplified model of how a parabolic solar collector (PTC) works. This system basically consists of a parabolic reflector that collects and focuses sunlight, and a receiver tube located at the focus point. When solar radiation reaches the reflective surface, it is redirected toward the receiver tube, where it is converted into thermal energy by passing a heat transfer fluid (HTF) through the tube. The receiver tube is the primary energy transfer element within the system, so its design plays a significant role in determining the system's optical and thermal efficiency. Typically, this tube is made of stainless steel and covered with a selective multi-layer ceramic material, which gives it a high ability to absorb solar radiation, low emissivity, and high tolerance to operating conditions **[1].**

Understanding heat transfer within PTC systems is based on the principle of thermal equilibrium between the fluid moving within the tube, the tube wall, and the surrounding environment. In this study, the receiver was modified by adding straight fins to the inner surface of the absorption tube, with the aim of enhancing convective heat transfer and improving thermal performance naturally and without adding external devices. Figure (3-1) shows a cross-section of the basic components of the complex and the energy transfer paths **[2].** Table (3.1) also provides engineering information

for the equivalent complex **[3],** while Table (3.2) shows details of the dimensions of the basic elements of the receiver, such as the absorption tube, fins, and glass casing used in the experimental and theoretical analyses within this study.
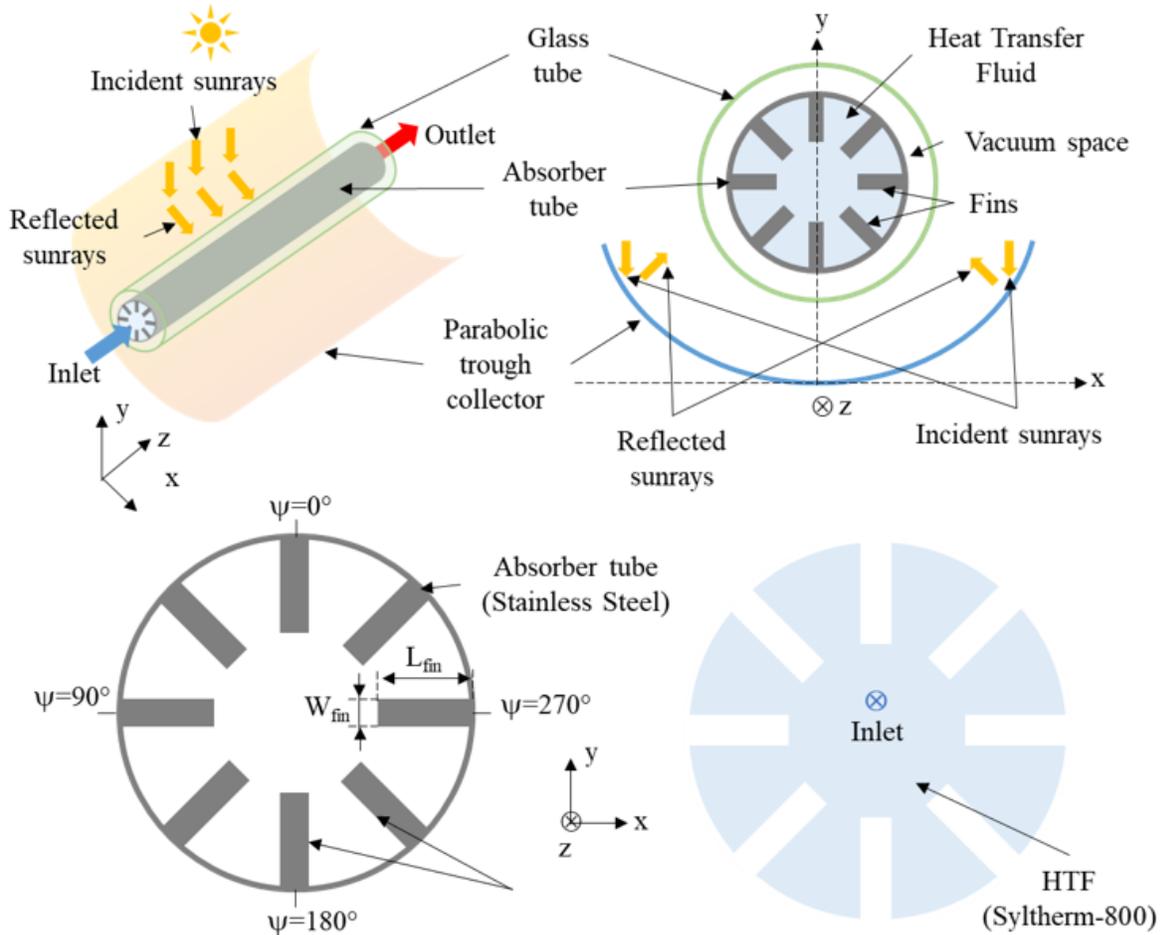
Figure 3-1 **Schematic representation of a typical parabolic trough collector**

Table 03-1 *Characteristics of the PTC collector*

	Parameters	Values
Parabolic Trough collector	Parabola width: Wc	5 m
	Parabola length: L	7.8 m
	Focal length: fc	1.84 m
	Reflectivity: ρ_m	0.93
	Trough material	CERMET & Chrome Noir

<div align="center">*Table 03-2 Characteristics of PTC*</div>

	Parameters	Values
Glass envelope	Glass inner diameter: D_{ig}	109 mm
	Glass outer diameter: D_{og}	115 mm
	Transmissivity: τ_g	0.95
	Emissivity	0.86
Absorber tube	Absorber inner diameter: D_{ia}	66 mm
	Absorber outer diameter: D_{oa}	70 mm
	Absorptivity: α	0.96
	Coating material	CERMET
Absorber fin	Thickness of fin: W_{fin}	0-6 mm
	Length of fin: L_{fin}	2-20 mm
	Material type	Stainless steel

3.2.2 Definition of Geometrical and Operating Parameters

The thermal and optical efficiency of a parabolic collector (PTC) depends on its engineering design and operating conditions. These factors control the system's ability to concentrate and absorb solar radiation and transfer heat to the heat transfer fluid (HTF) moving within the receiver tube. Therefore, accurately clarifying each given is essential to obtain correct modeling and improve system performance.

Indicates focal length (f_c) to the distance between the top of the parabolic reflector and the focal point at which the absorption tube is installed. This dimension is a fundamental factor in determining the collector's ability to concentrate solar radiation and can be calculated based on the geometric formula of the parabola **[4].**

$$f_c = \frac{w_c}{4 \tan\left(\frac{\theta_{rim}}{2}\right)} \tag{1}$$

The rim angle (θ_r) Expresses the angular extent of the reflective surface and determines the level of curvature of the collector and its geometric limit. This angle is related to the focal length and diameter of the aperture according to the relationship given in **[4].**

$$\theta_{rim} = \tan^{-1}\left(\frac{W_c/2}{f - W_c^2/(16f)}\right) \tag{2}$$

The total collector aperture area A_c and the external surface of the solar absorber A_a are calculated as follows:

$$A_c = w_c\, L \tag{3}$$

$$A_a = \pi D_{oa}\, L \tag{4}$$

The useful heat is defined based on fluid difference temperatures and the flow rate as [5]:

$$Q_u = \dot{m}\, c_p\, (T_{f,out} - T_{f,in}) \tag{5}$$

Where, c_p is the specific heat capacity of the working fluid (J/kg K), $T_{f,out}$ is the outlet temperature (K), $T_{f,in}$ is the inlet temperature (K) and $\dot{m}$ is the mass flow rate (kg/s)

The thermal efficiency of the solar thermal reflector can be easily defined as the ratio of useful heat Q_u, supplied per A_c, and the radiation, I, which is fallen on the aperture reflector:

$$\eta = \frac{Q_u}{A_c\, I} \tag{6}$$

Pressure drop refers to the amount of pressure drop as the heat transfer fluid flows inside the tube, and is caused by the effect of friction, turbulence, and thermal changes inside the absorption tube. It can be calculated using the following equation [5].

$$\Delta P = f\, \frac{L}{D_{ia}}\, \frac{\rho_f\, u^2}{2} \tag{7}$$

Where, ρ_f is the HTF density (Kg/m3), u is the HTF velocity (m/s) and, f is the friction factor, which can be calculated as follows [5]:

$$f = [0.79\ \text{Ln (Re)}-1.64]^{-2} \tag{8}$$

Where, Re is Reynolds' number that can be determined by the following expression [5]:

$$Re = \frac{4\,\dot{m}}{\pi\, D_{ia}\mu} \tag{9}$$

Where, μ is the dynamic viscosity of the working fluid (kg/m.s).

Represents the heat transfer coefficient (h) as the value between the absorption tube and the fluid flowing within it is the basic element in this model; its value is determined based on several factors including the shape of the tube, the flow rate, and the properties of the fluid, especially thermal conductivity, which is directly influential in the heat transfer performance. This coefficient is calculated using Nusselt's non-dimensional number, as shown in Equation (10)[6].

$$h = \frac{N_u.k}{D_{ia}} \tag{10}$$

3.3 Modeling Approach

The modeling in this study is based on a combination of optical and thermal analysis to obtain an accurate estimate of the performance of the parabolic collector (PTC). The general framework consists of two main parts: (1) optical modeling of the concentrator to quantify the distribution of solar flux on the receiver, and (2) thermal–fluid modeling of the receiver to analyze the heat transfer processes within the absorber tube.

3.3.1 Optical Modeling of the Collector

The optical model in this study was prepared to simulate the mechanism of focusing a mirror equivalent to direct solar radiation on an absorber tube. The model is based on the principles of geometric optics and ray tracing technology, where many rays emanating from the sun's disk are generated and their paths are tracked when they collide with the reflective surface. Every ray that falls on the mirror is reflected according to the law of reflection, and its path is traced until it reaches the surface of the receiver.

The model focuses on determining the local concentration ratio (LCR) and the density distribution of concentrated solar radiation (CSD) around the circumference of the receiver tube. The model accounts for the collector's geometrical characteristics, including focal length, rim angle, and aperture width, as well as the optical properties such as mirror reflectivity (ρ_m), glass transmissivity (τ_g), and absorber absorptivity (α).

The methodology was based on ray tracing strategies presented by Houcine et al. **[7–9]** in their studies. The solar flux distribution generated by the optical model is also used as the primary input to the thermal model, to ensure a realistic representation of the thermal flux change along the circumference of the absorption tube.

3.3.2 Thermal Modeling of the Receiver

<u>A. CFD Modeling Framework</u>

In this study, the computational fluid dynamics (CFD) method was used to perform a detailed 3D analysis of the parabolic collector (PTC), with an emphasis on understanding the interaction between heat transfer and flow behavior within the receiver tube. The CFD model is based on solving the energy equation in conjunction with applying standard k–ε turbulence model, allowing an accurate description of turbulent flow and a better ability to estimate load heat transfer under actual operating conditions.

The heat transfer fluid (HTF) used in this study is Syltherm-800 and was chosen for its high thermal stability and reliability in concentrated solar power systems. This liquid is classified as a silicone-based synthetic oil and allows a wide operating range extending from ($-40°C$) to ($400°C$), ensuring consistent performance both when starting up in cold climates and during continuous operation at high temperatures. In addition, Syltherm-800 features chemical inertness and reduced corrosion, reducing the risk of decomposition and facilitating its maintenance within the metal tubes of the receiver **[10]**.

Table (3-3) **[9]** provides a comparison between Syltherm-800 and several common heat transfer media in parabolic systems, and clearly demonstrates its higher temperature tolerance and thermal stability, factors that make its adoption in the CFD model used in this study justified. Due to these unique thermal properties, Syltherm-800 is a suitable choice for use as the primary heat transfer fluid in this research. The thermophysical properties adopted for this liquid in the study are presented in Table (3-4).

Table 03-3 Comparative analysis between Syltherm-80 and other fluids

Property	Water	Syltherm-800	Therminol VP-1	Dowtherm Q
Thermal Conductivity (W/m·K)	~0.6	~0.15	~0.12	~0.12
Specific Heat Capacity (kJ/kg·K)	~4.18	~1.6	~1.5	~1.7
Max Operating Temperature (°C)	~100 –150 (pressurized)	Up to 400°C	Up to 400°C	Up to 360°C
Vapor Pressure at 300°C	High	Very Low	Moderate	Moderate
Pumping efficiency at Low Temperature	Poor below 0°C	Excellent (–40°C)	Poor below 12°C	Good (–35°C)

Table 03-4 Thermos-physical properties of the Syltherm-800[11]

T (K)	ρf (kg/m^3)	Cp (J/kg K)	k (W/m K)	μ (kg/m.s)
300	929	1620	0.1337	0.00975
450	794.8	1876	0.1055	0.00133
600	640	2133	0.0773	0.00039

B. Governing Equations

The conservation equations used in the simulation are as follows:

Continuity equation: $\nabla(\rho u) = 0$ (11)

Momentum equation: $\nabla.(\rho \bar{u} u_i) = -\frac{\partial P}{\partial x_i} + \nabla.(\mu_{lam} + \mu_t)\nabla(\rho u_i) + S_i$ (12)

Energy equation: $\nabla(\rho u c_p T) = \nabla(k \nabla T)$ (13)

The $k - \varepsilon$ turbulence model was used for it is stability, simple, and low computational cost to resolve the turbulent effect on flow. Two equations were to be solved in this model, k represents the turbulent kinetic energy (m2/s2) and ε represents the dissipation of this energy (1/s):

k equation: $\nabla.(\rho \bar{u} k) = \nabla.\left(\mu_{lam} + \frac{\mu_t}{\sigma_k}\right)\nabla k + \mu_t G - \rho\varepsilon$ (14)

ε equation: $\nabla.(\rho \bar{u} \varepsilon) = \nabla.\left(\mu_{lam} + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon + \mu_t G - \rho\varepsilon + \frac{\varepsilon}{k(C_{1\varepsilon}\mu_t G - C_{2\varepsilon}\rho\varepsilon)}$ (15)

where ρ is the fluid density (kg/m3), $\bar{u}$ is the velocity vector (m/s), ui is the ith component of the velocity vector (m/s), μ_t and μ_{lam} denote the dynamic turbulent and laminar viscosities (N.s/m^2), respectively, G is the turbulence generation (kg/m3.s), and Si is the source term.

The turbulent viscosity is calculated:

$\mu_t = \rho C_\mu k^2/\varepsilon$ (16)

The effective viscosity utilized in the diffusion term of the k, ε, and momentum equations is the sum of the turbulent and laminar viscosities.

C. Boundary Conditions

In the CFD model used, the boundary conditions were determined based on the governing differential equations that describe the behavior of heat transfer and fluid flow through the finned absorber tube. The operating conditions and thermal conditions applied in the model are summarized in Table (3-5) **[12].**

Table 03-5 *Boundary Condition of the present work*

Parameters	Values
Masse flow rate (kg/s)	(0.533-3.87)
Density (Kg/m3)	(640-929)
Inlet temperature (K)	(300-600)
Inlet flow rate (L/min)	(50-250)
Outlet pressure	Fully developed flow and zero pressure gauge
Heat flux (W/m²)	Non-uniform heat flux with DNI = 1000
Absorber wall + fins material	Stainless steel
Absorber wall thickness (mm)	4

D. Basic Assumptions

The numerical analysis in this study was conducted according to a set of specific simplistic assumptions, to ensure stable convergence of the model and increase the efficiency of the calculations.

- Three-dimensional problem.
- There is no viscous dissipation.
- No gravity acts.
- Based on geometry/ Internal flow.
- Based on driving mechanism/ forced convection.
- Based on number of phases/ Single phase.
- Based on the nature of flow/ turbulence
- Steady state.
- Incompressible flow.

E. Finned absorber tube geometry and grid

Figure (3.2) shows the grid adopted in this simulation, where a hybrid grid was used to achieve an accurate representation of fluid dynamics and heat transfer inside the tube. A regular structured mesh with a minimum size of 1 mm was used to divide the fins and wall of the absorbent tube, while a four-sided mesh (Tetrahedral) was adopted to divide the heat transfer fluid (HTF) flow field, providing high accuracy in representing the flow and heat transfer behavior.

The mesh density near the inner wall of the tube and fins has been increased by (five grid layers at a growth rate of 1.5, to ensure accurate representation of the viscous layer and reliable estimation of the boundary layer effects on heat transfer. The final network deviation value (Skewness) was a maximum of 0.84.

A simple solution algorithm was used to relate pressure to velocity, with the residual convergence criterion set at 10^{-6} to ensure the stability of the numerical solution.
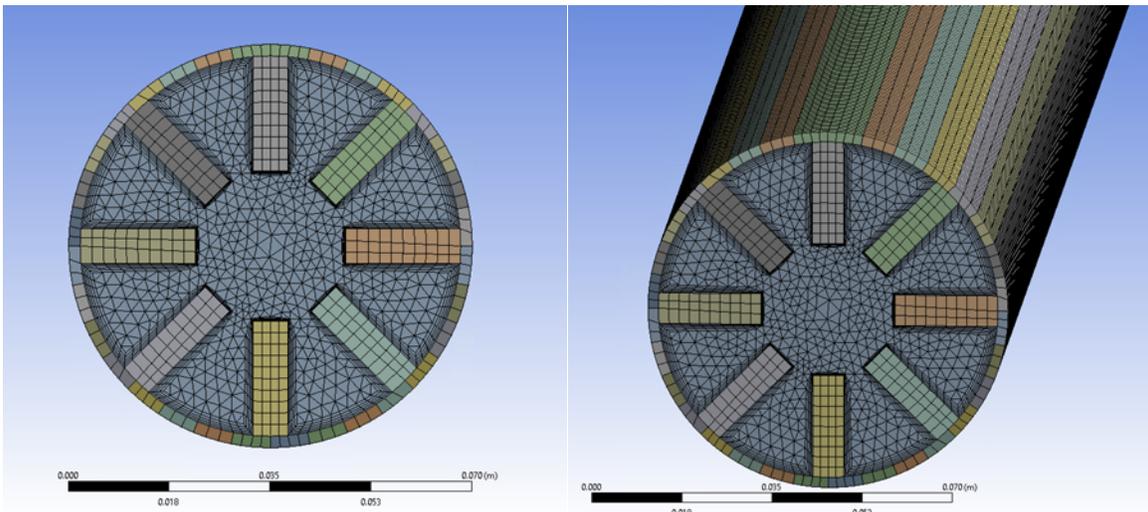
Figure 03-2 mesh distribution

A grid independence assessment was performed to verify that numerical results are not affected by the degree grid accuracy. Figure (3) shows that the grid has been optimized to ensure an appropriate balance between computational processing efficiency and result accuracy. This evaluation was performed using six different sets of grid elements

The initial height of the cells was determined to achieve a y+ value of less than 1, ensuring an accurate representation of the flow within the viscous layer, which is essential for accurate turbulence modeling. The outlet fluid temperature was used as a key indicator to evaluate mesh accuracy across all fin configurations. As Figure (3.3) shows, when the number of elements

approaches 12,549,393, the output temperature (Tout) values remain approximately constant, indicating the stability of the numerical results. Accordingly, a grid containing 12,549,393 elements was adopted to perform all simulations in this study.
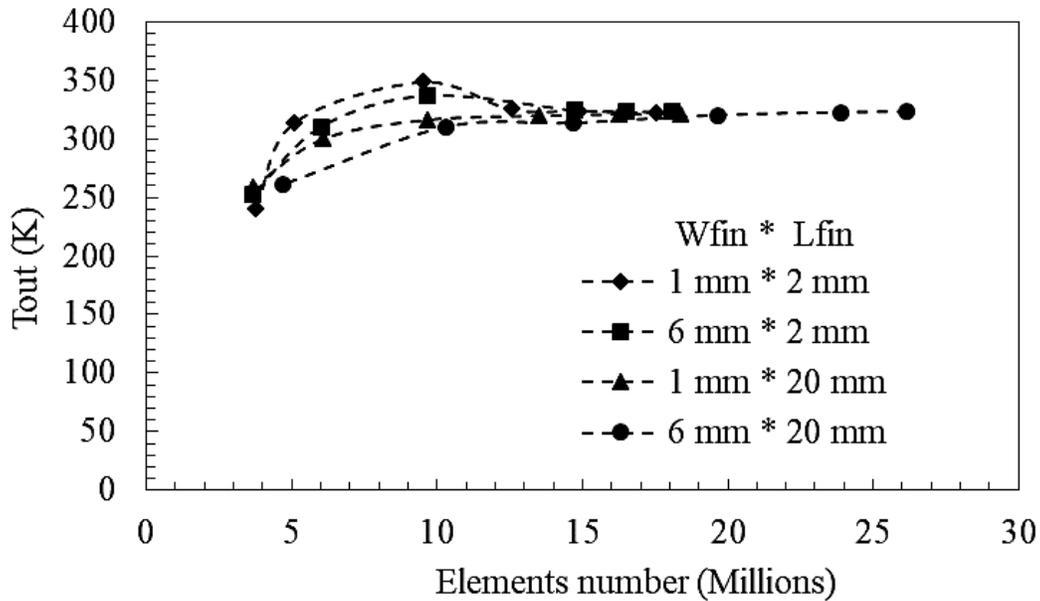
Figure 3-3 Grid independency test

3.4 Methodological Workflow

3.4.1 Flowchart of the Simulation Process

This study relies on a multi-stage numerical approach that combines optical and thermal analyses to describe the energy performance of a solar parabolic collector (PTC). As Figure (3.4) shows, the computational sequence begins with the optical ray tracing (Ray-Tracing) phase, which aims to analyze the distribution of concentrated solar radiation on the absorbent surface. This stage is based on the geometric and optical relationships reported in previous studies **[3, 7–9]** to determine the local concentration ratios and the shape of the irregular radiation flow around the receiver.

The computed concentrated solar density (CSD) data is used as a boundary input in the computational fluid dynamics-based thermal simulation (CFD) phase, where the absorbent tube, fins, and heat transfer fluid (HTF) are analyzed numerically through continuity, momentum, and energy equations **[12].** The CFD stage allows the determination of two main performance indicators: outlet temperature (Tout) and pressure loss (ΔP) for each specific geometry and operating conditions.

Subsequently, these results are incorporated into the Design of Experiments (DoE) framework to statistically evaluate the sensitivity of key variables and optimize both fin geometry and flow

conditions. This iterative approach allows for an integrated interconnection between optical focus, thermal-hydraulic response, and design optimization, providing a comprehensive numerical representation of the performance of a parabolic solar collector (PTC).

Figure 03-4 Flowchart of used methods

3.4.2 Validation Strategy

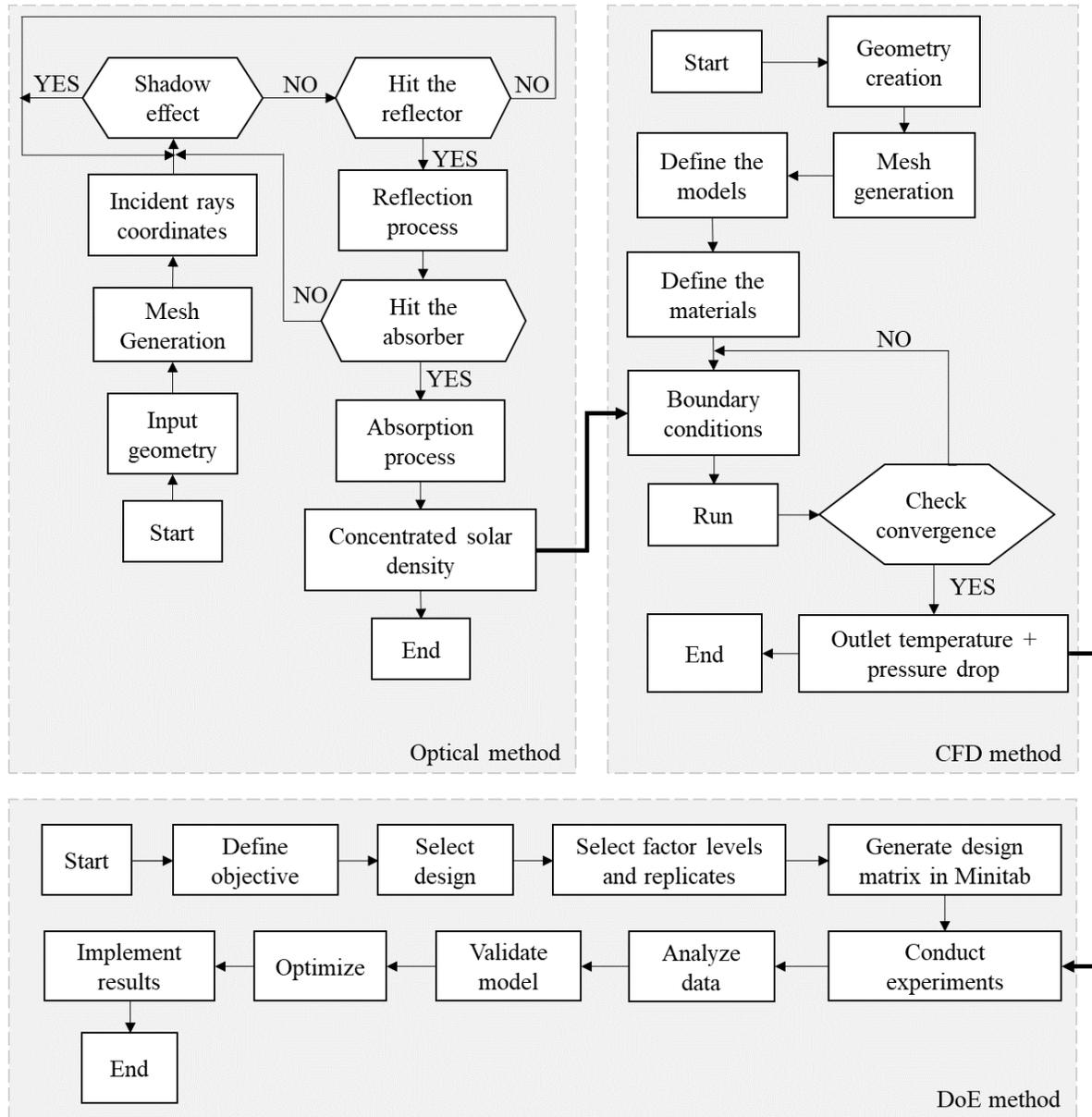To ensure the accuracy and reliability of the developed numerical models, a comprehensive verification approach was followed that combines the optical and thermal-hydraulic aspects.

Verification was based on two main stages: In the first phase, the optical model was tested by comparing local concentration ratio (LCR) results with reliable reference data from Jeter (1987) and He et al. (2011) under the same engineering and operational conditions. The goal of this comparison was to ensure that the ray tracing algorithm accurately represents the actual behavior of radiation concentration within the parabolic solar collector. In the second stage, the CFD-based thermal model was verified by comparing the calculated values of outlet temperature, thermal efficiency and load heat transfer coefficient with the results of previous numerical and experimental studies conducted by Saad et al. (2022) and Dudley et al. (1994). To ensure the reliability of the results, several indicators were used, including the network independence test, which proved that the accuracy of the results was not affected by network optimization, and the average deviation index (MED), which measured the quantitative difference between simulated values and reference data. These methodological steps confirm that the model combined between optical and thermal analysis accurately reflects real physical behavior before being applied in the final optimization phase.

3.5 Design of Experiments (DoE) for Optimization

Design of Experiments (DoE) is a statistical approach applied to study the interaction between input factors and outputs responses, with the aim of identifying the optimal performance of a studied system. In this rapport's case study, DoE is used to optimize the thermal performance of finned absorber tube of a parabolic trough collector (PTC) solar system.

3.5.1 Selection of Parameters and Levels

The first step in the DoE process is to identify the main input factors that influence the performance of the PTC finned absorber tube. Following a sensitivity analysis, the selected factors are classified into two categories: geometric and operational parameters, to investigate the maximum of the heat absorption.

Accordingly, fours influential factors are selected; fin length (L_{fin}), fin width (W_{fin}), volume flow rate (VFR) and inlet temperature (T_{in}). These are used to calculate two response parameters; the

thermal efficiency (η) and the pressure drop (ΔP). Each parameter is designed between two levels; representing its lower and higher values (Table 3-6).

Table 3-6 Low and high values for the input main factors

Parameters	Low value	High value
Fin length	2 mm	20 mm
Fin width	1 mm	6 mm
Volume flow rate	50 L/min	250 L/min
Inlet temperature	300 K	600 K

The chosen multi-level approach is crucial in the determination of the response surface model that allows the exploration of both linear and the interaction effects between main factors.

3.5.2 Experimental Design Matrix

The experimental plan is constructed using a structured design matrix, in which the selected input factors are varied across their designed levels. A full factorial design was chosen to evaluate all mains and interaction effects of the input factors. Indeed, for the four selected key factors, the full factorial design consists with 2^4 runs and 1 central point. Thus, the experimental design matrix contains 17 rows, each representing a distinct treatment combination (Table 3-7).

These selected runs generate an orthogonal data structure, allowing robust statistical significance of all estimated effects.

Table 03-7 Experimental design matrix for a full factorial design

T_{in} (K)	L_{fin} (mm)	W_{fin} (mm)	VFR (L/min)
300	2	1	50
300	2	1	250
300	2	6	50
300	2	6	250
300	20	1	50
300	20	1	250
300	20	6	50
300	20	6	250
450	11	3.5	150
600	2	1	50
600	2	1	250
600	2	6	50
600	2	6	250
600	20	1	50
600	20	1	250
600	20	6	50
600	20	6	250

3.5.3 Statistical Analysis and Evaluation Criteria

The analysis of the full factorial design results is conducted using statistical methods, integrating Analysis of Variance (ANOVA) and regression modeling. Both techniques investigate the effects of each input factors as well as the interactions between them on the response variables. The results of the analysis can be presented via several diagrams such as the Pareto chart of the normalized effects, the main effect plot, the interaction diagrams and the contour plots for the response variables. The evaluation criteria for the analysis process depend on several parameters such as statistical significance (p-value), model fit (R^2) and predictive accuracy. Indeed, the model is considered statistically significant when the p-value is lower than 0.05 and it is considered

adequate if the coefficient of determination (R^2) value indicates a good fit. Thus, the analytical outcomes provide the identification of the optimal factors and then selecting the optimum operating conditions and geometrics parameters.

3.6 conclusion

This chapter presents a numerical framework that combines ray tracing and fluid dynamics to understand how a fluid is heated inside an inner finned tube in a solar collector. The chapter explains the role of fin shape, flow rate, inlet temperature, and thermal fluid type in improving heat transfer. It also explains the steps for verifying the model to ensure its accuracy, and then shows how the DoE experimental design was used to identify the most influential factors and prepare the ground for the improvement phase in subsequent chapter.

CHAPTER IV:
RESULTS AND ANALYSIS

Chapter IV:

Results and Analysis

4.1 Introduction

This chapter presents the results resulting from the optical and thermal analysis of the solar collector with an absorbent tube equipped with internal fins. Here we present what the model arrived at step by step, from ensuring its accuracy, through how the solar flux is distributed on the tube, to the thermal response of the system. We also show how the Design of Experiments (DoE) methodology helped understand the impact of each variable and improve performance. In each part, we link the results to what is stated in the scientific literature to ensure that they are realistic and consistent with published knowledge.

4.2 Model Validation and Comparative Assessment

Before staring analyzing the thermal and optical performance of the system, it was necessary to first ensure that the computational models I developed worked correctly and reflected the true behavior of the solar collector. Therefore, at this stage, a comparison was made between the results of the optical model and the CFD model and what has been documented in previous studies, both experimental and numerical. The goal of this procedure was to ensure that the model was able to reproduce realistic thermal and optical properties, so that I would have a solid, reliable foundation before moving on to performance analysis and optimization processes later.

4.2.1 Validation against Literature and Experimental Data

In this part of the study, the accuracy and reliability of the simulation approach used were verified. The optical model was operated under the same operating conditions used by Jeter (1987), which include: GC = 20, edge angle θrim = 90°, mirror reflectivity ρm = 1, glass transmittance τg = 1, surface absorbance α = 1, and ray incidence angle θs = 0.0075 radians. The results obtained —shown in Figure 4.1— were then compared with results published in previous studies [1, 15, 16]. The comparison showed high agreement, which is consistent with the small deviations reported by these studies and the way the accuracy of the models is evaluated through mean error values [7–9].
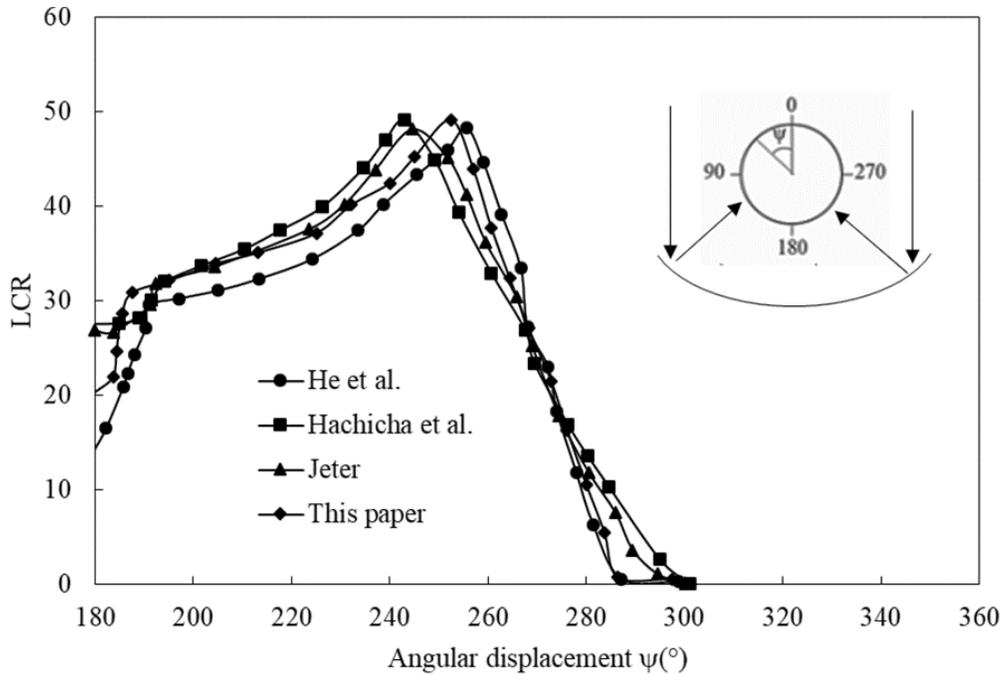
Figure 04-1 LCR distribution around the absorber tube

Figures 4-2 and 4-3 show a clear comparison between the results of the CFD model in this study and the numerical results published by Saad et al. **[12]** and the experimental data of Dudley et al. **[13].** To ensure fairness in the comparison, simulations were performed using the same operating conditions and parameters used in those studies, including fin length 25 mm, width 4 mm, circular rim radius 4 mm, fin spacing angle 45°, flow rate 150 L/min, and direct solar radiation value 1000 W/m². The results showed a change in thermal efficiency (Figure 4.2) and the convection heat transfer coefficient (Figure 4.3) with a change in the fluid entry temperature. This method ensures a direct and consistent comparison between the current model and published data and demonstrates the model's compatibility with the actual thermal behavior of the system.
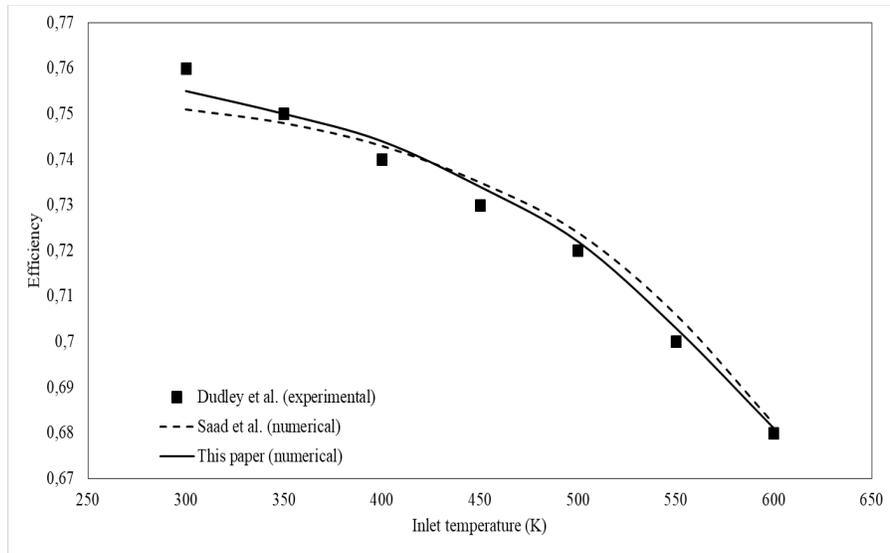
Figure 04-2 Efficiency evolution for different inlet temperature
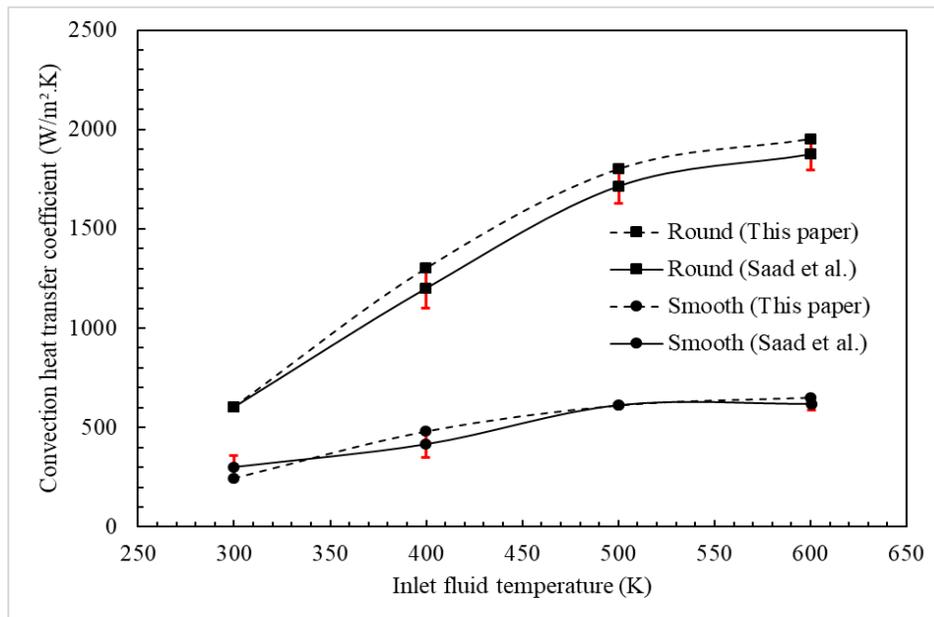
Figure 4-3 Convection heat transfer coefficient evolution for different inlet fluid temperature

Figure 4.3 shows that the load heat transfer coefficient predicted by the CFD model used in this study follows the same general trend as the reference results.

4.2.2 Error Analysis and Model Reliability

The numerical model used in this study is able to represent the thermal behavior reported by previous studies due to the high agreement between the simulation results and the reference data. To more accurately evaluate this match, I used the arithmetic mean deviation equation (MED)

contained in reference **[9],** which allowed the accuracy and reliability of the model to be measured objectively and clearly.

$$MED = \frac{1}{N} \sum_{i=1}^{N} \frac{|Y_i - X_i|}{Y_i} \times 100 \qquad (24)$$

Where, N is the total number of data points, Y_i are the reference values and X_i are the CFD outcomes values of this paper.

The direct numerical evaluation of the model's performance quality is shown by the MED values shown in Table 4.1. The high convergence between CFD model predictions and benchmark data demonstrates that the developed model performs accurately and reliably under the tested operating conditions.

Table 04-1 Validation of convective heat transfer coefficient: deviation from literature data

	Smooth	*Round*
Mean error deviation (%)	9.35	5.35

4.3 Optical Results: Concentrated Solar Flux Distribution

This part of the study focused on analyzing the optical behavior of the solar collector for the purpose of understanding the way solar radiation is concentrated on the absorbent tube. I used the ray tracing model I developed to simulate the motion of rays reflected from a mirror and plot how their energy is distributed on the surface of the tube. The results showed that the solar flux is not evenly distributed around the tube, a factor that directly affects its temperature and the way heat is transferred inside it. The following sections will discuss the most notable of these findings in more detail.

4.3.1 Flux Contour on the Receiver

Figure 4.4 shows that the polar and three-dimensional representations of both the concentrated solar flux density (CSD) and the local concentration ratio (LCR) generated by the optical model clearly reveal that the flux is not evenly distributed around the circumference of the tube [49, 50]. The results showed that the highest concentration value appears at the lower region of the tube, which is the point where the rays reflected from the mirror meet. The highest level of flux is also shown just above the bottom of the tube, a location that corresponds to the focal line generated by the mirror shape.

We noticed that as we move towards the center and edges of the lower surface of the tube, the intensity of the flux begins to gradually decrease because of partial shadow and some optical

losses resulting from imperfect mirror alignment. In contrast, the top of the tube shows very poor exposure to radiation because it receives very little reflected radiation. This unbalanced distribution of flood shows that the tube does not receive solar radiation evenly around its circumference, which is something that must be considered when performing thermal simulations to avoid overheating in specific areas and the stress this may cause to the materials.

4.3.2 Non-Uniformity and Optical Losses

The results of the optical analysis showed that the concentrated solar radiation reaching the surface of the absorbent tube is not distributed evenly at all. This variation in energy distribution leads to the formation of clear temperature differences along the tube wall, which may cause thermal stresses to build up and reduce the efficiency of the collector. The main reason for this heterogeneity was found to be minor deviations in the shape of the mirror, minor errors in tracking the sun, and partial shadows on parts of the receiver.

Accordingly, the lower part of the absorbent tube receives the highest heat flux values, while the upper part receives much less radiation. These visual disturbances lead to energy losses and contribute to the appearance of localized hot areas that may accelerate damage to the tube surface. To reduce these losses, I suggest using rectangular internal fins inside the absorbent tube, as they enhance load heat transfer and increase fluid mixing, which helps achieve a more uniform heat distribution. The observed flux contours and non-uniform characteristics shown in Figure 4-4 clearly demonstrate these behaviors, and my results are consistent with visual analyses reported by previous studies **[7, 8].**
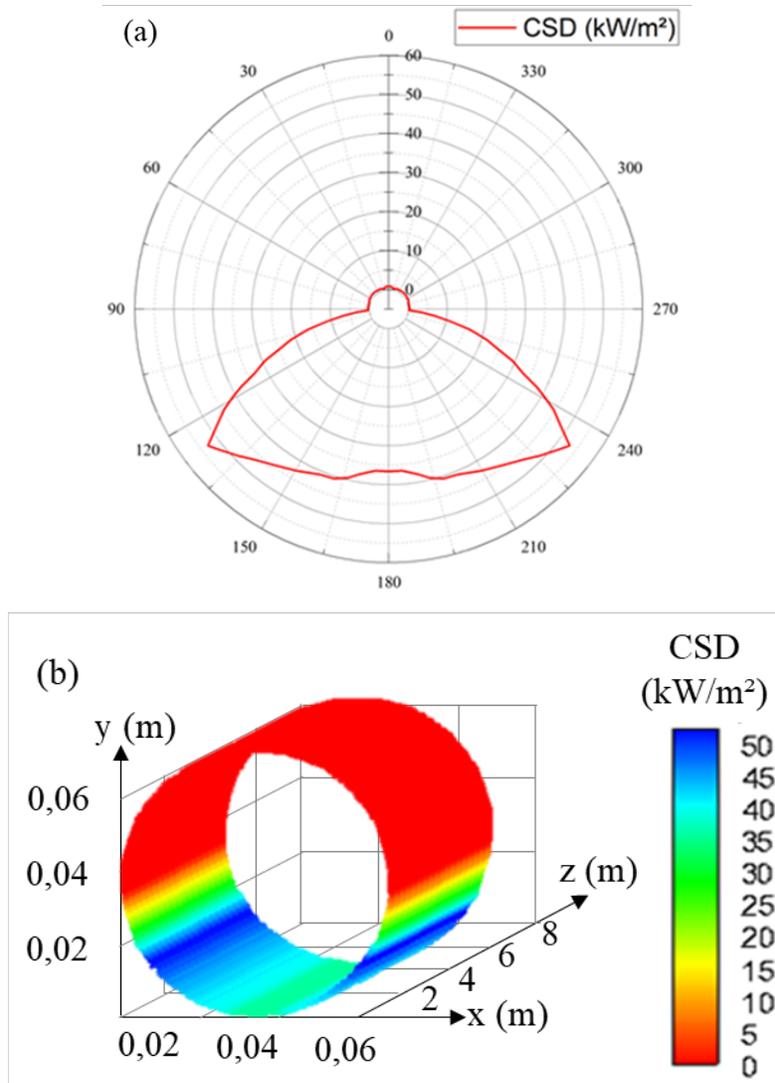
Figure 4-4 Polar (a) and 3D representations (b) of the CSD distribution around the absorber tube

4.4 Thermal Results: Temperature Distribution and Performance

This section deals with the analysis of the temperature distribution contour inside the absorber tube for all cases studied. Before delving into the internal heat distribution, it was important to first examine how heat is distributed on the outer surface of the tube, given its direct impact on the heat transfer mechanism inside the tube. Figure 4.5 shows three transverse sections along the z-axis: at the inlet plan cross-section, in the middle plan cross-section, and at the outlet plan cross-section. The results show that the temperature distribution follows the same profile as the CSD shown in

Figure 4.4. However, the outlet section shows heat reaching the entire circumference of the pipe, with a clear variation in temperature values.
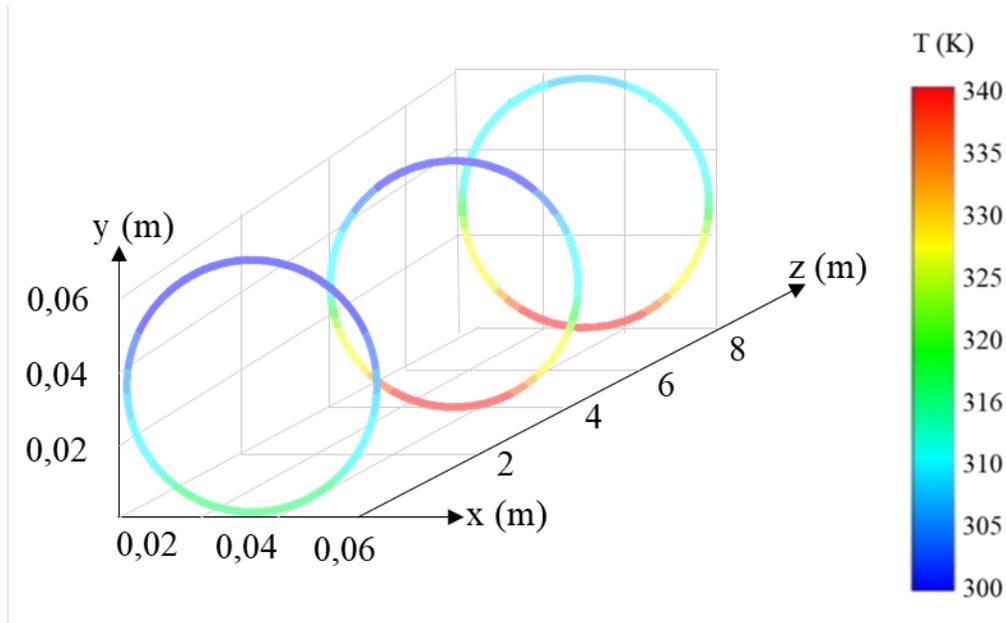

Figure 04-5 3D representation of the temperature distribution around the absorber tube

Figure 4.6 shows the temperature distribution contour inside the absorber tube, where convective heat transfer starts from the bottom of the tube. This results in a pronounced variation in thermal fluid temperature (HTF) around the circumference of the circular section. From the figure itself, as the fluid moves towards the outlet, its average temperature gradually rises, making the thermal difference between the inlet and outlet the largest across all the cases studied.

In addition, Figures 4.6 show that the outlet temperature of the solar collector is clearly affected by the value of the volumetric flow rate of the thermal fluid (VFR). When the flow is 250 l/min, the time the fluid spends inside the absorbent tube decreases, which limits the amount of heat it can gain, so the temperature rise is slight ($\Delta T \approx 5$ K). When the flow is reduced to 50 liters/minute, the residence time inside the tube increases, allowing the fluid to absorb more heat and reach a higher temperature at the outlet ($\Delta T \approx 23$ K).

It also turns out that fin length and width play an important impact in determining the shape of heat distribution. The larger the fin dimensions, the greater the surface area in contact with the fluid. This enhances heat transfer from the tube wall to the fluid and strengthens the convection within it. As a result, heat spreads more effectively within the fluid and reaches the top of the tube,

raising the thermal difference between the inlet and outlet. This improvement in heat diffusion reduces the formation of hot spots, thus reducing heat stress and material damage in the long te

Outlet cross-section

(a)

Middle cross-section

$L_{fin} = 2\ mm\ \&\ W_{fin} = 1\ mm$
$T_{in} = 300\ K\ \&\ VFR = 50\ L/min$

T (K)

Outlet cross-section

(b)

Middle cross-section

$L_{fin} = 20\ mm\ \&\ W_{fin} = 1\ mm$
$T_{in} = 300\ K\ \&\ VFR = 50\ L/min$

T (K)

(c)

Outlet cross-section

Middle cross-section

L_{fin} = 2 mm & W_{fin} = 6 mm
T_{in} =300 K & VFR = 50 L/min

T (K)

(d)

Outlet cross-section

Middle cross-section

L_{fin} = 20 mm & W_{fin} = 6 mm
T_{in} =300 K & VFR = 50 L/min

T (K)

(e)

$L_{fin} = 2 \ mm \ \& \ W_{fin} = 1 \ mm$
$T_{in}=300 \ K \ \& \ VFR=250 \ L/min$

Outlet cross-section

Middle cross-section

(f)

$L_{fin} = 20 \ mm \ \& \ W_{fin} = 1 \ mm$
$T_{in}=300 \ K \ \& \ VFR=250 \ L/min$

Outlet cross-section

Middle cross-section

(g)

Outlet cross-section

Middle cross-section

L_{fin} = 2 mm & W_{fin} = 6 mm
T_{in}=300 K & VFR=250 L/min

T (K)

310
309
308
307
306
305
304
303
302
301
300

(h)

Outlet cross-section

Middle cross-section

L_{fin} = 20 mm & W_{fin} = 6 mm
T_{in}=300 K & VFR=250 L/min

T (K)

310
309
308
307
306
305
304
303
302
301
300

(i)

Outlet cross-section

Middle cross-section

L_{fin} = 2 mm & W_{fin} = 1 mm
T_{in}=600 K & VFR=50 L/min

T (K)

640
635
630
625
620
616
610
605
600

(j)

Outlet cross-section

Middle cross-section

L_{fin} = 20 mm & W_{fin} = 1 mm
T_{in}=600 K & VFR=50 L/min

T (K)

640
635
630
625
620
616
610
605
600

(k)

Outlet cross-section

Middle cross-section

$L_{fin} = 2\ mm\ \&\ W_{fin} = 6\ mm$
$T_{in}=600\ K\ \&\ VFR=50\ L/min$

T (K)
640
635
630
625
620
616
610
605
600

(l)

Outlet cross-section

Middle cross-section

$L_{fin} = 20\ mm\ \&\ W_{fin} = 6\ mm$
$T_{in}=600\ K\ \&\ VFR=50\ L/min$

T (K)
640
635
630
625
620
616
610
605
600

(m)

Outlet cross-section

Middle cross-section

$L_{fin} = 2\ mm\ \&\ W_{fin} = 1\ mm$
$T_{in}=600\ K\ \&\ VFR=250\ L/min$

(n)

Outlet cross-section

Middle cross-section

$L_{fin} = 20\ mm\ \&\ W_{fin} = 1\ mm$
$T_{in}=600\ K\ \&\ VFR=250\ L/min$

Figure 04-6 Temperature distribution of the Syltherm-800 within the finned absorber tube for all cases studies

4.5 Results of the Design of Experiments (DoE)

4.5.1 Influence of Input Parameters

This research goes beyond traditional methods and uses advanced statistical modeling to achieve the best thermal performance of finned tubes in PTC systems. Through the Experiment of Design (DoE) methodology, the effect of each factor —such as fin shape and heat transfer fluid

flow rate — can be understood accurately and systematically, helping to choose settings that give the highest possible heat absorption.

Four main factors were adopted in this study to evaluate the performance of the finned tube: fin length (Lfin) and width (Wfin), volumetric flow rate (VFR), and inlet temperature (Tin). The effect of these factors is measured on two basic indicators: efficiency (η)and pressure drop(ΔP). To systematically analyze this, a full factorial design with 24 CFD simulation-based experiments was used. Each factor within its operational range between the minimum and maximum was examined : Lfin (2 mm, 20 mm), Wfin (1 mm, 6 mm), Tin (300 K, 600 K) and VFR (50 L/min, 250 L/min). To increase the accuracy of the results and reduce the margin of error, a central point was added that collects average values for the four factors: (Lfin=11 mm, Wfin= 3.5 mm, VFR=150 L/min and Tin=450 K).The final results for each combination of factors are shown in Table 4-2.

Table 04-2 Total results for all case studies

Tin (K)	Lfin (mm)	Wfin (mm)	VFR (L/min)	Tout (K)	η	ΔP (Pa)	f
300	2	1	50	322.8	0.736	80	0.0246
300	2	1	250	304.6	0.75	1320	0.0162
300	2	6	50	322.9	0.739	95	0.0292
300	2	6	250	304.6	0.753	1390	0.0171
300	20	1	50	321.0	0.742	130	0.0399
300	20	1	250	304.7	0.759	3365	0.0413
300	20	6	50	323.2	0.748	180	0.0553
300	20	6	250	304.72	0.76	7590	0.0932
450	11	3.5	150	457.5	0.72	728	0.029
600	2	1	50	622.38	0.653	74	0.033
600	2	1	250	604.7	0.689	1250	0.0223
600	2	6	50	622.62	0.66	85	0.0379
600	2	6	250	604.73	0.691	1360	0.0242
600	20	1	50	622.9	0.669	120	0.0535

600	20	1	250	604.75	0.693	3141	0.056
600	20	6	50	623.31	0.68	150	0.0669
600	20	6	250	604.77	0.696	7477	0.1333

4.5.2 Optimization Outcomes

The Pareto diagrams in Figure 4-7 show how different factors affect both efficiency and pressure drop. This analysis helps to know which factors have a real impact and which have a weak impact, through a vertical red line separating important and unimportant impacts. In Figure 4.7.a of efficiency, the inlet temperature (Tin) is shown to be the strongest influencing factor, followed by the flow rate (VFR), then the fin length (Lfin), as well as the interaction between Tin and VFR. The width of the fin (Wfin) does not leave a clear impact on efficiency. In Figure 4.7.b, which shows the effect of factors on pressure drop (ΔP), seven important effects appear beyond the line of significance: flow rate, fin length, fin width, and all interactions between them. While it turns out that the inlet temperature (Tin) has little effect on the pressure change.
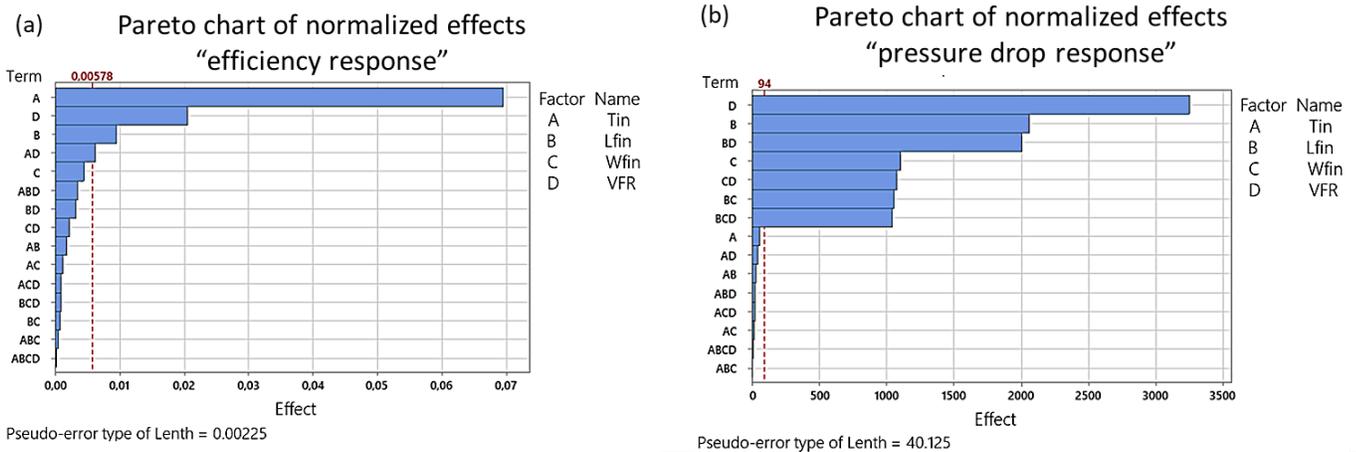

Figure 4-7 Pareto chart of normalized effects for both efficiency (a) and pressure drop (b)

The regression equations in un-coded units predict efficiency and pressure drop are presented in table 4-3.

Table 4-3 Regression equations of the efficiency and pressure drop response

Responses	*Regression equations*	*Goodness-of-fit statistics*
Efficiency	$0.8228 - 3.03 \times 10^{-4}\,A + 5 \times 10^{-4}\,B + 6.4 \times 10^{-4}C$ $+ 4.4 \times 10^{-5}\,D + 10^{-6}\,A.B + 2 \times 10^{-6}\,A.C$ $+ 1.7 \times 10^{-5}\,B.C - 2 \times 10^{-6}\,B.D$ $- 5 \times 10^{-6}\,C.D + 6.37 \times 10^{-3}\,E$	S = 6.124*10^{-3} R² = 99.83% R² (ajust) = 97.24% p = 0.126 f = 38.53
Pressure drop	$-212.6 + 3.369 \times 10^{-2}\,A - 16.07B + 24.8\,C + 5.772\,D$ $+ 7.324 \times 10^{-3}A.B - 8.13 \times 10^{-3}A.C$ $- 9.26 \times 10^{-4}A.D - 10.65\,B.C$ $+ 0.3714\,B.D - 0.4382\,C.D$ $- 1.352 \times 10^{-3}A.B.C - 1.54 \times 10^{-4}A.B.D$ $+ 1.18 \times 10^{-5}A.C.D + 0.2341\,B.C.D$ $+ 1.6 \times 10^{-5}A.B.C.D - 1010\,E$	S = 979.783 R² = 98.98% R² (ajust) = 83.75% p = 0.3 f = 6.5

Where ; A is the inlet temperature (T_{in}), B is the fin length (L_{fin}), C is the fin width (W_{fin}), D is the volume flow rate (VFR) and E is the center point.

Table 4-3 shows that most factor coefficients are positive, while the inlet temperature coefficient (T_{in}) appears negative. This decrease is evident in Figure 4.8.a, where efficiency decreases when the value of Tin increases. In contrast, increasing the fin length (Lfin), width (Wfin) and flow rate (VFR) values results in a significant improvement in efficiency.

In the same context, Figure 4.8.b shows how various factors affect the pressure drop value ΔP. It turns out that the inlet temperature (Tin) does not change the pressure value significantly, while the rest of the factors show a clear effect. When the fin length or width increases, the space available for the heat transfer fluid to pass through the tube decreases, creating greater flow turbulence, which directly leads to a higher pressure drop value. Equation (9) also states that the pressure drops increases when the speed of the heat transfer fluid increases, and this speed is directly related to the flow rate VFR.

Figure 4-8 also shows that the central point indicates a curved relationship (Quadratic) between all influencing factors and the ΔP response, rather than a simple linear relationship.
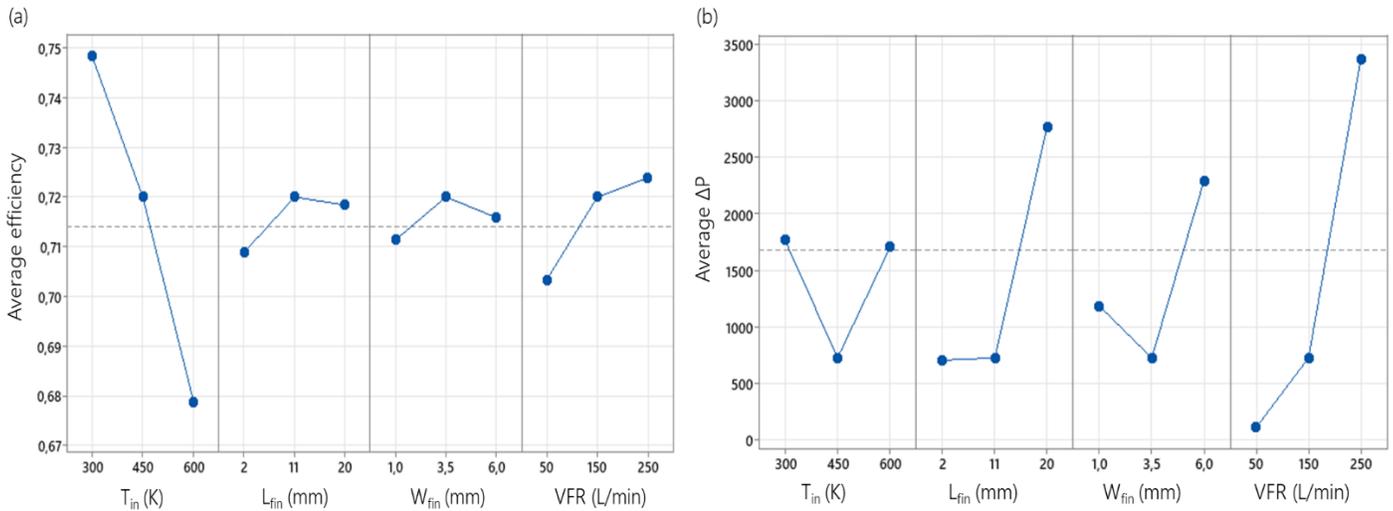
Figure 4-8 Main effect plot for efficiency (a) and pressure drop (b)

Figure 4.9 shows the interaction diagram between factors affecting efficiency and pressure drop. As shown in Figure9.a, the lines for the interaction of T_{in} and L_{fin}, T_{in} and W_{fin}, as well as L_{fin} and W_{fin} run almost parallel, meaning that these factors pairs have an independent effect with minimum interaction. However, the interaction between the VFRand other factors (Tin, Lfin and Wfin) appears with unparalleled trends, indicating that there are minor dependencies between VFR and Tin, VFR and Lfin as well as VFR and Wfin.

Figure 4-9.b shows the interaction of factors affecting pressure drop. It can be seen that the interaction between fin length (Lfin), width (Wfin) and flow rate (VFR) is clearly shown by the line spacing, indicating that the amount of pressure drop is actually affected by the combination of these factors together. In contrast, the inlet temperature factor (Tin) shows little interaction with other factors, which means that its effect on pressure drop is negligible and does not depend on influenced factors
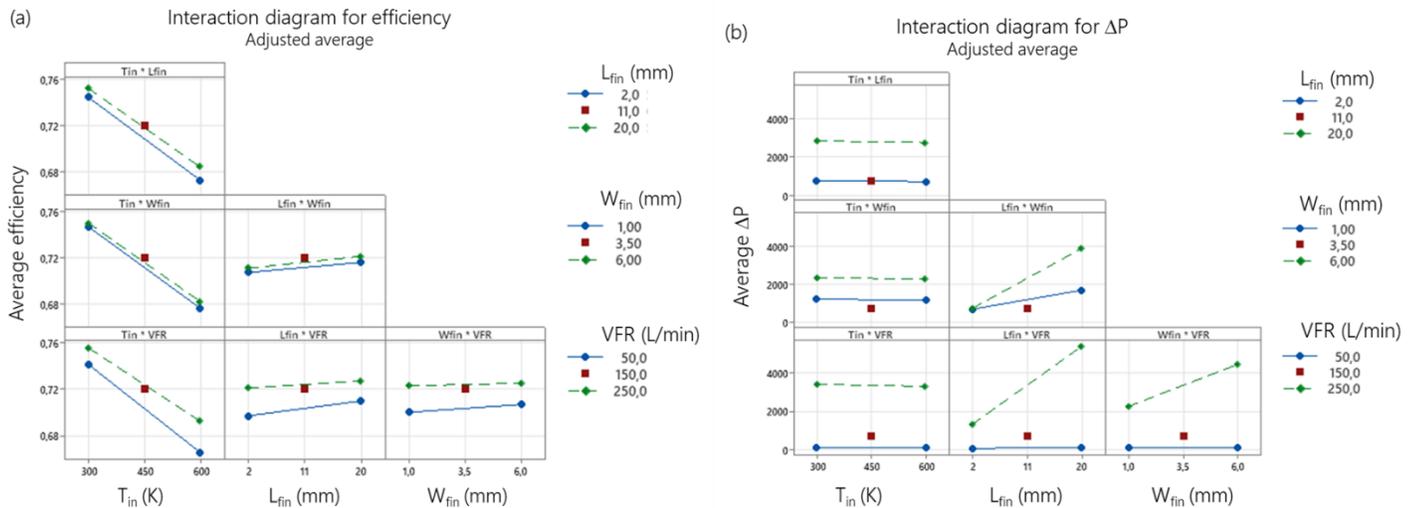
Figure 4-9 Interaction diagram for efficiency (a) and pressure drop (b)

The response optimizer identified the obtained responses (η, ΔT, ΔP and f) as constraints to figure out optimal parameters for the ideal PTC configuration. The objective is fixed by minimizing the pressure drop and friction factor and maximizing the efficiency and temperature variance while keeping the influenced factors within their tested range. The acquired finding (Table 4.4) implies a desirability score of 0.9 which confirms that the solution balances pressure drop and efficiency well. In fact, higher fin length and width (L_{fin}= 20 mm and W_{fin} =6 mm) and lower volume flow rate (VFR= 50 L/min) reduce the pressure drop (ΔP= 175.65 Pa) without sacrificing efficiency (η=0.75). These outcomes line up with prior studies, proving the accuracy of fin adjustments for enhancing the PTC efficiency.

Table 04-4 Response optimization

T_{in} (K)	L_{fin} (mm)	W_{fin} (mm)	VFR (L/min)	f	ΔP (Pa)	ΔT (K)	η	Desirability score
300	20	6	50	0.0536	174.563	23.2	0.7499	0.9024

4.5.3 Interaction Effects and Sensitivity Analysis

The ISO-surface contour plots in Figure 4-10 provide a clear view of how efficiency changes with influencing factors, focusing on the values that perform best. It appears from the distribution of diagonal bars that efficiency does not improve when each factor is adjusted separately, but rather when a common balance is found between the factors. In Figures 4-10.a, 4-10.c, and 4-10.d, the contour lines appear to diverge, meaning that the change in efficiency occurs gradually as the

values change. While in Figures 4-10.b, 4-10.e, and 4-10.f the lines are very close together, indicating a sharp and rapid change in efficiency. These observations are consistent with the results of the statistical model, especially about the interaction of variables. The optimum efficiency value given in Table 4.4, and shown in Figure 4-10, also confirms that the optimum point lies within the highest range in the contour plot.
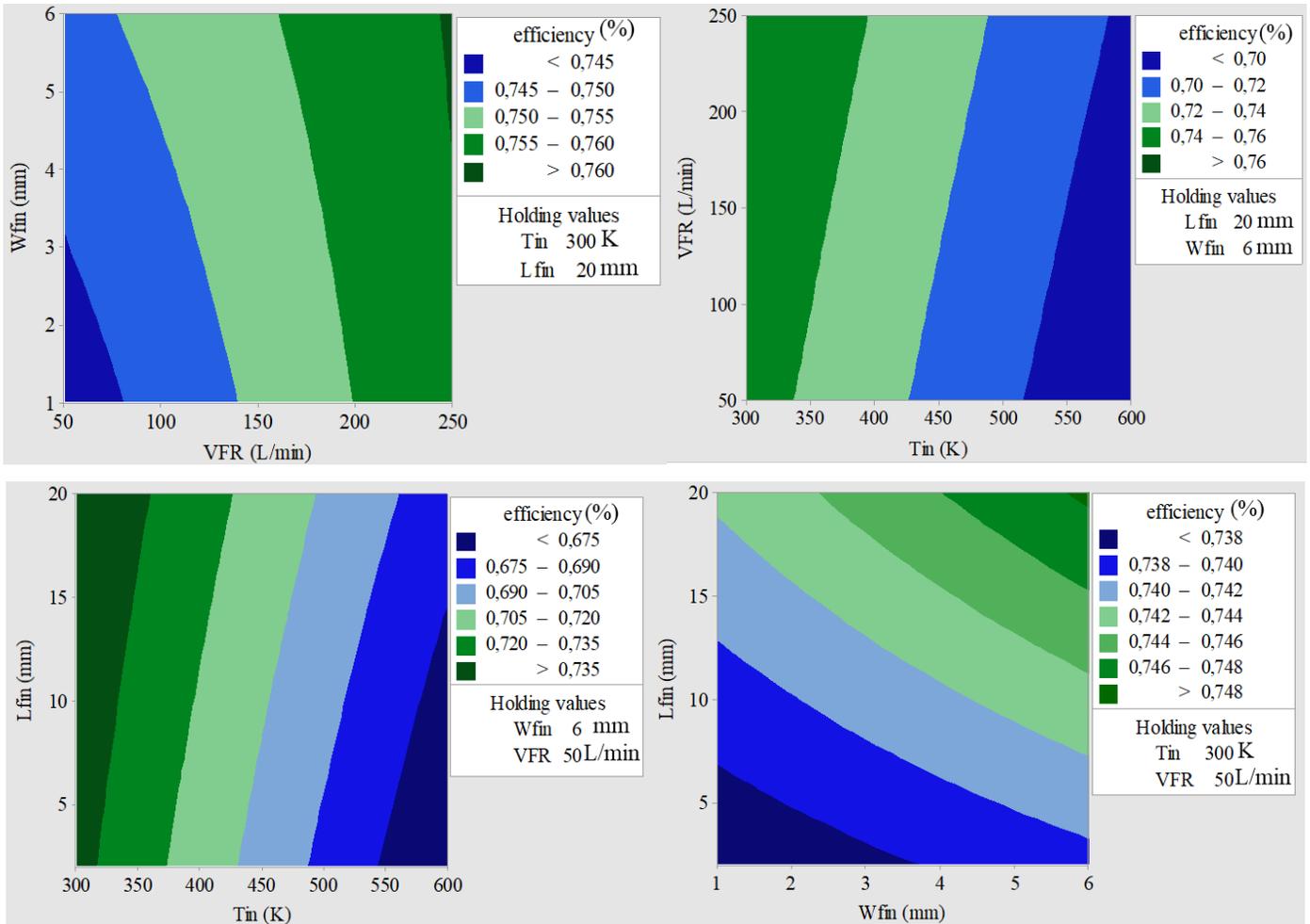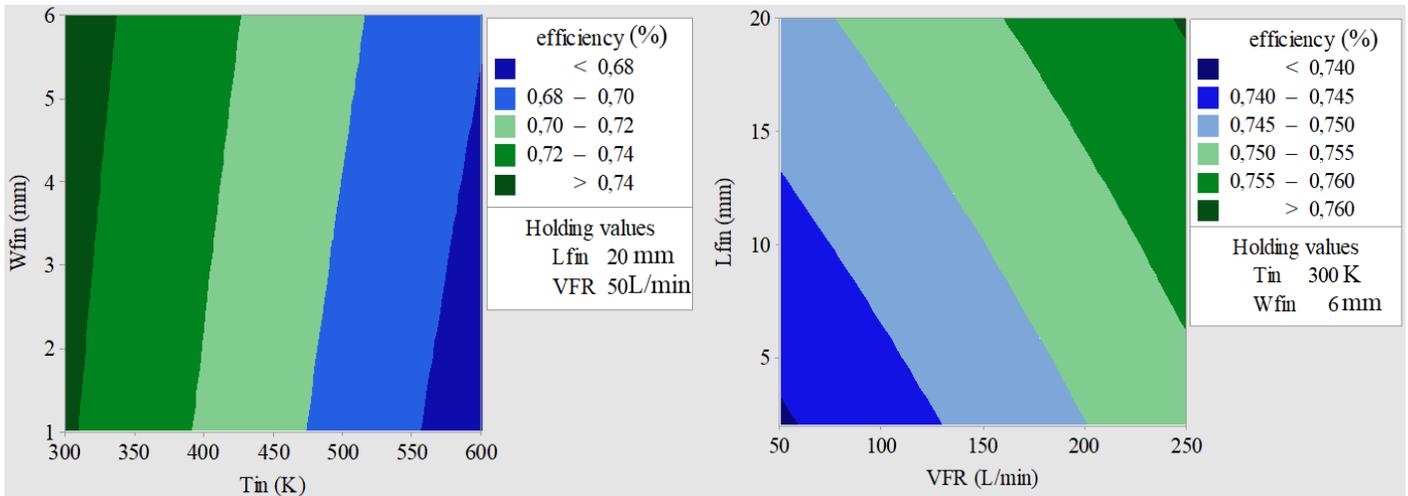
Figure 04-10 Contour plot of the efficiency for optimal factor values

Figure 4-11 shows the contour diagrams analyzing the pressure drop response across different parameter combinations. The curved contours (Figures 4-11.a and 4-11.d) indicate nonlinear quadratic effects between VFR and fin geometric parameters (L_{fin} and W_{fin}), suggesting complex interactions that require second-order terms in the model. However, Figures 4-11.c, 4-11.e and 4-11.f, show diagonal contour bands demonstrating a linear interaction between variables that necessitates inclusion of cross-terms in the regression model. Conversely, figure 4-11.b demonstrates parallel contours between the T_{in} and VFR variables, This confirms that there is no interaction between the factors. In reality, the effect of Tin on the pressure drop response is independent of the VFR variable. This visual analysis directly enhances the numerical results that appeared when adopting optimal values for the influencing factors
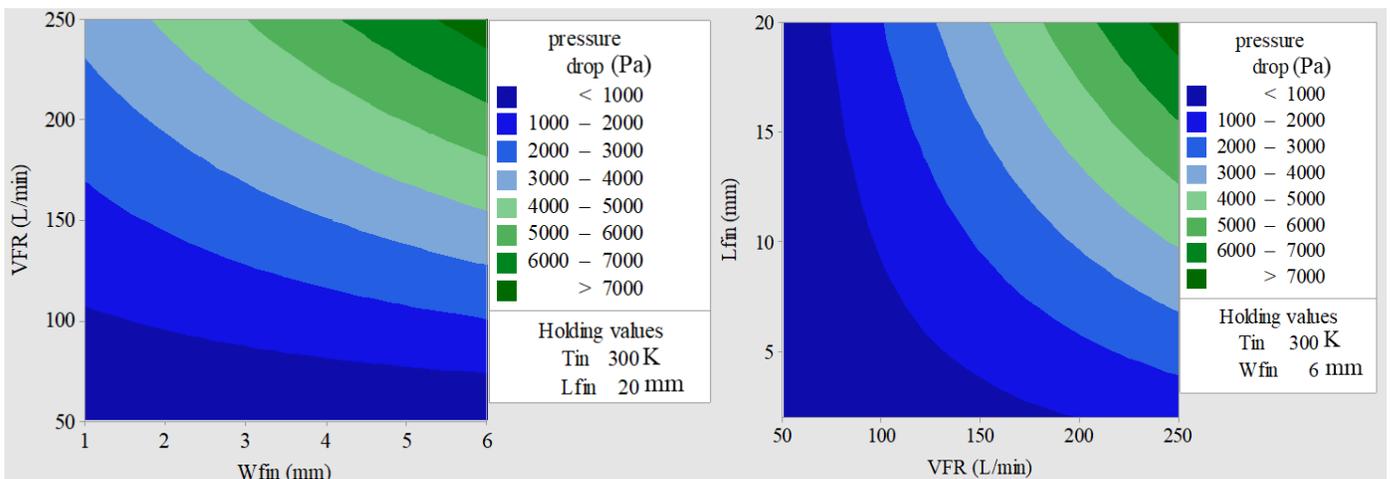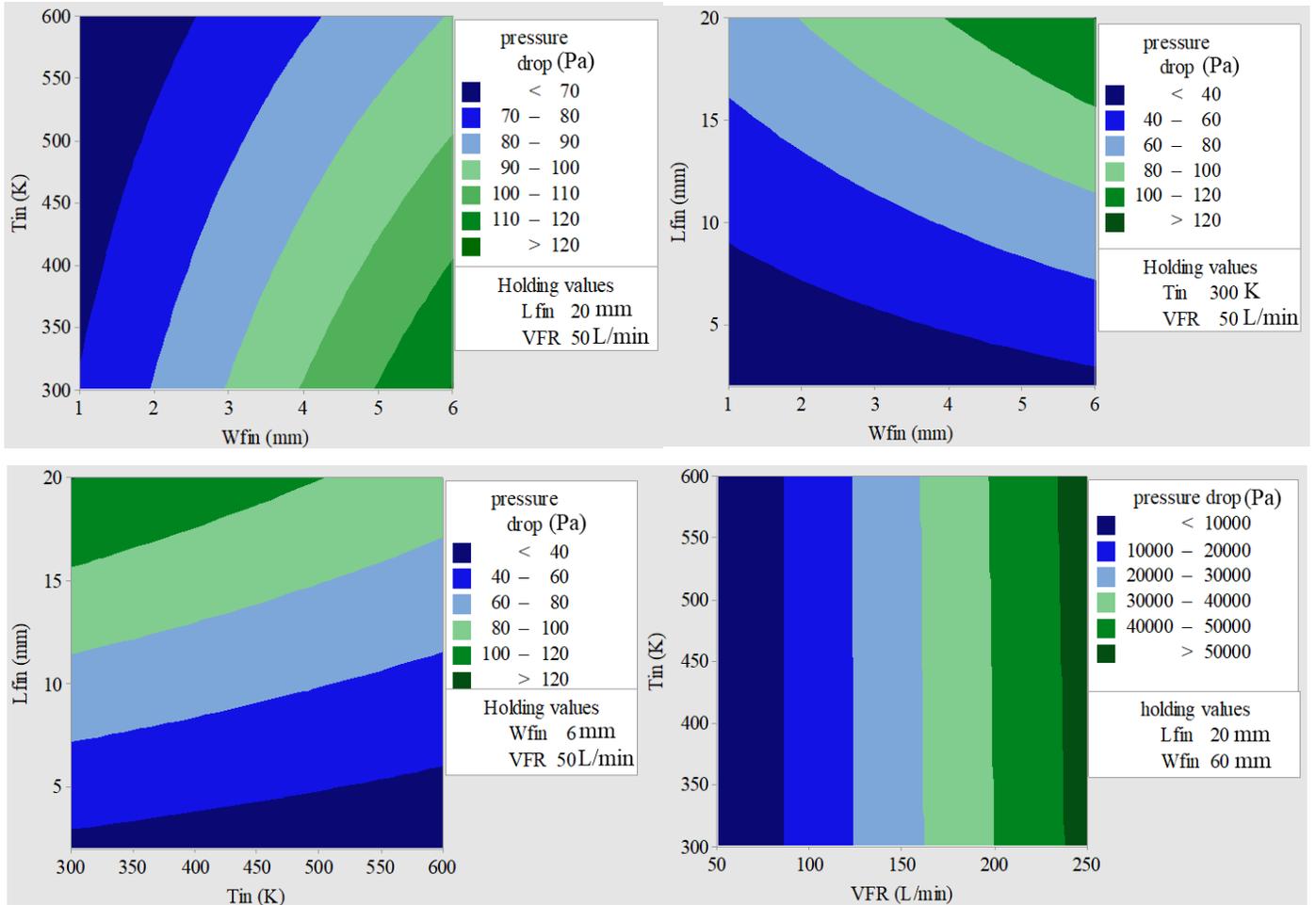
Figure 4-11 Contour plot of the pressure drop for optimal factor values

4.5.4 Discussion

Placing the fins inside the absorber tube represents a turning point in improving the efficiency of parabolic solar collector systems. In this work, the idea was redeveloped by integrating high-resolution CFD modeling with statistical design methodology for experiments. The study focused on analyzing the effect of four main factors —inlet temperature (T_{in}), volumetric flow rate (VFR), fin length (L_{fin}), and fin width (W_{fin}) — either separately or through their interaction together, with the aim of arriving at the best design that achieves the highest efficiency with the lowest possible pressure drop. The results confirmed that these four variables play a crucial influence in determining the performance of the PTC system.

- The inlet temperature of the heat transfer fluid has a crucial impact on raising the thermal efficiency, pressure drop and overall performance of PTC systems. When the temperature

is low, the HTF displays elevated fluid viscosity and density, promoting convective heat transfer. As a result, the greatest effectiveness occurs with a major temperature gradient and minimized thermal losses. Although increased density raises the pumping power, the pressure drop remains manageable due to laminar-turbulent transition.

- Volumetric flow rate is a factor influencing the thermal and hydraulic behavior of a solar collector when the tube is finned. At low flows, the flow remains laminar, which impairs heat transfer due to a thick thermal boundary layer and a low Nusselt number. Although pressure drop is very small in this range, poor thermal efficiency makes it an unsuitable option even if the required pumping capacity is small. The presence of fins helps increase fluid mixing and raise the level of turbulence, which clearly enhances heat transfer and raises the Nusselt number compared to the laminar flow state. It is true that the pressure drops increase according to the Plesius relationship, but the increase in thermal performance is greater than the cost of pumping. Thus, the effect of the VFR becomes nonlinear, and an optimal operational value appears when the flow reaches the turbulent phase.

- Volumetric flow rate is a factor influencing the thermal and hydraulic behavior of a solar collector when the tube is finned. In low VFR regime, heat transfer is limited by laminar flow conditions, resulting in a weak Nusselt number scaling and a thick thermal boundary layer that reduces the convective heat transfer coefficient. Although Darcy's law predicts a small pressure drop, a poor thermal efficiency dominates, rendering this regime undesirable even with minimal pumping power. The incorporation of fins improves fluid mixing by increasing turbulence, boosting the Nusselt number and improving heat transfer compared to laminar flow. While the pressure drop follows in accordance with the Blasius Correlation, the thermal gain outweighs pumping costs. Therefore, the PTC's effectiveness is nonlinear dependent on VFR, and an optimal operational value appears when the flow reaches the turbulent phase.

- Fin length is a key factor in determining the efficiency of finned absorber tubes. In fact, longer fins increase the heat transfer surface area, improving conduction and enhancing energy absorption. In addition, longer fins disrupt flow, increasing turbulent wake effects and pressure drop. For excessive fin length, the thermal resistance at its tip increases, so the fin's effectiveness decreases rather than improves.

- Fin width clearly affects the performance of the absorber tube, both in terms of heat transfer and flow behavior. Wider fins improve heat conduction but reduce the number of fins that can fit on the absorber tube. additionally, increased flow blockage from wider fins raises pressure drop due to greater flow restriction. in contrast, while narrow fins offer higher heat flux and reduced flow resistance, they face critical limitations risking material degradation and deformation under operational loads.

Therefore, the geometric parameters of fins must balance thermal enhancement against hydraulic losses by selecting the best fin length and width that maximize heat transfer efficiency and minimize pressure drop, maintaining structure integrity against stresses and avoiding material overuse. To ensure the accuracy of the improved results, several key parameters are calculated. Among these, particular attention is given to the aspect ratio (AR), the fin pitch ratio (λ_{fin}), the thermal enhancement ratio (TER) and the thermal performance factor (TPF). These parameters are defined and expressed, respectively, as follows:

$$AR = \frac{L_{fin}}{W_{fin}} \tag{25}$$

$$\lambda_{fin} = \frac{S_{fin}}{D_{ia}} \tag{26}$$

Where; S_{fin} is the spacing between fins.

$$TER = \frac{Q_u}{Q_{u,s}} \tag{27}$$

Where, $Q_{u,s}$ is the heat transfer flux of the smooth tube (W)

$$TPF = TER \times \left(\frac{f}{f_0}\right)^{-1/3} \tag{28}$$

Where, f0 is the friction factor of the smooth tube.

In this study, the best fin geometry parameters were defined as Lfin = 20 mm and Wfin = 6 mm. This configuration yields an AR of 3.33, indicating a balanced compromise between heat transfer enhancement and pressure drop limitations. Besides, λ_{fin} is found to be around 0.3, which effectively maximizes Nusselt's number without significantly obstructing fluid flow. These results conform well to prior studies that depict the optimal AR between 3 and 4, λ_{fin} in the range of 0.2 to 0.3 **[5],** thereby reinforcing the accuracy and reliability of the selected design parameters.

In relation to the operating factors, the selected parameters were Tin of 300 K and VFR of 50 L/min. Although these yield with their minimum tested values, the thermal enhancement coefficient (TER) showed a value of 1.15, which means an improvement of about (~15%) in heat

transfer compared to the smooth absorber tube. While this value is slightly below that reported for optimized finned tubes in previous studies **[5, 17],** the thermal performance coefficient (TPF) recorded a value of 1.16, confirming a net positive enhancement in overall thermal efficiency under the given conditions.

4.5.5   Comparison with previous studies

This study evaluates the effect of finned absorber tubes on parabolic trough collector (PTC) efficiency via CFD simulation. A parametric analysis investigates fin lengths (2–20 mm) and widths (1–6 mm) across various operational scenarios, including inlet temperature (300–600 K) and volume flow rate (50–250 L/min). A full factorial DoE methodology controls the CFD simulations results to evaluate the impacts of these parameters. The optimal fin configuration is chosen based on the two requirements: enhancing thermal efficiency and reducing pressure drop. The results indicate that a fin with a thickness of 6 mm and a length of 20 mm is the most efficient when operating the system at a flow rate of 50 l/min and an inlet temperature of 300 K. Table 4.5 shows a comparison showing the amount of improvement in thermal efficiency when using a finned absorbent tube.

Table 04-5 comparative chart of previous studies

Authors	Method	Fluid	Type of fins	Main outcomes
Fatouh et al. [24]	Numerical	Syltherm 800	Round + rectangular	The thermal enhancement index: • Increase by approximately 10.74% with a round radius. • Increase with the round edge fins length and thickness. • Increase with the inlet temperature and direct normal irradiance. • Decrease with the flow rate.
Anand et al. [27]	Numerical	Gas	Rectangular + triangular + trapezoidal + T-shaped + Y-shaped	• Increasing fin height and width increases thermal performance and pressure loss. • The optimum fin dimension of the rectangular fin is 5 mm in height and 4 mm in width.
Mohammad et al. [18]	Numerical	Water	Helical	An improvement of 23.1% in thermal performance compared to the case without fins.
Oveepsa el al. [46]	Numerical	Water + nonofluid	Helical	The maximum thermal efficiency in the case of nanofluid and water is about 78.4% and 67.7%, respectively.
Khan et al. [19]	Numerical	Al2O3 / Water	Twisted tape + Longitudinal	• The thermal efficiency of the studied cases is 72.26% for twisted tape insert, 72.10% for tube with internal fins, and 71.09% for the plain tube • The heat transfer coefficient of tested fins is greater than smooth absorber.
Gong et al. [20]	Numerical	D12 oil	Pin-fin	• The overall heat transfer performance is higher than the conventional PTR • The pressure drop increase with the number of pin fin inserted.
Bellos et al. [25]	Numerical	Syltherm 800	Rectangular	• The optimal thermal efficiency is about 68.59% • The location of the fins in the lower part of the absorber increases the thermal performance. • The location of fins in the upper part has not significant enhancement.
Badr et al. [21]	Numerical	Syltherm 800 + Al2O3	Rectangular	The finned absorber and nanofluid increase the hydrothermal performance

Munoz et al. [22]	Numerical	Oil	Helical	The efficiency increases about 3% with a 40% reduction in absorber temperature difference and an increase by 10 to 50 % in pressure drop
Abolarin et al. [33]	Experimental	Water	Twisted tapes	• The connection angle and the heat flux influence the transitional flow regime. • The increase of the heat flux enhances the heat transfer if the laminar flow regime.
Jamesahar et al. [23]	Numerical	Nanofluid	Flexible fins	• The oscillation of the fins increases the heat transfer rate • The increase of the thermal conductivity improves the heat transfer rate • The increase of the viscosity reduces the heat transfer rate
Benabderrahmane et al. [61]	Numerical	Nanofluid	Pin-fin	The overall hat transfer performance increase with 12%
Present work	Numerical	Syltherm 800	Rectangular	• The finned absorber tube enhances the thermal efficiency (74.99%). • The optimal fin configuration is about 6mm in width and 20mm in length for a 50L/min volume flow rate.

When comparing the improved configuration with the smooth tube, there is a significant increase in thermal efficiency, with the system achieving an energy gain of approximately 19.4%. This improvement can be directly reflected in reduced operational costs in the long term. In addition, the reduction in pressure drop with improved design reduces the required pumping power requirements, which means lower operating cost and higher system reliability. Overall, these results demonstrate that the proposed solar collector configuration has strong potential to make it a suitable choice for solar thermal applications in practical conditions.

4.6 Conclusion and Perspectives

This study mainly aims to understand how a finned absorber tube affects the efficiency of a PTC solar collector, using CFD models and simulations. Fins with lengths ranging from 2 to 20 mm and widths ranging from 1 to 6 mm were tested, and the simulation results were then analyzed using the experimental design method. All compositions were studied under different operating conditions, including inlet temperatures between 300 and 600 K, and flow rates from 50 to 250 l/min. Choosing the optimal fin configuration depends on achieving two main goals: increasing thermal efficiency and reducing pressure drop. Accordingly, the study concluded a set of important findings and recommendations.

- First, the CSD distribution is performed using an optical method. The results displayed a non-uniform component in a circular direction due to the concentration of the reflected solar rays.

- Second, the temperature distribution contour within the absorber tube is analyzed for all case studies. The findings demonstrated the important effects of the VFR and the fin geometries on the temperature distribution. Therefore, by applying the highest fin length and width, the hot spot localization is reduced, and the temperature remains nearly uniform.

- Third, the design of experiments is used to evaluate the best finned absorber configuration. In fact, a full factorial design is chosen with one central point added to improve model accuracy. The outcomes showed that:
  - The Pareto chart explains the key parameters affecting efficiency and pressure drop responses.
  - The un-coded regression equations estimate how factors affect the efficiency and pressure drop for the finned absorber.

- The main effect plot and interaction diagram explain the regression equation coefficients.

- Response improvement is achieved by reducing the pressure drop and friction coefficient, in parallel with increasing efficiency and increasing temperature variation. According to the optimization results, the best set of values was a fin length of 20 mm, a width of 6 mm, a flow rate of 50 L/min and an inlet temperature of 300 K.

- The ISO-surface contours of both efficiency and pressure drop are plotted for optimal factors values. The results are statistically verified by the significant interaction term in the regression model, showing the combined effect of the considered factors.

At the end of this work, a comprehensive discussion was provided to better understand the physical phenomena governing the system's behavior.

In summary, the result showed that the use of an internally finned absorber significantly enhances thermal efficiency. A fin thickness of 6 mm, a length of 20 mm, and a volumetric flow rate of 50 L/min were identified as the optimal configuration, demonstrating better heat transfer performance.

CONCLUSION AND PERSPECTIVES

Conclusion and Perspectives

In this research, we tried to understand how the performance of the receiver tube in solar parabolic collectors can be improved by incorporating modification of the internal shape of the tube. We used the longitudinal fin shape with different dimensions of fin length and thickness while incorporating nanofluid. During the research, we used cuo as nanoparticles with syltherm 800 as the base fluid, and experimented with three different concentrations, as well as a range of inlet temperatures. This diversity of variables allowed us to see the picture more clearly and know how these factors interact with each other when operating.

The results we obtained showed that improving tube performance does not depend on just one step, but rather is a combination of several factors working together. The inner fins significantly increase heat transfer, but they also increase the pressure inside the tube. The nanofluid improves thermal conductivity, but its effect depends on particle concentration and temperature. Therefore, it has become clear that achieving stable and efficient performance requires a balance between these two aspects: increasing heat on the one hand and reducing hydraulic losses on the other hand. Numerical simulation (CFD) helped us understand step by step what goes on inside a tube: how the fluid moves, where the temperature rises, and where the resistance increases. While the Experiment Design Methodology (DoE) arranged the variables for us and explained which had the greatest impact. Combining the two methods makes evaluation more accurate and realistic than just studying one factor at a time.

As a result, this research provided a clear look at how to improve future tubes in PTC systems in a practical way, based on an understanding of the interaction of internal geometry, fluid properties and operating conditions. This kind of understanding is very important now, especially with the global trend toward using clean energy systems that require higher thermal performance and lower operating energy consumption.

Based on the results, there are several steps that can be developed in future work:

1-used different nano fluid: Because we only used one type, it is useful to test other nanoparticles or hybrid nano-mixes to see if better performance can be achieved with lower losses.

2-Changing the base fluids: using more than one type of base fluids, such as water and other fluids, and studying the extent of its effect on improving the thermal performance of the system

2- Improve the design of the internal fins: Using more than one type and knowing which types can give better results or adjusting the length and thickness of the fin may give higher thermal performance without a significant increase in pressure.

3-Expand operating conditions: Such as testing higher flow rates or greater inlet temperature to see the limits of the system and how it behaves under different operating conditions.

4-Considering actual environmental conditions : Solar systems operate outdoors, so it is useful to include the influence of real conditions in the analysis, such as changes in solar radiation throughout the day, temperature differences, wind, and even dust. These factors affect the actual performance of the system and studying them brings expectations much closer to what happens on the ground rather than relying on ideal and constant conditions.

5-Evaluating real economic profitability: After the results we obtained, a future study can be conducted that includes: Cost of manufacturing fins, Nano cost, Pumping cost against the amount of heat gained which makes the research amenable to industrial use.

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