ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OVERALL EFFICIENCY ANALYSES OF THE SELECTED PVT INTEGRATED SOLAR SYSTEM APPLICATIONS

M.Sc. Thesis by

HAMZA ALI KAREEM

Department of Energy Systems Engineering

November, 2025

ANKARA

OVERALL EFFICIENCY ANALYSES OF THE SELECTED PVT INTEGRATED SOLAR SYSTEM APPLICATIONS

A Thesis Submitted to

Graduate School of Natural and Applied Sciences

Ankara Yıldırım Beyazıt University

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Energy Systems Engineering, Department of Energy Systems Engineering

by

HAMZA ALI KAREEM

November, 2025

ANKARA

M.SC. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled " **OVERALL EFFICIENCY ENALYSES OF THE SELECTED PVT INTEGRATED SOLAR SYSTEM APPLICATIONS** " completed by **HAMZA ALI KAREEM** under the supervision of **PROF. DR. BÜLENT YEŞİLATA** and we certify that, in our opinion, it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Dr. BÜLENT YEŞİLATA

Supervisor

Prof. Dr. Gökhan Sürücü

Jury Member

Doç. Dr. Furkan Soysal

Jury Member

Prof. Dr. İlyas ÇANKAYA

Director

Graduate School of Natural and Applied Sciences

ETHICAL DECLARATION

I hereby declare that, in this thesis which has been prepared in accordance with the Thesis Writing Manual of Graduate School of Natural and Applied Sciences,

- All data, information and documents are obtained in the framework of academic and ethical rules,
- All information, documents and assessments are presented in accordance with scientific ethics and morals,
- All the materials that have been utilized are fully cited and referenced,
- No change has been made on the utilized materials,
- All the works presented are original,

and in any contrary case of above statements, I accept to renounce all my legal rights.

Date: **Signature:**

Name & Surname: Hamza Ali KAREEM

ACKNOWLEDGEMENTS

As I reflect on my Master's degree in Energy Systems Engineering, I am deeply grateful for my collaboration with Professor Dr. Bulent Yesilata. His valuable advice, understanding, and encouragement, as my supervisor, were invaluable in helping me overcome obstacles and achieve academic success. I am deeply grateful for his significant contribution to my achievement.

I would like to thank my dear family: my parents, my mother, and my sister, for their unwavering support throughout my educational journey.

A special thanks to my second father, Uncle Musaria, for his support and academic guidance throughout the preparation of this research.

Thanks to Uncle Musaria's family: Suleiman, my aunt, Diana, Farah, and Fatima, for their continuous support throughout my Master's studies.

Thanks also to my colleague Ömer Önder for his advice and assistance.

Finally, to all my friends and colleagues... thank you for your support.

2025, 12, November **Hamza Ali KAREEM**

OVERALL EFFICIENCY ANALYSES OF THE SELECTED PVT INTEGRATED SOLAR SYSTEM APPLICATIONS

ABSTRACT

Renewable energy production based on photovoltaic cells is a key pillar of the modern energy market. One of the most significant limitations of this type of energy production is its low efficiency. The photovoltaic/thermal PVT system is one of the solutions to increase efficiency through a hybrid structure.

This research presents a proposal to improve heat extraction by reducing losses and enhancing electrical and thermal energy outputs. It investigates the improvement of the overall efficiency by incorporating tubing with fins on the back surface of the converter.

A detailed computational fluid dynamics (CFD) analysis was performed using ANSYS Fluent 2024 R1 software. A comparison is conducted between finned and classical smooth tube configurations under identical operating conditions.

The results obtained from the model show that the finned configuration significantly increases the Nusselt number, heat transfer coefficient, useful heat, and thermal efficiency, showing an improvement of up to 5.7% compared to the classic smooth configuration.

A simulation of the annual climate conditions in Baghdad city was also conducted, where the proposed design resulted in an overall efficiency ranging from 55% at the peak of summer to 70% in winter, with a slight change in the electrical coefficient.

The key conclusion of our research confirms that integrating helical fin tubes into solar PVT systems effectively enhances the overall energy harvesting capacity, making this approach promising for areas with high irradiance.

Keywords: PVT, helical coil, finned tubes, CFD simulation, ANSYS Fluent, heat transfer enhancement.

SEÇİLMİŞ ENTEGRE FOTOVOLTAİK/TERMAL GÜNEŞ ENERJİSİ UYGULAMALARI iÇİN TOPLAM VERİM ANALİZLERİ

ÖZ

Fotovoltaik hücrelere dayalı yenilenebilir enerji üretimi, modern enerji piyasasının temel taşlarından biridir. Bu tür enerji üretiminin en önemli sınırlamalarından biri düşük verimliliğidir. Fotovoltaik/termal PVT sistemi, hibrit bir yapı aracılığıyla verimliliği artırmanın çözümlerinden biridir.

Bu araştırma, kayıpları azaltarak ve elektrik ve termal enerji çıkışlarını iyileştirerek ısı çıkarımını iyileştirmeye yönelik bir öneri sunmaktadır. Dönüştürücünün arka yüzeyine kanatlı borular yerleştirilerek genel verimliliğin iyileştirilmesi araştırılmaktadır.

ANSYS Fluent 2024 R1 yazılımı kullanılarak ayrıntılı bir hesaplamalı akışkanlar dinamiği (HAD) analizi gerçekleştirilmiştir. Aynı çalışma koşulları altında kanatlı ve klasik düz boru konfigürasyonları arasında bir karşılaştırma yapılmıştır.

Modelden elde edilen sonuçlar, kanatlı konfigürasyonun Nusselt sayısını, ısı transfer katsayısını, faydalı ısıyı ve termal verimliliği önemli ölçüde artırdığını, klasik düz konfigürasyona kıyasla %5,7'ye kadar bir iyileşme gösterdiğini göstermektedir.

Bağdat şehrinin yıllık iklim koşullarının bir simülasyonu da gerçekleştirilmiş ve önerilen tasarım, yaz aylarında zirvede %55 ile kış aylarında elektriksel katsayıda küçük bir değişiklikle %70 arasında değişen genel bir verimlilik sağlamıştır.

Araştırmamızın önemli sonucu, helezon kanatlı boruların güneş PVT sistemlerine entegre edilmesinin genel enerji toplama kapasitesini etkili bir şekilde artırdığını ve bu yaklaşımın yüksek ışınım yoğunluğuna sahip bölgeler için umut verici olduğunu doğrulamaktadır.

Anahtar Kelimeler: PVT, helezon bobin, kanatlı borular, CFD simülasyonu, ANSYS Fluent, ısı transferi iyileştirmesi.

CONTENTS

M.Sc. THESIS EXAMINATION RESULT FORM ii
ETHICAL DECLARATION iii
ACKNOWLEDGEMENTS iv
ABSTRACT v
ÖZ vi
NOMENCLATURE ixi
LIST OF TABLES xi
LIST OF FIGURES xii

CHAPTER 1 INTRODUCTION 1
1.1 Background 1
1.2 Problem Statement 2
1.3 Research Objectives 3
1.4 Methodology Overview 3
1.5 Thesis Structure 4

CHAPTER 2 THEORETICAL BACKGROUND 5
2.1 Introduction 5
2.2 Literature Survey 5
2.3 The impact of the panel temperature on the PV efficiency 12
2.4 Overview of Photovoltaic-Thermal (PVT) Systems 14
2.4.1 System classification according to the cooling process: 14
2.4.2 General structure and operation of a PVT collector. 15
2.5 The importance of integrating thermal and electrical energy conversion. 12
2.6 Photovoltaic Principles 18
2.7 Basic operation of a solar cell 19
2.8 Fluid Flow and Heat Transfer in Tubes 19

CHAPTER 3 METHODOLOGY 21
3.1 Introduction 21
3.2 Geometric Design 21
3.3 Mesh Generation 24

3.4 Boundary Conditions 25
3.5 Physics Setup in ANSYS Fluent 26
3.6 Governing Equations & Solver Settings 26
3.7 PVT Performance Modeling 29
3.8 Simulation Scenarios: 31

CHAPTER 4 SIMULATION AND DISCUSSION 32
4.1 Effect of Fins on Flow Channels: 32
4.2 System implantation in the Baghdad region: 39

CHAPTER 5 CONCLUSIONS AND FUTURE WORK 46
5.1 Conclusions 46
5.2 Future Work 47

REFERENCES 48

CIRRICULUM VITAE 54

NOMENCLATURE

Roman Letter Symbols

AC	Alternating Current
A_{PV}	PV panel area
C_p	Specific Heat
FF	Fill Factor
$F^{\rightarrow}$	External Force Vector
HTC	Heat transfer coefficient
H	Convection heat transfer coefficient
Irr	irradiation
I_{SC}	Short Circuit Current
I	Current
K	Thermal Conductivity Coefficient
L	Pipe length
$\dot{m}$	Mass flow rate
N_u	Nusselt number
P_{sun}	Light Power
P	Pressure
Q_{useful}	Useful heat
Q	Heat Sources (solar radiation)
Re	Reynolds number
T_{in}	Inlet temperature
T_{out}	Outlet temperature
T_{Ref}	Reference Temperature
T	Temperature
V_{oc}	Open Circuit Voltage
V	Voltage
$v^{\rightarrow}$	Velocity Vector
v	Fluid velocity

Greek Letter Symbols

β	Temperature Coefficient

η	Efficiency
η_{Elec}	Electrical Efficiency
$\eta_{overall}$	Overall Efficiency
η_{Ref}	Reference Efficiency
η_{Th}	Thermal Efficiency
$\eta_{\circ}$	Panel efficiency at STC
μ	Viscosity
ρ	Density

Subscripts

CFD	Computational Fluid Dynamics
DC	Direct Current
MPP	Maximum Power Point
PCM	Phase -Change Material
PVT	Photovoltaic Thermal
PV	Photovoltaic
SHC	Solar Heating & Cooling
SH	Space Heating
STC	Standard Test Condition

LIST OF TABLES

Table 3.1 PVT used specification 24
Table 3.2 PV Layers specifications 25
Table 3.3 Boundary conditions. 26
Table 3.4 Layers' physical properties 27
Table 3.5 Materials properties 28
Table 3.6 values are used in our simulation 31
Table 3.7 Simulation scenarios 31
Table 4.1 Simulation input values 33
Table 4.2 Nusselt number for collected points 34
Table 4.3 heat transfer coefficient values 35
Table 4.4 Useful heat values 36
Table 4.5 Thermal efficiency 37
Table 4.6 Temperature outlet values 39
Table 4.7 Monthly useful heat 40
Table 4.8 Monthly electrical output power 42
Table 4.9 Monthly thermal efficiency 43
Table 4.10 Monthly electrical efficiency 44
Table 4.11 Monthly overall efficiency 45

LIST OF FIGURES

Figure 2.1 Irradiance effect on electrical efficiency 13
Figure 2.2 Panel Temperature effect on electrical efficiency 13
Figure 2.3 PVT technologies..... 14
Figure 2.4 PVT system configuration 16
Figure 2.5 PVT collector system..... 17
Figure 2.6 PV solar cell technologies 19
Figure 3.1 ANSYS Simulation steps..... 22
Figure 3.2 PVT system modeling in ANSYS 23
Figure 3.3 Solar Panel layers..... 24
Figure 3.4 Mechanical properties..... 27
Figure 3.5 Residuals of Governing Equations in ANASYS 29
Figure 4.1 Nusselt number vs PV temperature 33
Figure 4.2 Heat transfer coefficient (HTC) vs PV temperature 34
Figure 4.3 Useful heat vs PV temperature 36
Figure 4.4 Thermal efficiency vs PV temperature 37
Figure 4.5 Temperature outlet vs Fluid velocity..... 38
Figure 4.6 Average hourly irradiation in Baghdad city 39
Figure 4.7 Useful heat vs Average radiation..... 40
Figure 4.8 Electrical power output vs Average radiation..... 41
Figure 4.9 Thermal efficiency vs Average radiation..... 43
Figure 4.10 Electrical efficiency vs Average radiation..... 44
Figure 4.11 Overall efficiency vs Average radiation 45

CHAPTER 1

INTRODUCTION

1.1. Background

Traditional fossil fuels result in many issues, like energy shortages and environmental harm. This stands out as a challenge that humanity must face today. Renewable energy emerges as a solution offering advantages such as availability and eco-friendliness. Solar power shines as an energy source, valued for its widespread accessibility, safety features, and diverse origins. Over recent years, the global capacity expansion underscores its growing utilization worldwide [1].

Photovoltaic (PV) panels are characterized by their low efficiency, which hovers around 20% where most of the received irradiation is not turned into electricity [2,3]. Part of the energy losses is converted into heat, leading to PV warming up and a further decrease in PV efficiency and lifespan. Particularly in regions with intense sunlight and high temperatures, such as tropical, desert, or equatorial areas, PV cells often experience reduced efficiency and lifespan. Conversely, in temperate regions during summer seasons, efficiency loss is typically more pronounced. This is because the PV output energy is inversely proportional to the operating temperature increase. The use of a thermal collector with the basic PV system results in a hybrid PV-thermal (PVT), that takes advantage of both converted electricity and accumulated heat in the system. Heat is reduced through the cooling system to increase efficiency while at the same time raising the temperature of a fluid [4]. A solar thermal collector is a device designed to convert solar radiation energy into heat. The accumulated thermal energy is transferred through a flowing fluid and utilized for various specific purposes [5]. Integrating thermal and electricity cogeneration into PV thermal collectors proves to be an effective method for mitigating losses from collected solar radiation by dissipating heat and controlling the temperature of the PV module [6]. The temperature can be lowered by extracting heat through a heat transfer process. Therefore, the efficiency of the hybrid PVT collector is increased. The solar collector

has contributed through modifications in design, insulating materials, process improvement, and advanced working fluids. Flat panel solar collectors are simpler, cost-effective, and popular [7]. Active solar technologies include PV systems, concentrated solar power, and solar water heating to harness. Use solar energy to reduce the grid-supplied energy to residential and commercial buildings. Solar Heating & Cooling (SHC) technologies collect thermal energy from the sun and use this heat to provide hot water, space heating, cooling, and pool heating for residential, commercial, and industrial applications. These technologies displace the need for electricity or natural gas.

Research on hybrid PVT started in the 70s of the last centuries [4]. PVT solar systems convert solar radiation into electrical energy and heat energy. The solar cells convert the solar radiation into electricity, and the solar thermal collector absorbs excess energy and heats the cooling fluids. Thus, cools the solar cells and extracts the remaining heat from the PV cells. Therefore, PV/T is more efficient than solar PV [8].

1.2. Problem Statement

The energy conversion efficiency of the materials used in PV modules is very low. it is important to optimize the generation of power by using the maximum energy drawn from the system. The PVT system includes a PV panel and a solar collector equipped with a cooling system. The cooling is performed through the passage of a fluid through tubes fixed on the collector. The heat exchange between the tubes and the collector body decreases the system temperature and then increases the overall efficiency.

This work aims to analyze and optimize the heat exchange and fluid flow using ANSYS simulation software. Tubing with fins is used as an improvement of the classical tube with water as fluid. The system efficiency is expected to be increased by increasing the effective area for heat exchange. This study will address the numerical representation of fluid motion, heat transfer characteristics, and optimal flow operating conditions to maximize the solar collector efficiency while ensuring moderate resistance to fluid flow.

1.3. Research Objectives

The main objective of this research is to evaluate the steady-state thermal and flow behavior of a fin-tube PVT collector using ANSYS software. This research aims to achieve the best possible heat transfer efficiency and maximize solar energy production while maintaining acceptable fluid flow resistance. This objective is achieved through many operations as:

- Numerical analysis of a PVT collector with normal and finned tubes using ANSYS simulation.
- Evaluate the effect of fins on the thermal performance of the fluid flowing inside the tubes, to enhance the achievement of better heat transfer from the absorber surface.
- Evaluate Nusselt number, heat output, efficiency, and heat transfer coefficient of finned tubes to characterize the optimum operating conditions.
- Determine the optimal configuration that balances heat extraction development and fluid flow resistance, thus improving thermal and electrical efficiency.

Performance of the finned PVT system compared to its conventional smooth counterpart under similar boundary conditions

1.4. Methodology Overview

This analysis applies a numerical simulation approach to characterize the thermal and fluid flow performance of a PVT collector containing finned tubes. The goal is to enhance heat transfer efficiency while maintaining satisfactory flow resistance. The simulation is performed using ANSYS Fluent, a powerful Computational Fluid Dynamics (CFD) tool. This methodology optimizes a three-dimensional geometric model representing the main components of a PVT system, including the absorber plate, glass cover, and finned tubes. It focuses on fin design, which potentially increases the heat exchange surface area and improves thermal performance. The mass, momentum, and energy equations are used at steady-state conditions. The results

are then discussed to analyze the temperature distributions, velocity patterns, and heat transfer coefficients. These variables are evaluated to review the feasibility of fin design in developing a PVT collector system for the application of numerical simulation techniques.

1.5. Thesis Structure

This thesis includes five chapters, which are:

- Chapter 1: Presents an overview of renewable energy with a special focus on solar. A short literature survey about some important works in the field is also presented. The problem statement, research objective, and methodology are also outlined.

- Chapter 2: Gives a Clarification about the basic structure of the PVT system, including panels, collectors, tubing, fluid, and weather effects.

- Chapter 3: Explains in detail the methodology followed in this research.

- Chapter 4: The simulation results and a discussion are shown in this part. All scenarios and case studies are explained, and input data is presented.

- Chapter 5: concludes the thesis and proposes some future research ideas.

CHAPTER 2

THEORETICAL BACKGROUND

2.1. Introduction

Renewable energy technology that harnesses sunlight to generate heat is one of the most appealing solutions. The hybrid PVT systems, using PV panels as electricity and heat-generating elements, represent a very promising technology for the combined production of electric and thermal power [9]. PVT collectors combine the generation of solar electricity and heat in a single component and thus achieve a higher overall efficiency and better utilization of the solar spectrum than conventional PV modules.

2.2. Literature Survey

An increased penetration of renewable energy into the energy infrastructure can play a central role in shifting the use of fossil fuels to cleaner energy. In the recent literature, many papers have been published about the design and improvement of PVT systems. Efficiency improvement is the prominent objective of most of the published papers.

In [10], a modelling methodology is developed to investigate the techno-economic performance of solar combined cooling, heating, and power systems based on hybrid PVT collectors. While many designs exist for both active and passive solar heating, advances in active solar technologies are needed for smaller, simpler, cost-effective systems, with improved maintenance and ease of operation. The University Campus of Bari is selected as a case study to demonstrate how the methodology can be used to analyze the suitability and value of the proposed systems when providing Space Heating (SH), cooling, and electricity to the Campus buildings. Results from this research are very promising.

Heating, ventilation, and air-conditioning are parts of major energy consumers in a modern building. Conventional heating and cooling systems contribute to carbon dioxide emissions, as well as to the security of the energy supply. A review of the passive solar technologies for space heating and cooling is presented in [11]. The

reviews are discussed according to the working mechanisms, i.e., buoyancy and evaporative effects. The advantages, limitations, and challenges of the technologies have been highlighted, and the future research needs in these areas have also been suggested.

A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications is depicted in [12]. The proposal includes various approaches to implement thermoelectric cooling and heating power generators to augment the efficiency of solar energy systems. In thermoelectric heating applications, the heat generated by the hot side of the thermoelectric module is harnessed to elevate the temperature of the solar working fluid, as seen in applications like water desalination systems, water heaters, and air heaters. Conversely, in electrolytic cooling, the cold side of the unit assumes a supplementary or primary role in reducing temperatures. This is particularly beneficial for applications such as cooling photovoltaic panels and serving as a condensing area for desalination units. The integration of thermoelectric technology thus presents a promising avenue for advancing the capabilities of solar energy systems across various domains.

The solar energy spectrum absorbed and converted by PV modules is mainly located in the high-frequency band (380–1200 nm). Other bands fail to generate electricity but can be converted to heat. Spectral beam splitting utilization is a potential technology to improve the efficiency of solar energy utilization, as mentioned by [2]. In this article, a novel combined cooling, heating, and power system with solar energy spectral beam splitting is developed to match the energy grade and the operating characteristics of refrigeration cycles. The total energy utilization and converted generation efficiency of the novel system can reach 82.7 % and 44.9 %, respectively, which is a remarkable improvement from 30.7 % of the conventional single photovoltaic system.

A new PVT collector is proposed based on assembling successive flat heat sinks and winding copper tubes in a closed container filled with paraffin wax in [13]. The proposed model is experimentally tested in real weather conditions using various fluids as a cooling medium. A comparison with a system without a cooling process proves

that the proposed model accomplishes a better temperature decrease and improved efficiency.

Various researchers are using simulation programs to conduct their research on the PVT system evaluation and improvement. These simulation tools are proven to be efficient, reliable, cost-effective, and yield accurate results.

MATLAB model is used to develop a mathematical model, and evaluate the performance of a PVT system in [14]. The parameters are analyzed to provide an efficient and reliable system based on the PV part. The mathematical model is used to evaluate the performance of the electrical and thermal parts of the hybrid PVT system. The maximum power point of the electrical part is analyzed as part of the overall PVT efficiency evaluation.

[15] uses TRNSYS software to analyze an air-type, curved-fin PVT heat exchanger, which is confirmed by experimental tests. TRANSYS is an efficient validation tool for new energy concepts used for modeling and simulation. The thermal efficiency is improved by using curved baffles, with results indicating that the effective design achieved a thermal efficiency of 37.1% and an electrical efficiency of 6.4%.

Energy Plus software, a free and open-source tool used for cooling and heating load analysis, is used in [16]. In this work, an experimental/ numerical model is developed to study the thermal performance of two solar collector types. Energy Plus is used for the numerical analysis to extend the results collected from the experimental model. Experimental results are collected for one cloudy-sky day, while numerical analysis shows results for a wide range of periods that confirm the data collected from the experimental part.

The thermal efficiency of PVT collectors is evaluated using the Polysun simulation [17]. The collector is used as a source for a heat pump for a house located in Denmark. The analysis shows a negligible effect on the system performance due to the variable optical efficiency of the thermal characteristic for one year, while the heat loss coefficient has a greater effect on the PV panel. A large heat coefficient in summer decreases the PV temperature and then improves the electricity efficiency. ANSYS is

one of the most important and widely used simulation programs to evaluate PVT efficiency. We found that it has been used in most of the scientific research related to this matter, which makes it our first choice for the purpose of completing our research.

In [18], the problem of the temperature distribution in a PVT system is investigated using ANSYS software. A PVT collector with a flat panel cooled with water is studied based on a three-dimensional model using the finite element numerical method. The accuracy of the simulation results has been validated by experimental data. The effects of tube spacing, flow velocity, and tube arrangement on the temperature distribution are evaluated. The tubing spacing is revealed to be the most impacting factor. Reducing the tube interspacing will increase the temperature uniformity. Absorber materials with better thermal properties have less effect by a partial improvement of the temperature distribution. The change in the inlet fluid velocity has a marginal effect on the temperature distribution.

[19] performed a numerical evaluation of the performance of a glass-based PVT system integrated with a phase-change material (GPVT/PCM) employing ANSYS Fluent 18.2 software. Validation of the simulation results is accomplished via comparison with available data. The results demonstrated that a higher PCM volume fraction reduces the module temperature and boosts its electrical efficiency, while lowering its thermal efficiency.

An analysis was conducted to examine the performance of an air-cooled thermoelectric collector using ANSYS Fluent 19.1 software [20]. The simulated program is validated using available data from the literature. The analysis focused on the effect of airflow rate and tube depth on thermal and electrical efficiency. The results indicated that reducing the tube depth improves thermal efficiency without significantly affecting electrical efficiency. This also leads to increased airflow rate, resulting in an enhancement of the thermal efficiency with a slight effect on electrical efficiency.

The ANSYS Fluent 18.2 simulation tool is used in [21] to evaluate the performance improvement using various cooling fluids in a PVT system. These fluids are mono and hybrid nano-fluids, compared to normal water. The numerical analysis uses a range of fluid inlet velocities from 0.02 to 0.08 m/s. The results indicate that increasing the fluid

velocity positively affects the thermal efficiency; however, it has little effect on the electrical efficiency, with a noticeable increase in the pressure drop. The efficiency improvement gradually goes through a limit after 0.06 m/s velocity, reaching a stable limit. It has been demonstrated that for a Volume concentration of nanoparticles of 2%, the hybrid nano-fluid shows a maximum improvement in the thermal and electrical efficiency of 5.4% and 2.14% compared to water. At the same time, it is 3.33% and 1.32% of the mono-nanofluid.

The PVT system suffers from a decrease in efficiency due to the high temperatures resulting from exposure to sunlight. Therefore, applying an effective cooling mechanism is important to maintain a good performance of the system by regulating its temperature. [22] presented a method based on a reversed circular flow jet impingement, designed to regulate the temperature of a PVT solar collector. The energy analysis of this method is evaluated through simulation using CFD in an indoor experiment with solar radiation of 700 and 900 W/m2 with a flow rate ranging from 0.01 to 0.14 kg/s. The results showed that the highest photovoltaic efficiency obtained in this simulation is 11.09%, while the highest thermal efficiency is 63.2%. Experimental results for efficiencies are slightly less than the results obtained using simulation.

[23] compares efficiency results from experimental and CFD simulation models for a new PVT system based on water as a cooling fluid. The analysis is based on the modification of the inlet water temperature to evaluate the thermal-electrical efficiency. The cooling fluid flow is considered constant during the experiment, and an irradiance of 700 W/m^2 is used. The testing process is carried out using a set of four inlet temperatures: 28, 38, 48, and 58 ^oC with a constant average air velocity of 3 m/s. Experimental results showed an electrical efficiency of 16.74% without active cooling, while the total thermal/electrical efficiency has a peak of input peaked at 86.67% using a water inlet temperature of 28°C. This efficiency drops to 53.92% if the inlet temperature is 58°C. Analysis of the instantaneous thermal efficiency curve of the system indicates that heat transfer to the photovoltaic cells begins when the standard temperature difference exceeds 6.153 kW. Dynamic simulations also revealed an

irregular temperature gradient across the cells, which determines an efficiency loss of 1.17% for every 1°C increase in cell temperature.

A CFD computation model is developed in [24] to investigate the PV thermal absorber designs. A new design of absorber based on spiral circular and spiral rectangular shapes with water as a heat transfer medium is proposed. A comparison of the performance with a classical PV system without an absorber is conducted. The effect of solar radiation, absorption geometry, water flow pattern, and rate on properties such as solar panel temperature, outlet water temperature, electrical and thermal performance, and overall performance of the solar power system is the main objective of this study. Tests are performed under constant inlet fluid temperature and variable water flow rate, and radiation. The results showed that water cooling improves the electrical efficiency by reducing the temperature of the PV system. It was also shown that the design of the rectangular spiral electrical absorber performs better in terms of electrical and thermal performance than the spiral circular design.

The use of photovoltaic thermal energy systems contributes to reducing the temperature of the electrical power units and collects thermal energy at the same time, thus resulting in raising the efficiency of the system. To explore the possibility of using a Phase Change Material (PCM) to store the thermal energy effectively and maintain a uniform temperature distribution on the surface of the electrical unit, a study was conducted based on numerical analysis in [25]. The study focuses on changing the position of the water pipes within the system. The results showed that the use of a copper porous medium reduces the temperature of the PV unit significantly while maintaining high efficiency. The peak efficiency reached about 19% with the porous medium compared to 17% in the case without it. This study concluded that the optimal position of the water pipe is in the middle or at the highest point inside the container to maximize the thermal energy with the least decrease in electrical efficiency. However, using a porous medium, it is electrically recommended to place the water pipe in the middle because there is a cold area around it.

The CFD solver ANSYS-FLUENT is used in most of the research as a mathematical simulation to evaluate the PVT system performances, as in [26,27, 28,29,30, 31].

In [26], a numerical analysis is conducted to evaluate the effects of fins on PVT performances. Several parameters and operational weather conditions are under consideration. Research results show that the air velocity and channel dimensions are the most impacting parameters on the PVT efficiency. Best efficiency is obtained using narrow channel geometries, regardless of the operating conditions or weather data considered. A collector length of 1.5 m, with 1 cm of height and an air velocity of 2.3 m/s, presents the optimal conditions. Also, the addition of fins improves the total PVT efficiency by up to 19%, while it does not affect the outlet air Temperature.

The analysis of PV system efficiency in high temperature conditions is investigated in [27]. A hybrid cooling system is proposed using a heat collector. Parameters for this collector are under investigation to improve system efficiency. Parameters include the collector design, fluid flow rate, and the concentration of the nanofluids. Results confirmed that the collector with fins shows better performance. A maximum electrical efficiency of 11.7% is achieved with such a collector and a water/nanofluid with a concentration of 1% at a flow rate of 0.09 kg/s.

Built-in corrugated channels, a super-thin absorber, are simulated to identify factors affecting PVT efficiency. The effect of the corrugation number, the corrugation area, and the flow channel width on the water outlet temperature and heat collection is investigated in [28]. The simulation results confirmed the experimental results in that they resulted from a decrease in the outlet temperature in the case of increasing the water inlet velocity. It is also found that the corrugation area and the channel width affect the outlet temperature of the PVT collector plate. When reducing the area of the channel of the absorber unit from 4 to 3 mm, the outlet temperature ranges between 298 and 302 K, and the heat collection ranges between 16.2 and 51.4 MJ per hour.

Cooling PV panels is one of the most important objectives to increase the system's performance. In [29], two models (M-C and M-S) are proposed based on the open-flow flat collector for a better cooling process. Simulation using ANSYS FLUENT 17.0 is conducted, where results showed that the fins in the open-flow collector helped the system enhance its performance in both models. An innovative PVT system is proposed in [30] using V-shaped fins to increase the cooling process. Cooling and heat dissipation are improved by the use of this fin type reflects better PV temperature. The

proposed system performance is evaluated by comparing results with three systems: perforated straight fins, a channel-box design, and a standard PV system without cooling. It is found that there is a 31.27 % reduction in solar cell temperature with the V-shaped fins, surpassing the 19.93 % reduction by straight fins and 17.57 % by the channel box. This reduction is positively impacting electrical efficiency. The system demonstrated performance under various temperatures, with V-shaped fins increasing 20–30 % over perforated straight fins and 30–40 % over channel boxes in energy and exergy outputs.

Using fins for a better cooling process has become a popular solution for its improved heat transfer properties. Simulation using ANSYS is a good tool for system performance evaluation due to the high number of fin parameters. A 3-dimensional numerical model of a PVT system containing an inner finned tube is developed in [31]. The Taguchi method is used to analyze the effects of inner fin width, number of cross-sections, height, and number of intervals on the performance of the PVT system. Results show that the height and number of inner fins have a significant effect on system performance.

2.3. The impact of the panel temperature on the PV efficiency

The output power of the photovoltaic panel is significantly influenced by both solar radiation and the panel's temperature. This effect is characterized by a non-linear behavior that causes a sharp change in the harvested power [3,32]. Solar radiation represents the energy received by the panel, and thus, an increase in solar radiation logically causes an increase in the harvested power, as shown in Figure 2.1. On the other hand, if the radiation is constant, a change in temperature results in a change in the output power of the PV panel with an inverse relationship. Figure 2.2 shows that by raising the panel temperature, the harvested energy is decreased by decreasing the maximum power point (MPP). This proves the negative effect of the temperature on the PV system's electrical efficiency. Thus, we see that the output power is inversely proportional to the temperature of the panel, and thus we are required to try to lower the temperature of the panel to obtain a higher efficiency for the system [33].

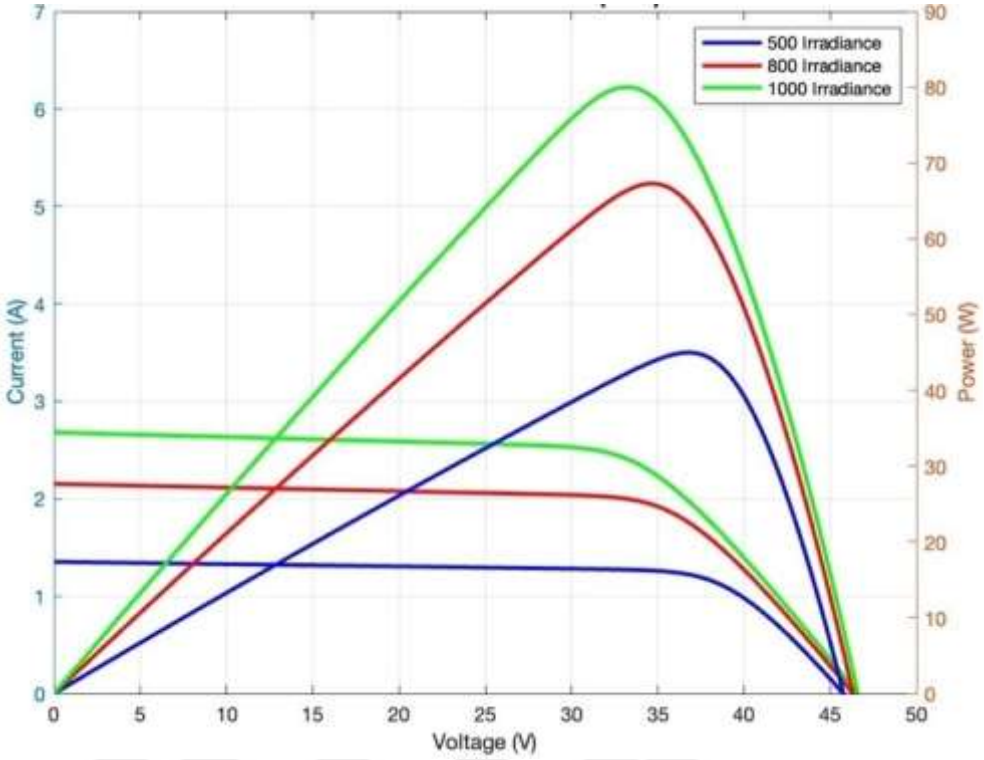


Figure 2.1 Irradiance effect on electrical efficiency

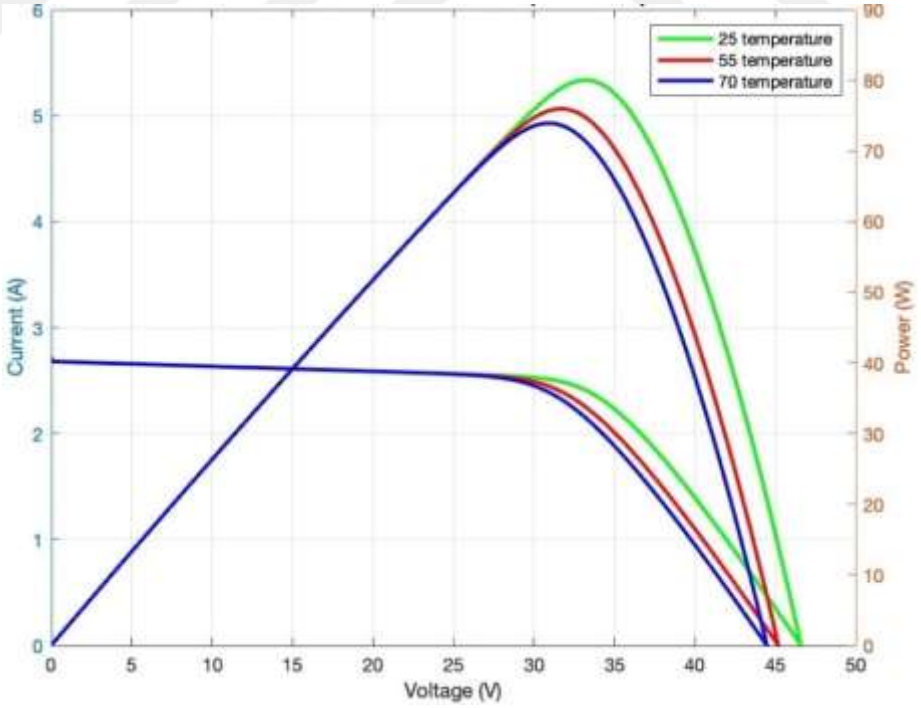


Figure 2.2 Panel Temperature effect on electrical efficiency

2.4. Overview of Photovoltaic-Thermal (PVT) Systems

2.4.1. System classification according to the cooling process

Within the framework of solar panel cooling methodologies, multiple approaches are executed with various materials to boost thermal control. Figure 2-3 shows a classification of cooling systems according to the primary materials applied in these applications. It also explains various methods, including PCMs, heat sinks, water tubes, and alternative systems employed to control thermal energy in photovoltaic systems. Each class illustrates diverse techniques for developing energy utilization and improving the cooling efficiency of solar panels [34].

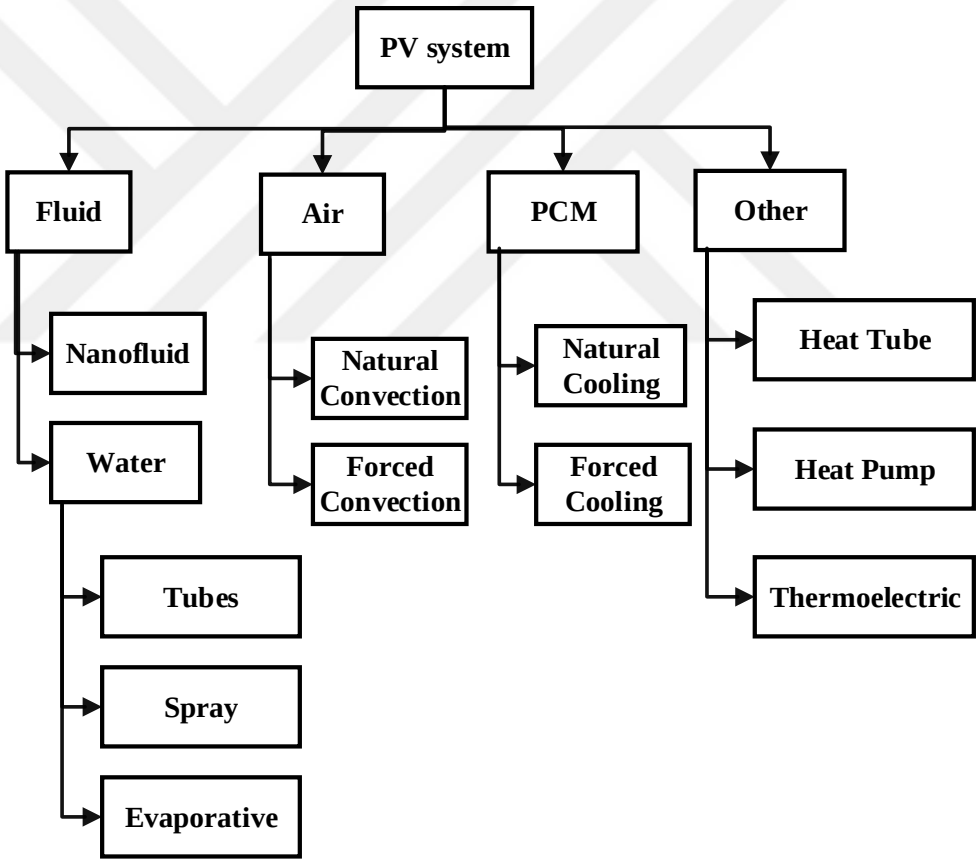


Figure 2.1 PVT technologies

The water-cooling techniques have developed as essential solutions for improving the efficiency and lifetime of photovoltaic systems, delivering a powerful tool for resisting the negative impacts of high service temperatures on PV panels. Water cooling

methods, involving water cooling tubes, evaporation, water cooling channels, and water nano cooling, have acquired important attention owing to their capacity to sustain optimal performance conditions for PV collections [34].

The air-based cooling, whether using natural convection or compulsory convection, performs a crucial task in temperature management of photovoltaic systems. These cooling strategies are necessary for maintaining ideal controlling conditions and play a key role in lowering the controlling temperature of PV modules, as a result, increasing their efficiency and total energy production.

PCMs are compounds capable of changing their physical state (liquid or solid). This process results in the absorption and release of latent heat energy as a result of the transition from one phase to another over a specific temperature range [35] There are other ways to cool solar panels, such as heat pipes, heat pumps, electric heat, etc.

2.4.2. General structure and operation of a PVT collector

A PVT collector system can be generally described as an open-air collector, a cylindrical storage tank, a forced water circulation loop, and a pump, as shown in Figure 2.4. The collector is connected to the lower part of the tank, while hot water circulates from it in the upper part. Thermal stratification in the tank occurs due to the lower density of the hot water, which enhances thermal efficiency and lowers the temperature of the photovoltaic cells [9]. The PVT system used in this research consists of a highly efficient monocrystalline solar panel (up to 20-22%) and a solar collector coated with an ETFE layer to concentrate solar radiation onto the panel, prevent dust from passing through, and reduce convective heat loss. Behind the solar panel is a copper absorber plate, which is highly efficient at absorbing heat from the panel.

This plate forms the upper portion of the collector. Four copper tubes transport the fluid (water) along the collector to ensure optimal heat exchange. On the upper surface of the tubes are copper fins, totaling 172 fins evenly distributed across the tubes. Each tube contains 43 fins, each 3 mm thick, with a spacing of approximately 27.88 cm between each fin. The bottom and sides of the solar collector are supported by plywood

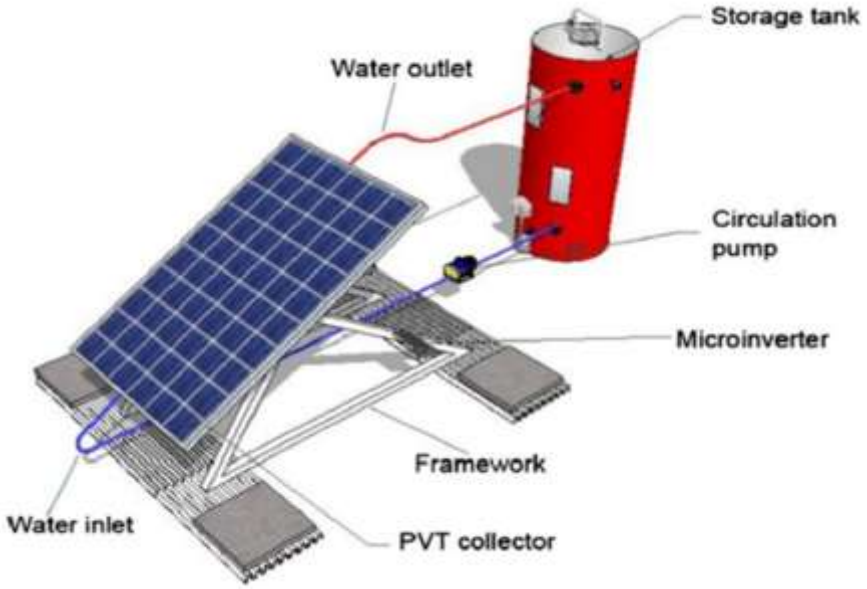


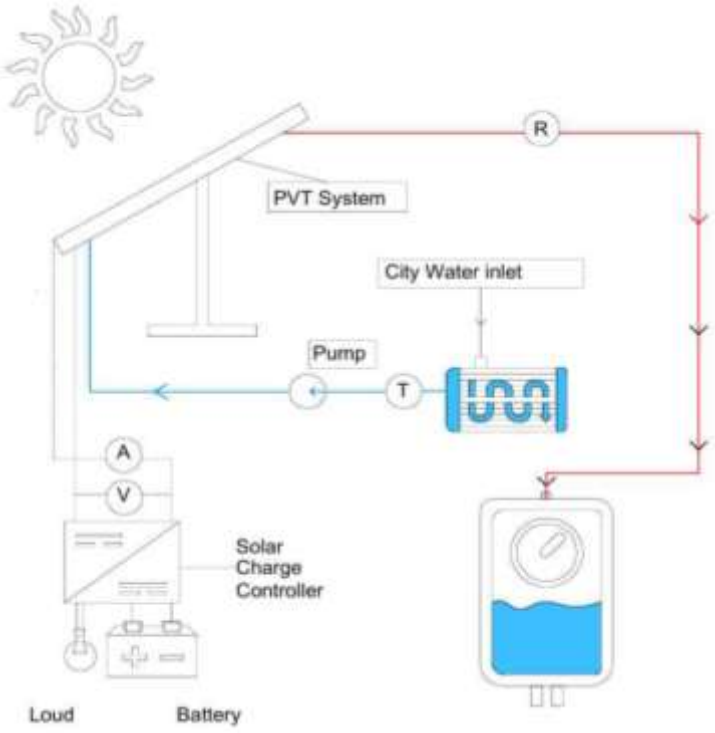
Figure 2.2 PVT system configuration

to provide support and good thermal insulation. Pump: Transports water from the city water inlet to the solar collector. Hot water storage tank: Collects hot water from the solar collector and stores it for other uses. A thermometer is also used to monitor the tank temperature.

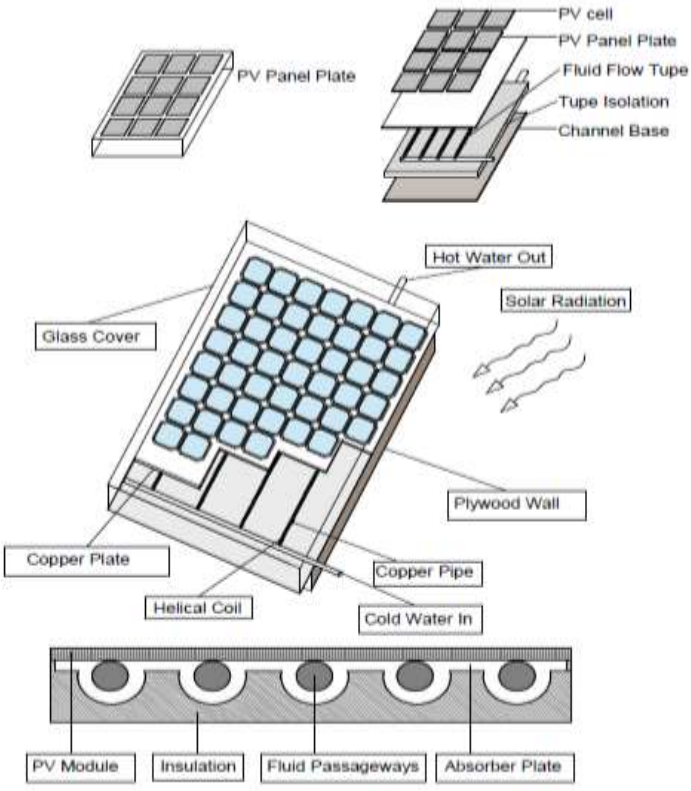
Solar charge controller (inverter): This unit converts the direct current (DC) electrical power generated by the solar panels into alternating current (AC) electrical power for the load. It also protects the battery from unstable electricity, which can affect its lifespan. Additionally, it includes a control panel that displays the battery charge level, as shown in Figure 2.5.

2.5. The importance of integrating thermal and electrical energy conversion

PVT systems constitute a major advancement in solar energy systems, utilizing solar energy to create electricity and heat in a single model. This integration enhances energy efficiency and minimizes waste relative to utilizing split systems. By adding a thermal collector behind the solar cells, this lost heat can be retrieved and applied for



(a) PVT collector system cycle



(b) PVT collector parts

Figure 2.3 PVT collector system

applications like water heating or space heating, climbing total system efficiency to over 60-70% in a few cases [36].

Furthermore, integrated energy extraction enhances land-use efficiency, generating solar photovoltaic systems appropriate for metropolitan applications with limited space. The cogeneration capability of solar photovoltaic systems assists in the improvement of net-zero energy buildings and reduces carbon emissions in the energy industry [37].

2.6. Photovoltaic Principles

There are several types of photovoltaic panels, each with different characteristics depending on the generation they are manufactured. Three generations can be distinguished as shown in Figure 2.6 [38]. The development of PV systems started with monocrystalline silicon material as the first generation. Its use in photovoltaic cells has increased due to its abundance and ease of production. It is a sustainable, non-toxic element with a band gap of approximately 1.12 eV, making it close to the solar spectrum. Flexible silicon is ideal for microelectronic fusion applications, which will be converted into transistors and integrated circuits in photovoltaic cells. It represents approximately 90% of global market production. Thin-film cells are the second generation of silicon-based photovoltaic cells. The thin films of semiconductor materials are approximately 2 micrometers thick. These cells operate efficiently in indirect light thanks to their bandgap, which ranges between 1.5 and 1.8 eV.

These thin-film photovoltaic cells are more flexible due to their lightweight and ease of installation compared to silicon cells. They are also less expensive, depending on the materials used. Their lifespan is approximately 25 years. Emerging technologies are designed for renewable energy and represent a new generation of solar cells, featuring materials and technologies that enhance solar energy conversion efficiency. Several technologies are available, for example, organic solar cells, which are less expensive than inorganic cells such as silicon; dye-coated cells, combining organic and inorganic components; and perovskite cells, which consist of metal-organic semiconductors of triacyl octyl.

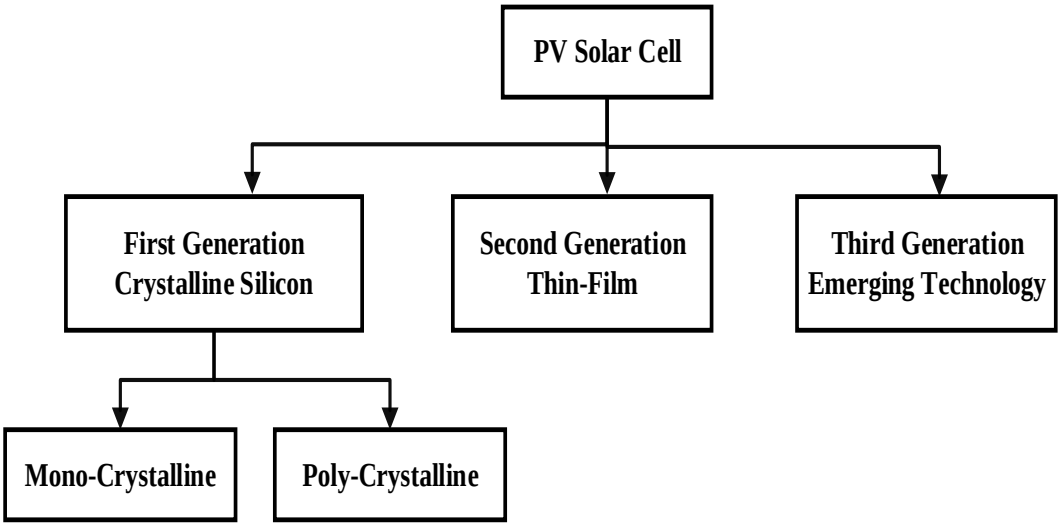


Figure 2.4 PV solar cell technologies

2.7. Basic operation of a solar cell

A solar cell transforms sunlight instantly into electrical energy through the photoelectric effect, where photons liberate electron-hole pairs in a semiconductor material, producing an electric current under the influence of an internal electric field [39]. PV cell parameters: short-circuit current, open-circuit voltage, fill factor, efficiency This relies on principally on the variation in crystalline solar cells, which spans from 15% to 22%. A few solar cell efficiency parameters are referred to as: short circuit current (Isc), open circuit voltage (Voc), light power, Fill Factor, and efficiency. These parameters can be analyzed mathematically below [40].

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{Sun}} \tag{2.1}$$

2.8. Fluid Flow and Heat Transfer in Tubes

Heat transfer and fluid flow through pipes are critical in modeling thermal systems. Particularly in the design of systems requiring heat transfer, including applications such as PVT systems. Heat transfer is affected by several factors, including fluid type (liquid or air), flow velocity, and physical properties. Pipe design, such as pipe length, diameter, and material, also affects heat transfer. Heat transfer within pipes occurs by convection as fluids flow through them. This flow can be divided into two main types:

- Laminar flow: The fluid flow is low because the flow velocity is low and the fluid motion is uniform, and no significant heat transfer occurs when the Reynolds number (Re < 2300)

- Turbulent flow: It occurs when the fluid flow is turbulent, i.e. the flow velocity is large and unorganized, leading to a greater heat transfer process than laminar flow, and it occurs when the Reynolds number (Re < 4000).

In models that use gas as the flowing fluid in pipes, the heat transfer coefficient is relatively low because the properties of air, such as density, heat capacity, and thermal conductivity, are low compared to liquids, and therefore the heat transfer is relatively small [41].

CHAPTER 3

METHODOLOGY

3.1. Introduction

This study aims to simulate a PVT solar collector. ANSYS Fluent, a highly flexible and multidisciplinary engineering software tool, is used to model multiple scenarios and achieve high accuracy. It also improves the solar collector thermal efficiency analysis, saving time and costs due to its free-form and reliable nature. This research aims to evaluate the thermal performance of a solar collector, with or without a helical coil, using plain water as the in-tube fluid. The engineering methodology in ANSYS includes geometric design, meshing, physical setup, boundary conditions, and post-processing, as shown in Figure 3.1. Although these blocks are the principal ones, the order of blocks changes by adding other elements according to the engineering problem under consideration.

3.2. Geometric Design

A PVT system consists of a PV panel and a solar collector as represented in Figure 3-2 [21]. PVT is combining a normal PV panel with a flat solar collector to optimize energy efficiency and usability. PV accomplishes its primary function of converting sunlight into electrical power, while the thermal collector transforms the unusable excess heat in the PV into a usable form via a heat transfer process. Heat is exchanged by the fluid passing through the pipe network, which cools the PV cells, which positively affects electrical efficiency. Table 3.1 gives the specifications and dimensions of the PVT's various parts used in the simulation. These parts are designed to be an ideal solar panel model, with no gaps between them. The layers were also arranged optimally to facilitate more accurate and efficient simulations. The PV panel consists of a multilayer model as shown in Figure 3.3. Many layers serve as protected frames, while others are active for energy conversion. Table 3.2 details every part with

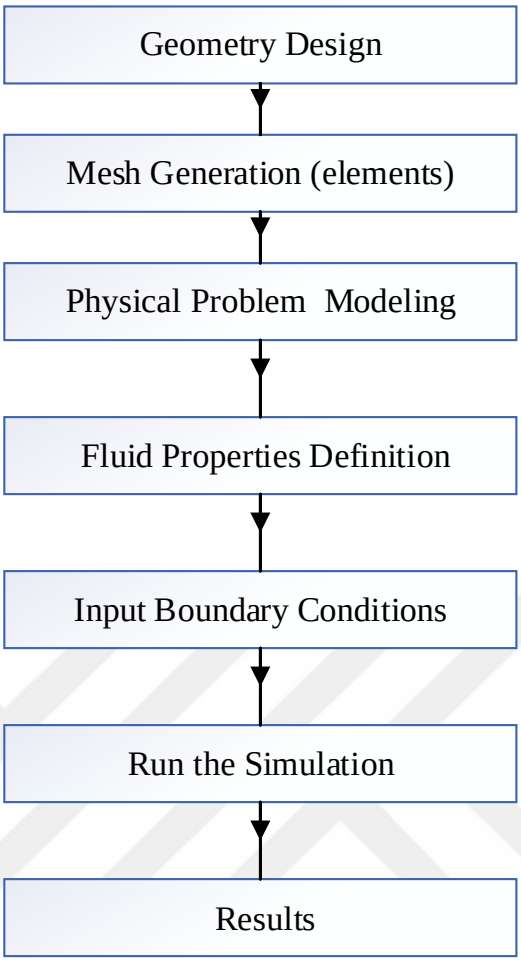
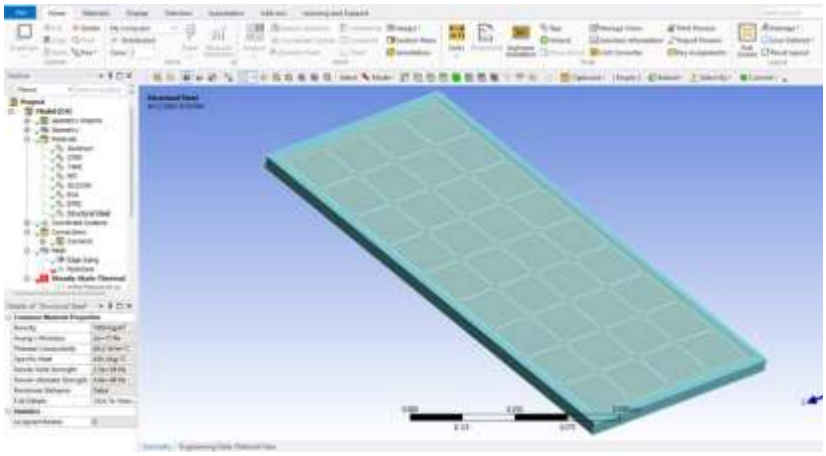
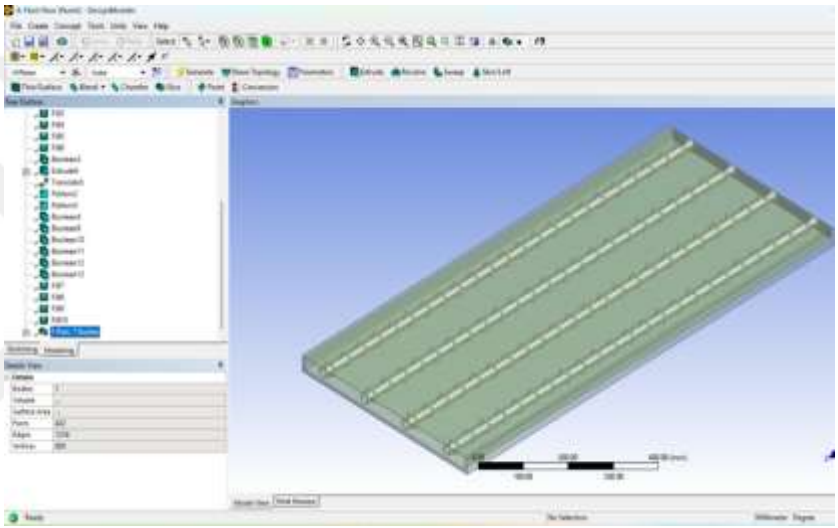


Figure 3.1 ANSYS Simulation steps

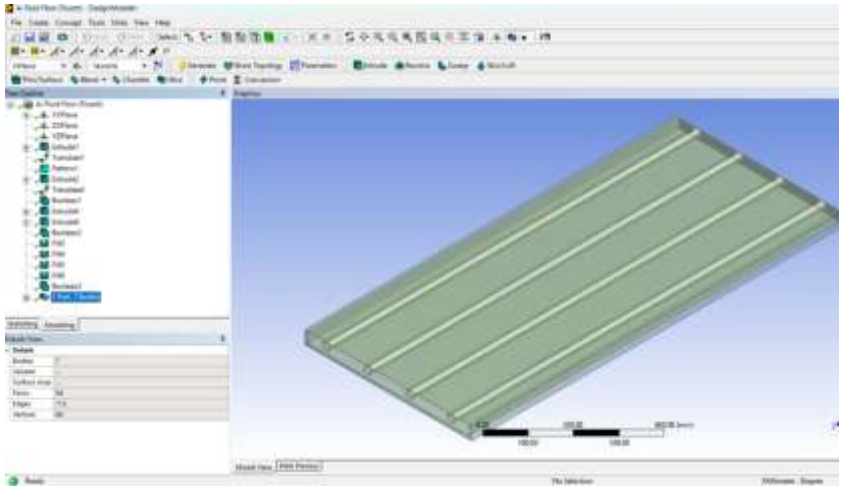
the materials it is made of, its purpose, properties, and function. The model's complexity is directly proportional to the simulation time, which is why layers that do not significantly affect the model's heat exchange process were neglected. The layers of the solar module, the absorber plate, the pipes, and the fluid are considered. The other layers were neglected, assuming the model is thermally insulated, and therefore their thermal impact is negligible or almost nonexistent. A 3D model of the thermal collector was developed using ANSYS Design Modeler.



(a) Solar panel



(b) Finned solar collector



(c) Smooth solar collector

Figure 3.2 PVT system modeling in ANSYS

Table 3.1 PVT used specification

Component	Material	Length (mm)	Width (mm)	Thickness (mm)	Diameter (mm)
PV panel	Silicone	1153	518	37	
Absorber plate	Copper	1153	518	1	
Pipe	Copper	1153	24	2	20
Supporting material	Plywood	1153	538	10	
Helical coil	Copper			3	35

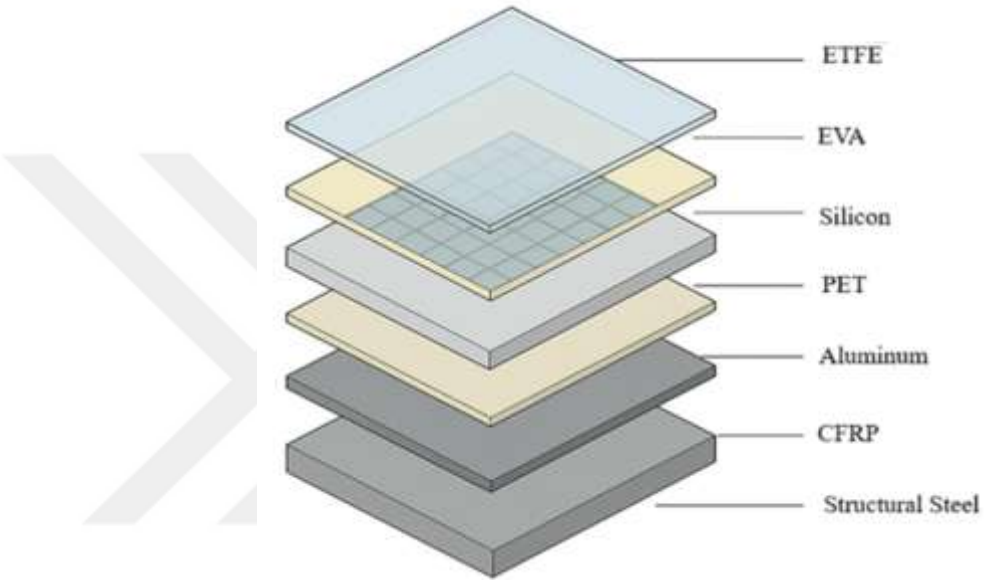


Figure 3.3 Solar Panel layers

3.3. Mesh Generation

ANSYS includes mesh creation, a fundamental step in producing numerical simulations. This step greatly depends on the accuracy and stability of the solution. Since the energy equations are partial differential equations, mesh transforms these equations into algebraic equations to facilitate their solution in the simulation. It was used in a three-dimensional model of a photovoltaic solar thermal collector. Because the shape of the PV and absorber consists of rectangular channels, the mesh used consists mainly of hexagonal structural mesh elements. Also, the cylindrical geometry of the pipe in the fluid domain is used [21]. This structural mesh provides a wide range of solutions to the heat and fluid transfer equations, as well as better convergence during solution, allowing for better numerical propagation and interpolation. The mesh

Table 3.2 PV Layers specifications

Materials	Purpose	Properties	Function
Aluminium	conductor of heat	Light metal with high thermal conductivity	Heat distribution in solar cells-conductive medium
CFRP (carbon fibre reinforced plastic)	Lightweight mechanical support	Heat-resistant and strong compound	support layer for the board
TAPE	Insulation and protection	thermal insulation	Install layers
PET (Polyethylene Terephthalate)	electrical insulation	Strong plastic packaging	Protection
SILICON	Energy generation	semiconductor material	Electrical energy generation
EVA (Ethylene-Vinyl Acetate)	Shock absorption and packaging	Transparent back-cell polymer	Protects solar cells from environmental factors.
ETFE (Ethylene Tetrafluoroethylene)	Top protective cover	Transparent, durable, UV-resistant polymer	Radiation passage/ internal parts protection.
Structural Steel	Support	Strong, solid, and highly durable metal	Mechanical support

cells on which the analysis was performed, i.e., the elements, where the optimized model with the spiral coil contains more elements than the model without the spiral coil, because the model with the spiral coil requires more reference points due to the presence of fins, which requires geometric complexity for further optimization**.** The finned collector model exhibits greater geometric complexity than its counterpart, with approximately 688,684 nodes and 2,145,757 elements, compared to approximately 290,887 nodes and 204,960 elements for the smooth collector. This demonstrates that the finned collector is more complex to solve than its counterpart.

3.4. Boundary Conditions

In this simulation, the boundaries of the solar collector require both the initial temperature and fluid velocity at the entrance. They are considered basic conditions in the simulation, and also to know the nature of the model's work, since the pressure at the exit is the same as the atmospheric pressure. Water is used as the fluid with a

constant density, an incompressible liquid, and the presence of air between the tubes, which has a very low velocity compared to the flow of water. This will minimize the heat exchange process between the air and the PV panel. The solar collector contains suspended fins, resulting in an increase in the surface area for improving the exchange process, while the supporting walls are thermally insulated, and the velocity on the walls is zero. The heat flow and temperature are constant, and this gives stability in the numerical solution process. Solar radiation received by PV is also provided as a boundary condition in Table 3.3. Various values are entered as received radiation from the standard (1000 W/m2) and the annual data of radiation in the city of Baghdad (Iraq). The sun's radiation is equivalent to the heat flux that can be monitored through the ANSYS tool.

Table 3.3 Boundary conditions

Boundary conditions	Value	Unit
Inlet temperature	298	K
Inlet velocity (water-air)	$1\text{-}10^{-5}$	m/s
Outlet pressure	1	atm
Heat flux	Variable	W/m2

3.5. Physics Setup in ANSYS Fluent

At this simulation stage, a physical model of the solar panel and the solar collector was required. The physical properties of each layer were entered as shown in Table 3.4. The mechanical properties of the panel are set up in ANSYS as shown in Figure 3.4. The solar collector was modeled in three dimensions, with the simulation being steady-state, indicating that the flow was constant and unchanged over time. The power command is activated from the Models menu because the simulation concerns heat exchange. The material and fluid properties are specified in Table 3.5 at 298 K for finned and finless solar collectors.

3.6. Governing Equations & Solver Settings

Some mathematical equations are important for simulation execution that must be activated through the ANSYS tool. These equations include the momentum equation,

Table 3.4 Layers' physical properties

Materials	Density kg/m^3	Isotropic Thermal Conductivity $(W/m.K)$	Specific Heat Pressure Constant $J/kg.K$
Aluminium	2689	237.50	951
CFRP	1490	6.83	1130
TAPE	1012	0.19	2000
PET	1350	0.28	1275
SILICON	2330	148.00	700
EVA	945	0.35	2090
ETFE	1730	0.24	1172
Structural Steel	7850	60.50	434

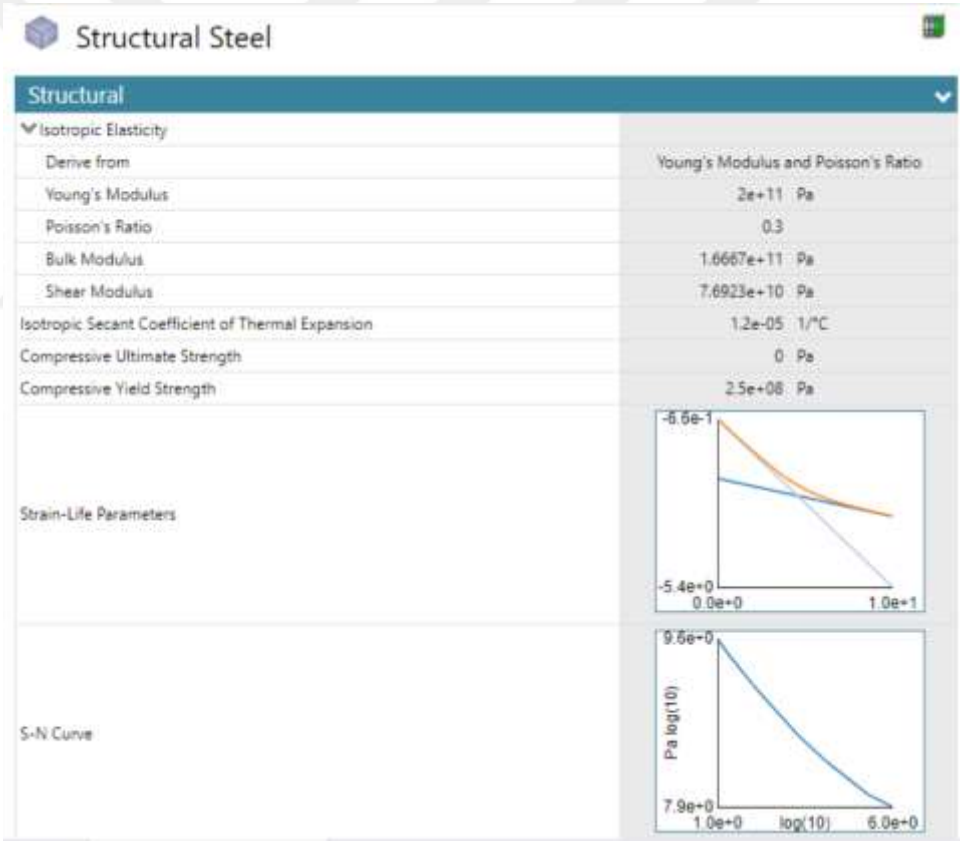


Figure 3.4 Mechanical properties

Table 3.5 Materials properties

Materials	Density Kg/m^3	Specific Heat $J/Kg.K$	Thermal Conductivity $w/m.K$	Viscosity $Kg/m.s$
Air	1.225	1006.43	0.024	1.7894e-05
Water	998.200	4182.00	0.600	0.001003
Copper	8978.000	381.00	387.600	-
Plywood	700.000	2310.00	0.173	-

the energy equation, and the continuity. The momentum equation is used to find some external forces resulting from any fluid flow in the simulation. The determination of factors such as velocity, pressure, viscosity, and external force vector is the result of the following equation:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}.\nabla\vec{v}\right)=-\nabla p+\mu\nabla^2\vec{v}+\vec{F}\ ) \tag{3.1}$$

Where:

$\vec{v}$: velocity vector, p : pressure, μ : Viscosity, and $\vec{F}$: External force vector The heat exchange in the solar collector activates the energy equation given by:

$$\rho C_p\left(\frac{\partial T}{\partial t}+v^{\rightarrow}.\nabla T\right)=\nabla.(K\nabla T)+Q \tag{3.2}$$

Where:

T: Temperature, C_p: Specific heat, K : Thermal conductivity coefficient, and Q: Heat sources (solar radiation) Finally, the continuity equation translates the first law of thermodynamics. The amount of fluid mass entering a system equals the amount of mass leaving it. This equation is automatically true because the system involves a fluid flow process, and the equation is based on a steady-state flow. The general formula is given by:

$$\nabla.(\rho\vec{v}\ )=0 \tag{3.3}$$

The light incident on the solar panel's surface represents the heat source for the solar collector and is calculated in ANSYS Fluent using the solar radiation model function. The factors affecting the model are the tilt angle and the radiation intensity, which is estimated based on the location of the solar collector. The incident light on the solar panel represents the heat source for the solar collector and is calculated in ANSYS Fluent using the solar radiation model function. The factors affecting the model are the tilt angle and the radiation intensity, which is estimated based on the location of the solar collector. Figure 3.5 represents the extent to which the governing equations are successfully solved.

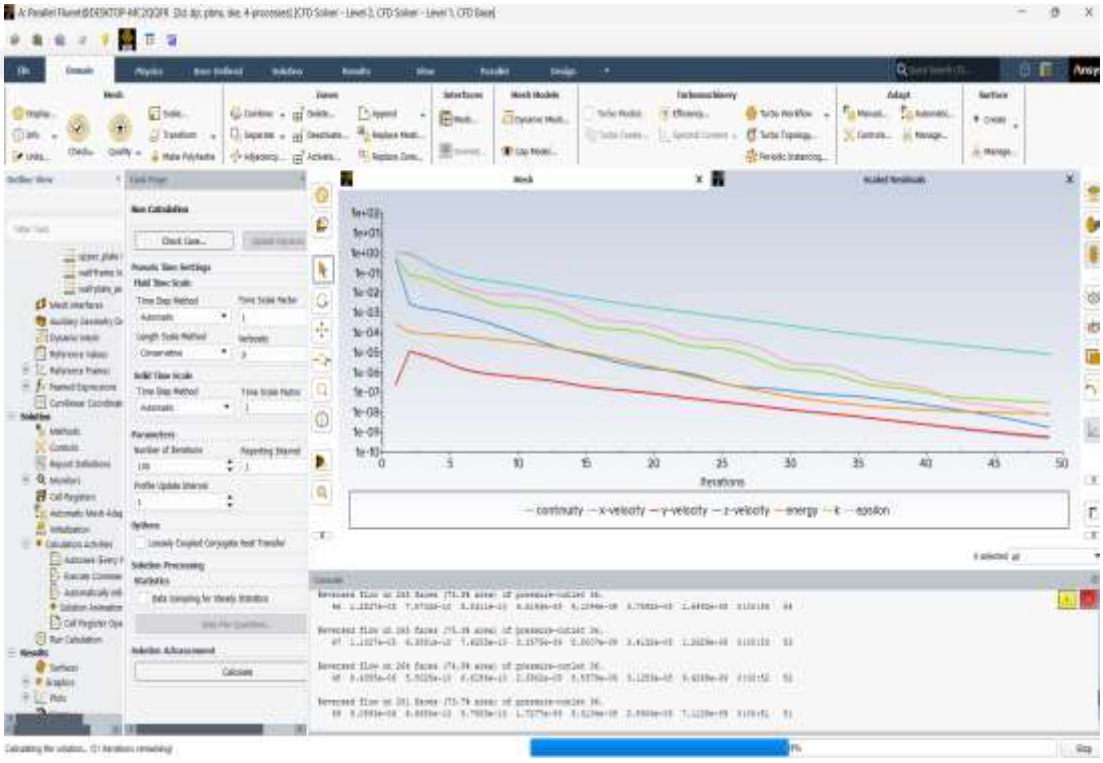


Figure 3.5 Residuals of Governing Equations in ANSYS

3.7. PVT Performance Modeling

The performance evaluation of the PVT system is based mainly on the efficiency evaluation. Since the PVT system produces electricity and thermal energy, the overall efficiency equals the sum of the two efficiencies (electrical and thermal) [42]:

$$\eta_{overall} = \eta_{PVT} = \eta_{Elec} + \eta_{Th} \tag{3.4}$$

where, η_{Elec} is the electrical efficiency, while η_{Th} represents the thermal efficiency. The electrical efficiency can be calculated by:

$$\eta_{Elec} = \frac{Power\ output\ of\ the\ PV}{Incident\ power} = \frac{I \times V}{Irr \times A_{PV}} \tag{3.5}$$

Where I and V are current and voltage produced by the PV panel, Irr is the incident irradiation (W/m^2), and A_{PV} is the PV panel area (m^2). Another representation of the electrical efficiency is in a function of temperature, which is more convenient as [43]:

$$\eta_{Elec.} = \eta_{Ref}(1 - \beta(T_{PV} - T_{Ref})) \tag{3.6}$$

Where, η_{Ref} is the reference efficiency, β is the temperature coefficient equal to 0.0045 K^{-1}, $T_{PV}$is the PV panel temperature, andT_{Ref} is the reference temperature.

$$\eta_{Ref} = FF \times \eta_o \tag{3.7}$$

where FF of the PV, which represents how much of the panel area is active cell area. It is between 0.85 to 0.95 according to the fabrication method and quality of the panel. η_o is the panel efficiency at STC (Standard Test Condition) with $Irr = 1000\frac{W}{m^2}$, and $T = 298\,K$. For monocrystalline Silicon, research demonstrated that its value is between 19% to 23%.

The capability of the PVT system to capture thermal energy is represented by η_{Th}. The thermal efficiency for a standard flat collector is equal to [42]:

$$\eta_{Th} = \frac{Q_{useful}}{Irr \times A_{PV}} \tag{3.8}$$

where Q_{useful} is the useful heat, which is equal to

$$Q_{useful} = \dot{m} \times C_p \times (T_{out} - T_{in}) \tag{3.9}$$

where $\dot{m}$ (kg/sec) is the mass flow rate, C_p (J/kg. K) is the fluid specific heat capacity, T_{out} (K) is the outlet temperature, and T_{in} (K) is the inlet temperature. The following values are used in our simulation in Table 3.6

Table 3.6 Values are used in our simulation

	Variable	Value	Unit
1	Irradiation (Irr)	Variable according to the case study	W/m^2
2	Area of the panel (A_{PV})	0.620314	m^2
3	Reference efficiency (η_{Ref})	0.19	
4	β	0.0045	K^{-1}
5	(T_{PV})	Taken as an output variable from the simulation	K
6	(T_{Ref})	298	K
7	$\dot{m}$	Variable as an input to the simulation. It depends on the fluid flow velocity	Kg/s
8	Fluid velocity (v)	From 0.04 to 0.1	m/s
9	C_p (Water)	4186	J/kg. K
10	Outlet temperature: T_{out}	Taken as an output variable from the simulation	K
10	Inlet Temperature: T_{in}	298	K

3.8. Simulation Scenarios

We planned many simulation scenarios to evaluate the performance of the proposed model in Table 3.7.

Table 3.7 Simulation scenarios

	Scenario No.	Variables under evaluation	Remarks
	S1	Effect of fins on the system efficiency	Evaluation of the system efficiency in two cases, with and without fins
	S2	Evaluation of fluid outlet temperature	Two cases: with and without fins
	S3	Evaluation of Nusselt number	Two cases: with and without fins
	S4	Evaluation of heat coefficient	Two cases: with and without fins
	S5	Evaluation of useful heat	Two cases: with and without fins
	S6	Evaluation of the system under variable irradiation	Using Data for Baghdad City (Iraq)

CHAPTER 4

SIMULATION AND DISCUSSION

This chapter provides an overview of the simulations conducted to evaluate the system under study. The effects of using fins in a PVT collector cooling tube are analyzed. Two systems with the same inputs were simulated: one with fins and the other without. The purpose of this simulation is to conduct a comparative study to evaluate the positive effects of fins in tubes. ANSYS Fluent 2024 R1 is used as the simulation tool for this analysis [44]. Several parameters are evaluated using two scenarios with multiple case studies. First, the effect of fins on flow channels was analyzed in five different case studies: the effect on the Nusselt number, the effect on the heat transfer coefficient (HTC), the effect on useful heat, the effect on thermal efficiency, and the effect of the fluid velocity on the outlet temperature. The second scenario focuses on a selected region, Baghdad, Iraq. Official data for this geographic location is used to evaluate the same PVT system throughout the year. Three case studies using finned tubes are simulated for this region: heat used by the fins, electrical power output, and system efficiency.

4.1. Effect of Fins on Flow Channels

Simulations are conducted with and without fins in the tubing to evaluate the system's performance. Various results are collected on the effect of fins on Nusselt number, heat transfer coefficient, useful heat, thermal efficiency, and the temperature outlet. Table 4.1 shows the input for the simulation program.

- **Case study 1: Effect on Nusselt number**

The Nusselt number is dimensionless, representing the ratio of heat transferred by convection to heat transferred by conduction. Increasing the value of the Nusselt number increases the efficiency of heat transfer from the solar cell surface to the liquid. It is represented by the following equation:

Table 4.1 Simulation input values

Input	Explanation	Value	Units
V	Fluid velocity	0.04	$^{m}/_{s}$
K	Thermal conductivity	0.60	$^{w}/_{m.K}$
ρ	Fluid density	998.20	$^{Kg}/_{m^3}$
I_{rr}	Received Irradiation	1000.00	$^{W}/_{m^2}$
L	Tube Length	1.15	m
C_p	Specific Heat	4182.00	$^{J}/_{Kg.K}$
T_{in}	Inlet Temperature	298.00	K
d	Tube diameter	0.02	m

$$N_u = \frac{h.L}{k} \tag{4.1}$$

where: h: convection heat transfer coefficient ($^{w}/_{m^2K}$), L: Pipe length (m), and k: Thermal conductivity ($^{w}/_{m.K}$)

Figure 4.1 represents the Nusselt number result for tubing with and without fins, while Table 4.2 gives these values for the collected test points. In the x-axis, the solar panel temperature ranges from 312 to 325 K at a standard irradiance of 1,000 W/m².

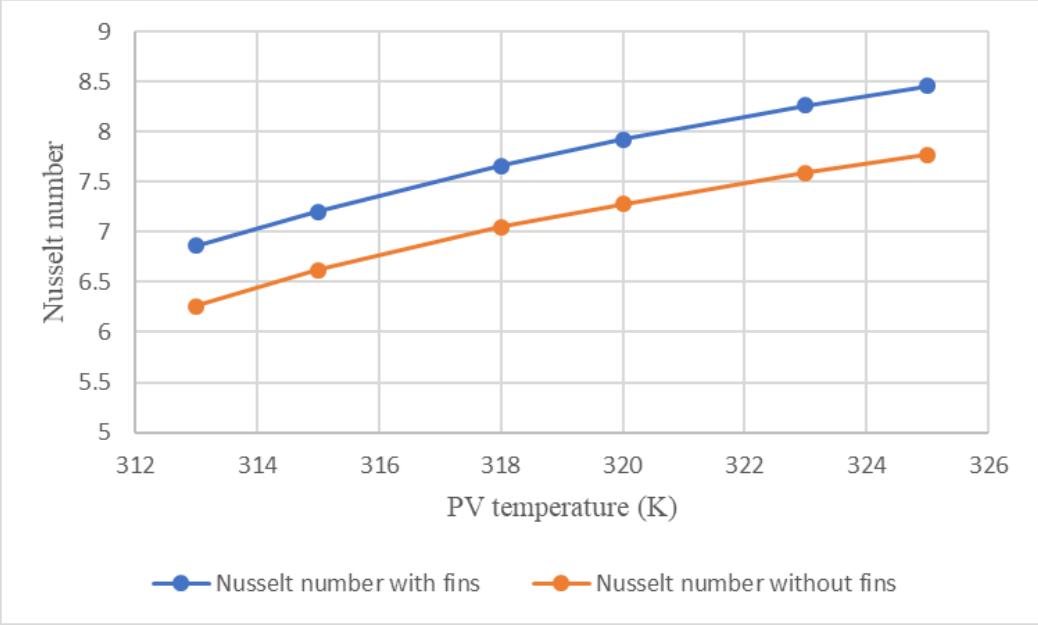


Figure 4.1 Nusselt number vs PV temperature

Table 4.2 Nusselt number for collected points

Temperature of PV	Nusselt number with fins	Nusselt number without fins
313	6.863	6.269
315	7.203	6.621
318	7.663	7.047
320	7.924	7.280
323	8.262	7.590
325	8.457	7.769

Results for a collector with fins are represented by the blue curve, while the orange represents those for a collector without fins. The curve indicates an increasing Nusselt number with the temperature increase for all types of collectors. The Nusselt number is higher for a collector with fins than for a smooth collector. This is due to the increased surface area for convective heat exchange. This is accomplished via the fluid flow turbulence, resulting in an increased cooling rate for the solar panel.

- **Case study 2: Effect on heat transfer coefficient (HTC)**

HTC at the standard test condition, incident radiation of 1000 W/m², is shown in Figure 4.2.

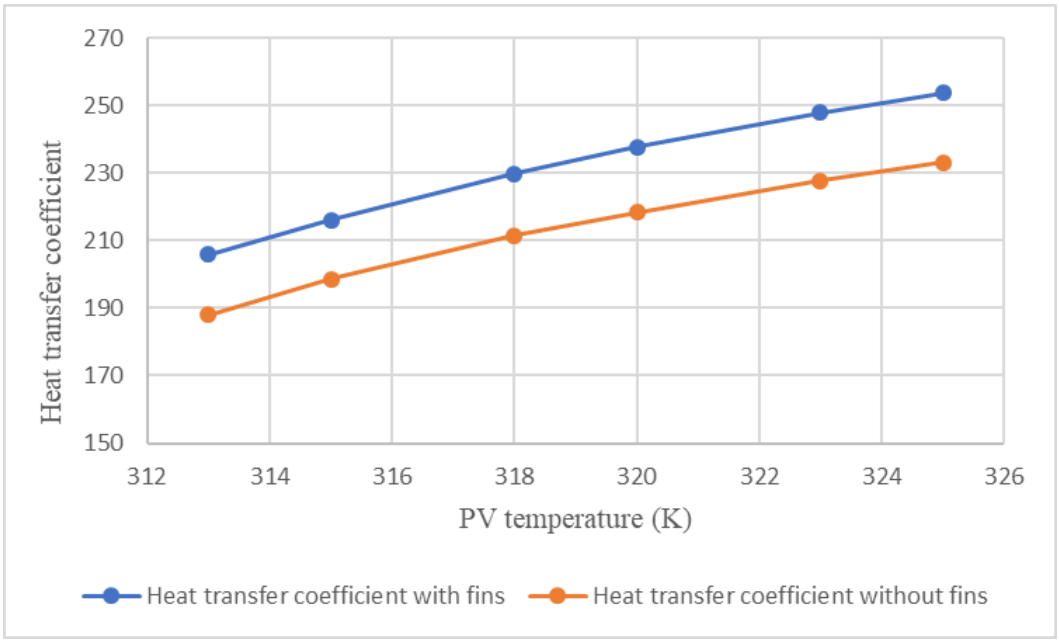


Figure 4.2 Heat transfer coefficient (HTC) vs PV temperature

The horizontal axis represents the PV temperature in Kelvin, which ranges from 312 to 325 at the surface of the solar panel, while the vertical axis represents the heat transfer coefficient ($W/m^2 \cdot K$). The blue line is the HTC for a finned PVT collector, and the orange one represents a collector without fins. It is observed that the greater the temperature, the higher the HTC. The curve indicates that the presence of fins increases the HTC due to an increased rate of heat dissipation to the medium and, consequently, increased fluid flow. This will increase the HTC and then contribute to the improvement of the system efficiency. The higher the HTC, the higher the rate of heat dissipation to the medium, and the higher the efficiency of the collector. HTC is further improved with the presence of fins, which improve the thermal stability of the system and enhance the performance of the photovoltaic cell. Table 4.3 represents HTC values with and without fins and PV temperature

Table 4.3 Heat transfer coefficient values

Temperature of PV	Heat transfer coefficient with fins	Heat transfer coefficient without fins
313	205.88	187.89
315	216.09	198.63
318	229.89	211.43
320	237.72	218.39
323	247.84	227.71
325	253.71	233.08

- **Case study 3: Effect on useful heat**

The relationship between the useful heat and the PV surface temperature is depicted in Figure 4.3. The vertical axis indicates the useful heat generated by the solar collector in watts. The blue line represents the useful heat of a finned solar collector, while the orange line represents the useful heat of a finless solar collector. It has been observed that the useful heat increases with increasing temperature. The useful heat of a finned solar collector is higher than its counterpart due to the presence of fins, which increase the surface area and thus enhance the heat exchange process, improving heat transfer. Also, the higher the temperature, the greater the efficiency of the fins. This indicates

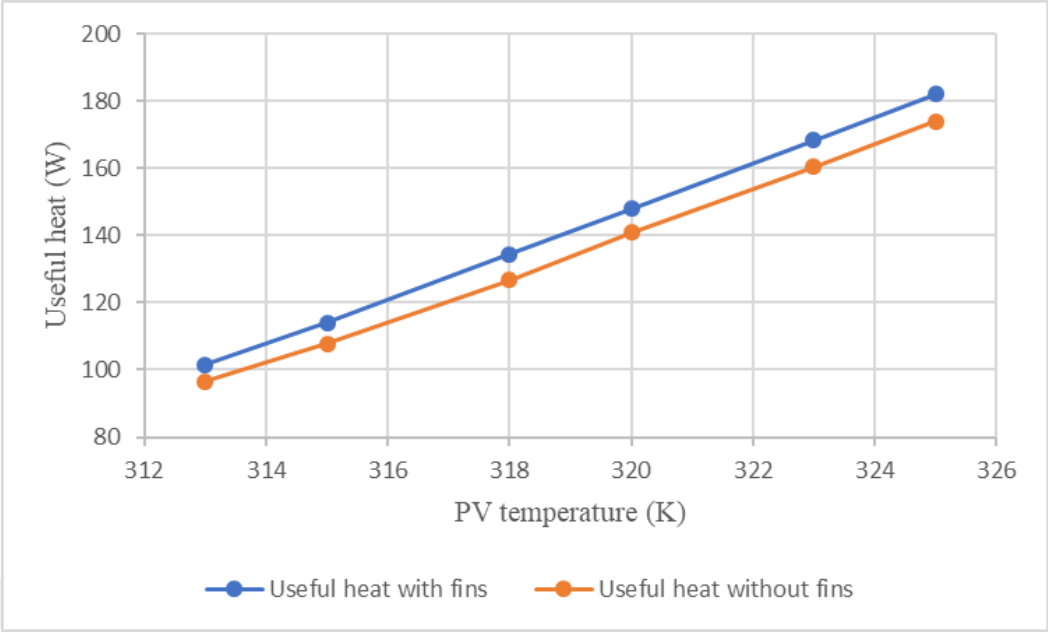


Figure 4.3 Useful heat vs PV temperature

that optimizing the thermal design of the system is beneficial for generating more energy.

Table 4.4 represents useful heat values with and without fins and PV temperature. The useful heat values are between 101.54 W to 181.98 for collectors with fins and from 96.65 to 173.95 without fins for a range of temperatures from 313 to 325 K.

Table 4.4 Useful heat values

Temperature of PV	Useful heat with fins	Useful heat without fins
313	101.54	96.649
315	113.96	107.710
318	134.47	126.780
320	148.05	140.790
323	168.40	160.530
325	181.98	173.950

- **Case study 4: Effect on thermal efficiency**

The behavior of the thermal efficiency for varying PV temperature is shown in Figure 4.4. The vertical axis represents thermal efficiency, ranging from 15% to 32%. The blue line represents the thermal efficiency of a finned collector, and the orange line

represents a finless collector. The curve shows that thermal efficiency increases with increasing temperature due to the increased heat output resulting from a larger temperature difference, thus increasing heat exchange. Note that the finned collector is more efficient than the other due to the increased surface area and, therefore, more useful heat. According to the law of thermal efficiency, when useful heat, or heat output, increases, efficiency increases, especially under high irradiance conditions. As a conclusion, the collector efficiency with fins is better by approximately 5% than without fins. Table 4.5 represents thermal efficiency values with and without fins and PV temperature.

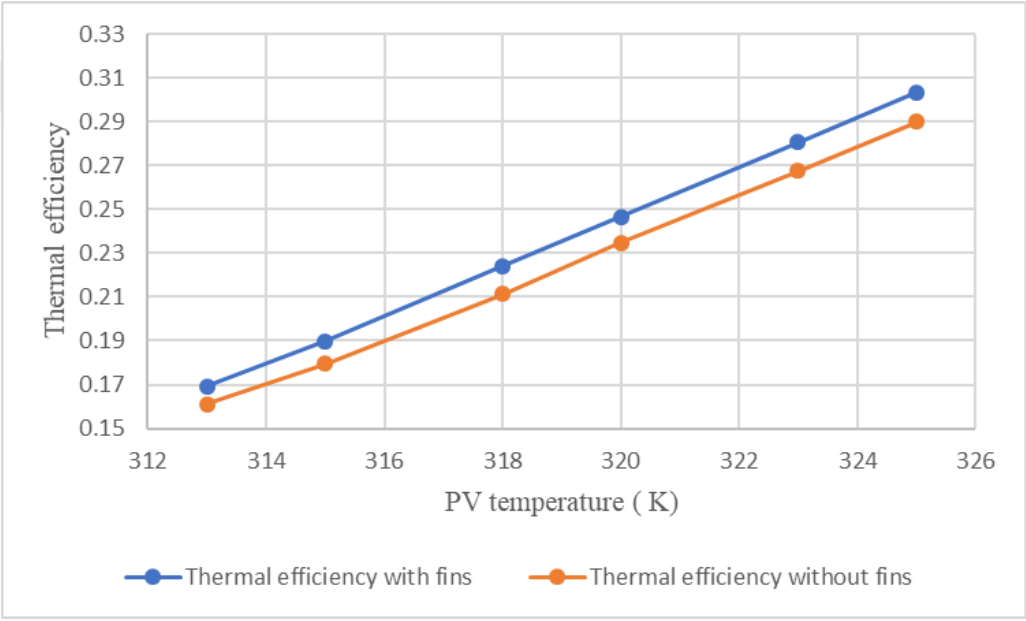


Figure 4.4 Thermal efficiency vs PV temperature

Table 4.5 Thermal efficiency

Temperature of PV	Thermal efficiency with fins	Thermal efficiency without fins	Relative percent Improvement
313	0.16923	0.16108	4.80
315	0.18993	0.17952	5.48
318	0.22412	0.21131	5.70
320	0.24675	0.23466	4.90
323	0.28067	0.26754	4.68
325	0.30330	0.28992	4.40

- **Case study 5: Effect of the fluid velocity on the outlet temperature**

The effect of fluid velocity variation on the outlet temperature was analyzed for a velocity ranging from 0.04 to 0.09 m/s, as shown in Figure 4.5. It is observed that at 0.04 m/s, the outlet temperature is higher than at other velocities due to convective heat exchange. This is higher due to the slower fluid movement and the longer time it spends in the collector. Also, the finned collector has a higher exit temperature, as the fins increased the surface area for heat exchange. At 0.04 m/s, the output temperature for the finned collector reached about 305.14 K, compared to about 304.18 K for the finless collector. We can see that the difference is significant due to the presence of the fins, which are efficient at convection. At 0.09 m/s, the output temperature decreased due to the higher fluid velocity. Good heat exchange does not occur because the contact between the fluid and the tube is minimal. As shown in the curve, the temperature of the finned collector reached approximately 303.5 K, and for the finless collector, it reached approximately 302 K. We conclude that the fluid velocity at low temperatures increases heat exchange, and the presence of fins increases heat exchange due to the increased surface area of the collector. It was also observed that as the velocity increases, the resulting temperature decreases due to the shorter time it takes for the fluid to absorb heat. Table 4.6 represents temperature outlet values with and without fins and PV temperature.

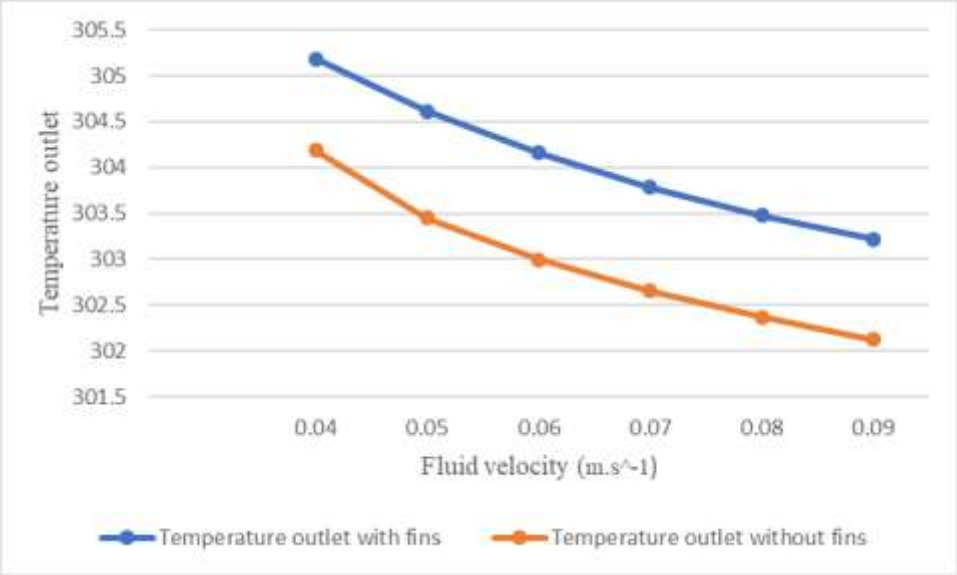


Figure 4.5 Temperature outlet vs Fluid velocity

Table 4.6 Temperature outlet values

Fluid Velocity $^{m}/_{s}$	Temperature outlet with fins	Temperature outlet without fins
0.04	305.18487	304.1850
0.05	304.61600	303.4500
0.06	304.16100	302.9998
0.07	303.78654	302.6561
0.08	303.47700	302.3705
0.09	303.22100	302.1280

4.2. System implantation in the Baghdad region

Official data for the Baghdad region (Iraq) is used in the present scenario for system analysis. Figure 4.6 is a colored chart of Baghdad irradiation in Wh/m^2 [45]. The Monthly average is used for simulation by averaging data over 12 Hours.



Figure 4.6 Average hourly irradiation in Baghdad city

- **Case study 1: Useful heat with fins**

The variation in useful heat produced by a fin's solar collector relative to the average monthly solar radiation over a full year in Baghdad, at a suitable velocity of 0.04 m/s is presented in Figure 4.7. The x-axis shows the average radiation in W/m² for each month of the year. The y-axis represents the power output (thermal) in W. It represents the useful heat used to heat the fluid (water). The curve indicates that the useful heat

in January is approximately 101.277 W, and gradually increases with the increasing irradiance, reaching a peak of 128.1 W in June. The curve gradually decreases with cold weather, reaching its lowest point in December (101.087 W). This explains the increased heat falling on the solar panel, which increases the temperature difference and thus results in a greater heat exchange process than in winter. Table 4.7 represents useful heat values for a collector with fins and the Monthly average radiation.

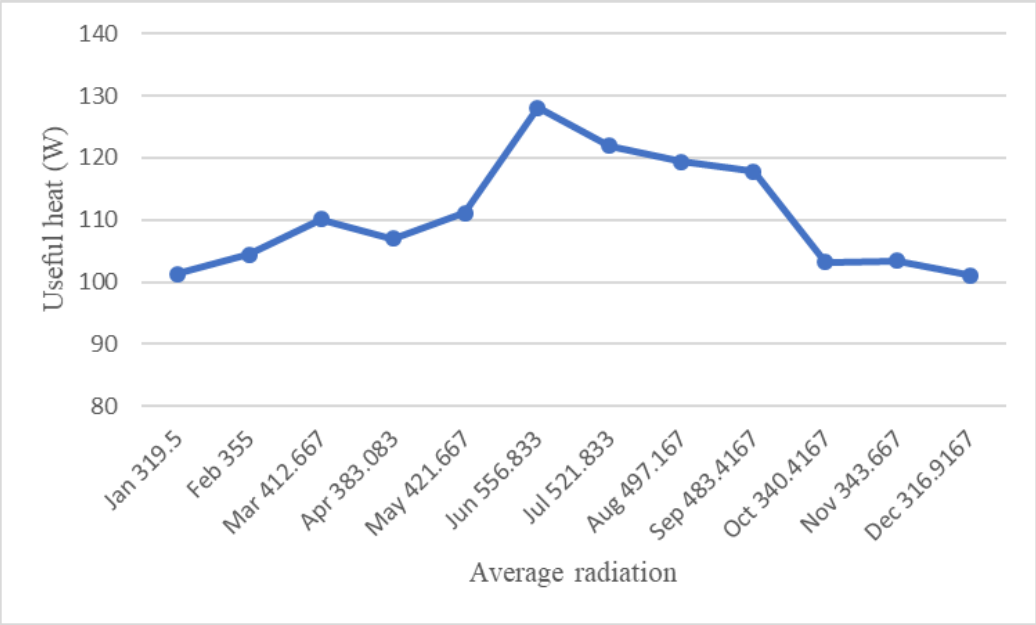


Figure 4.7 Useful heat vs Average radiation

Table 4.7 Monthly useful heat

Month	Average irradiation ($^{W}/_{m^2}$)	Useful Heat (W)
Jan	319.500	101.277
Fab	355.000	104.434
Mar	412.667	110.130
Apr	383.083	107.023
May	421.667	111.133
Jun	556.833	128.100
Jul	521.833	121.965
Aug	497.167	119.300
Sep	483.417	117.830
Oct	340.417	103.187
Nov	343.667	103.427
Dec	316.917	101.087

- **Case study 2: Electrical power output**

The variation in electrical power output produced by a fins-based solar collector relative to the average monthly solar radiation over a full year in Baghdad, at a suitable velocity of 0.04 m/s, is presented in Figure 4.8. The x-axis represents the average radiation in W/m² for the months of the year. The y-axis represents the power output (electrical). The blue line represents the electrical power produced. It begins in June at around 34.091W in winter, gradually increasing to around 57.414W in June, then declining as the weather cools and radiation decreases until December, around 33.829W. This is due to the direct dependence of electrical power production on solar radiation. Although the high temperature of the solar cell in summer negatively affects electrical efficiency, the large amount of incident radiation compensates for the decreased efficiency. Table 4.8 represents electrical power output values for a collector with fins and the Monthly average radiation.

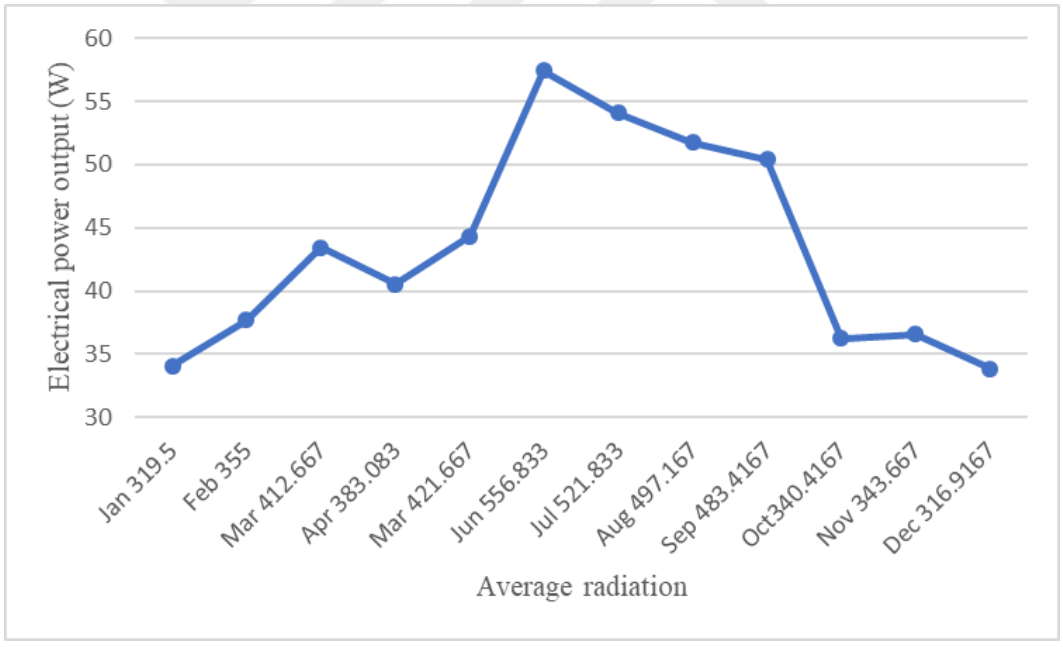


Figure 4.8 Electrical power output vs Average radiation

- **Case study 3: System efficiency**

The variation in thermal efficiency produced by a fins-based solar collector relative to the average monthly solar radiation over a full year in Baghdad, at a suitable velocity

Table 4.8 Monthly electrical output power

Month	Average irradiation ($^{W}/_{m^2}$)	Electrical power (W)
Jan	319.500	34.091
Fab	355.000	37.689
Mar	412.667	43.450
Apr	383.083	40.507
May	421.667	44.340
Jun	556.833	57.414
Jul	521.833	54.082
Aug	497.167	51.711
Sep	483.417	50.382
Oct	340.417	36.216
Nov	343.667	36.545
Dec	316.917	33.829

of 0.04 m/s is presented in Figure 4.9. The average radiation is higher in summer than in winter. The vertical axis represents the thermal efficiency. The blue line indicates that the thermal efficiency increases in winter and reaches its peak in December. The thermal efficiency ranges from 51 to 54% during this season, compared to its summer counterpart, where the efficiency is about 39%. Although the radiation is much lower in winter, the heat loss between the system and the environment is small. In addition, the amount of heat transferred to the fluid increases due to the large temperature difference between it and the external environment. Table 4.9 represents thermal efficiency values for a collector with fins and the Monthly average radiation. The variation in PVT electrical efficiency produced by a fins-based solar collector relative to the average monthly solar radiation over a full year in Baghdad, at a velocity of 0.04 m/s is presented in Figure 4.10. The blue line represents the electrical efficiency, ranging from about 17.18% to 17.8% along the line. This indicates that the electrical efficiency is almost constant, given that the material used in solar panels is monocrystalline. Electrical efficiency is affected by the temperature of the solar cell, and radiation increases its temperature. A slight decrease in electrical efficiency is observed in the summer compared to the winter. The solar collector stabilizes the efficiency of the PVT system by cooling the fluid in these cells. Table 4.10 represents electrical efficiency values for a collector with fins and the Monthly average radiation.

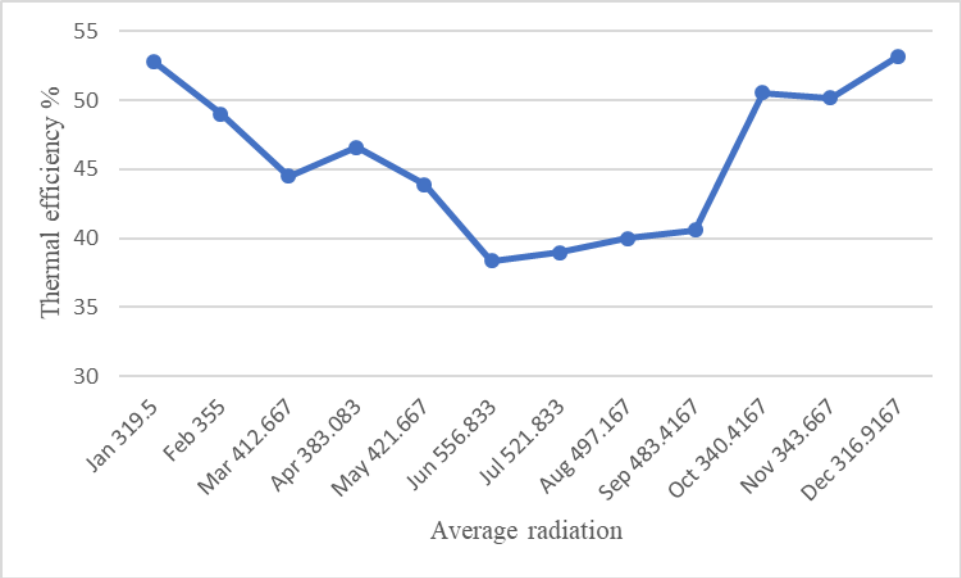


Figure 4.9 Thermal efficiency vs Average radiation

Table 4.9 Monthly thermal efficiency

Month	Average irradiation W/m^2	Thermal efficiency %
Jan	319.500	52.80
Fab	355.000	49.00
Mar	412.667	44.48
Apr	383.083	46.60
May	421.667	43.90
Jun	556.833	38.34
Jul	521.833	38.95
Aug	497.167	39.99
Sep	483.417	40.60
Oct	340.417	50.52
Nov	343.667	50.16
Dec	316.917	53.16

The variation in overall efficiency produced by a fin's solar collector relative to the average monthly solar radiation over a full year in Baghdad, at a suitable velocity of 0.04 m/s is presented in Figure 4.11. The x-axis represents the average radiation for the months of the year. The y-axis indicates the overall efficiency. The curve is shown in blue. Efficiency is observed to be high in January, around 70.58%, and gradually decreases in March to around 62.03% as the radiation increases. This is due to the high temperature of the fluid, which negatively affects efficiency.

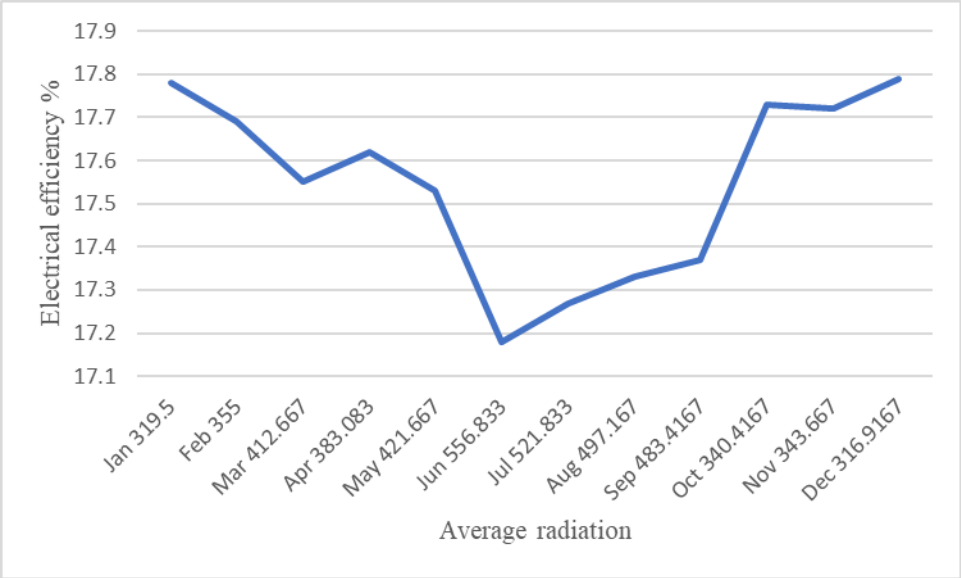


Figure 4.10 Electrical efficiency vs Average radiation

Table 4.10 Monthly electrical efficiency

Month	Average irradiation W/m^2	Electrical efficiency %
Jan	319.500	17.78
Fab	355.000	17.69
Mar	412.667	17.55
Apr	383.083	17.62
May	421.667	17.53
Jun	556.833	17.18
Jul	521.833	17.27
Aug	497.167	17.33
Sep	483.417	17.37
Oct	340.417	17.73
Nov	343.667	17.72
Dec	316.917	17.79

The efficiency reaches around 55.52% in the summer, in June, and then gradually increases to around (57.32 and 68.25 %) in August and October. Despite the intense radiation, the ambient temperature gradually decreases, reaching a maximum efficiency of 70.95% in December. This is due to the low radiation and ambient temperature, which causes no heat loss. Table 4.11 represents overall efficiency values for a collector with fins and the Monthly average radiation.

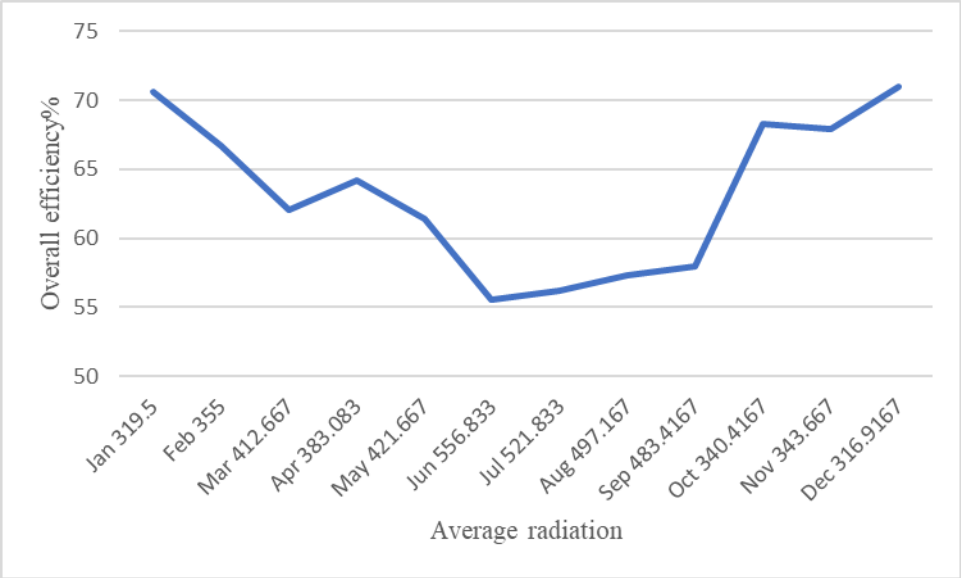


Figure 4.11 Overall efficiency vs Average radiation

Table 4.11 Monthly overall efficiency

Month	Average irradiation W/m^2	Overall efficiency %
Jan	319.500	70.58
Fab	355.000	66.69
Mar	412.667	62.03
Apr	383.083	64.22
May	421.667	61.43
Jun	556.833	55.52
Jul	521.833	56.22
Aug	497.167	57.32
Sep	483.417	57.97
Oct	340.417	68.25
Nov	343.667	67.88
Dec	316.917	70.95

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

PVT systems convert solar energy into usable electrical and thermal energy. This technology combines solar panels, which convert received light into electrical energy, with a solar collector that harnesses radiant heat to produce thermal energy and cool the solar panels, increasing the overall efficiency of the system. A PVT system has better overall performance than its corresponding classical PV system. While the efficiency of the PV system is about 20%, the efficiency of the PVT increases to twice this amount or more due to the thermal efficiency. This outstanding performance makes PVT systems economically more beneficial by producing two energy forms. Because solar energy is one of the most important renewable energy sources, significant research efforts are directed toward PVT systems to maximize their overall efficiency. In this research, a PVT collector system is developed to increase its overall efficiency. The cooling of the private complex is based on ordinary water, but using finned tubes. This is simulated using ANSYS Fluent 2024 R1 to analyze the thermal behavior of a PVT collector system. A comparison is made between a collector with fins and a conventional smooth collector. The comparison of the two collectors in terms of Nusselt number is made, and it is found that the collector with fins had a higher Nusselt number than its counterpart under the same conditions due to the increased surface area used for convective heat exchange. In comparison with HTC, the collector with fins also had a higher fin number due to the increased rate of heat dissipation to the medium, thus increasing the fluid flow. The useful heat output of the collector with fins ranged between 101.54 and 181.98 W, while the counterpart collector ranged between 96.65 and 173.95 W due to the increased surface area for heat exchange. It is found that the fins increase the heat exchange surface area, increasing the efficiency of this system by approximately 5%.

The average daytime solar radiation over a year is calculated under the climate of the city of Baghdad for the finned PVT system. The efficiency rate is found to be 55% in the summer, while it increased to approximately 70% in the winter. This indicates that the designed system improves its efficiency under different climatic conditions, which improves its thermal and electrical efficiency, and thus optimizes the use of solar energy in various applications.

5.2. Future Work

Based on this research, future research could be developed to investigate the possible improvement of PVT systems' performance:

- Investigation of the impact of improving the fin design by making them curved or stepped, as well as increasing their thickness and number, to achieve the greatest possible balance between heat exchange area and hydraulic resistance;
- Changing the cooling media using nanofluids to study their potential to enhance the system's thermal efficiency;
- Incorporating PCM s into the system design to enhance heat storage capacity so that the absorber plate retains its heat for a maximum duration during the peak period.

REFERENCES

[1] Ge, T.S., Wang, R.Z., Xu, Z.Y., Pan, Q.W., Du, S., Chen, X.M., Ma, T., Wu, X.N., Sun, X.L., & Chen, J.F. Solar heating and cooling: Present and future development. Renewable Energy, 126, pp (1126-1140), ELSEVIER.2018

[2] Hao, X., Shan, S., Gao, N., Chen, G., Wang, Q., & Gu,T . Performance analysis of a novel combined cooling, heating and power. Energy Conversion and Management,276, pp (116500), ELSEVIER.2023

[3] Addawe, A., Mahmood, M.K., Karim, S.M., & Nezam, A.M. Analysis of Perturb and Observe MPPT under varying PV operating climatic conditions. In 21st International Multi-Conference on Systems, pp (92–97), Signals & Devices (SSD) .2024

[4] Hissouf, M., Feddaoui,m., Najim, M., & Charef, A. Numerical study of a covered Photovoltaic-Thermal Collector (PVT) enhancement using nanofluids. Solar Energy, 199, pp (115-127) ELSEVIER.2020

[5] Suman, S., Khan, M. K., & Pathak, M. Performance enhancement of solar collectors—A review. Renewable and Sustainable Energy Reviews, 49, pp (192-210), ELSEVIER.2015

[6] Rejeb, O., Gaillard, L., Giroux-Julien, S., Ghenai, C., Jemni, A., Bettayeb, M., & Menezo, C. Novel solar PV/Thermal collector design for the enhancement of thermal and electrical performances. Renewable energy, 146, pp (610-627), ELSEVIER .2020

[7] Verma, S. K., Gupta, N. K., & Rakshit, D. A comprehensive analysis on advances in application of solar collectors considering design, process and working fluid parameters for solar to thermal conversion. Solar Energy, 208, pp (1114-1150), ELSEVIER. 2020

[8] Khelifa, A., Attia, M. E. H., Driss, Z., & Manokar, A. M. Performance enhancement of photovoltaic solar collector using fins and bi-fluid: Thermal efficiency study. Solar Energy, 263, pp (111987), ELSEVIER.2023

[9] Aste, N., Del Pero, C., Leonforte, F., & Manfren, M. Performance monitoring and modeling of an uncovered photovoltaic-thermal (PVT) water collector. Solar Energy, 135, pp (551-568), ELSEVIER.2016

[10] Herrando, M., Pantaleo, A. M., Wang, K., & Markides, C. N. Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. Renewable Energy, 143, pp (637-647), ELSEVIER.2019

[11] Chan, H. Y., Riffat, S. B., & Zhu, J. Review of passive solar heating and cooling technologies. Renewable and Sustainable Energy Reviews, 14(2), pp (781-789), ELSEVIER. 2010

[12] Shoeibi, S., Kargarsharifabad, H., Sadi, M., Arabkoohsar, A., & Mirjalily, S. A. A. A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications. Sustainable Energy Technologies and Assessments, 52, pp (102105), ELSEVIER.2022

[13] Madadi, M., & Arani,A.A.A. Experimental evaluation of photovoltaic thermal (PVT) system using a modular heat collector with flat back shape fins, pipe, nanofluids and phase change material. Solar Energy Materials and Solar Cells, 280, pp (113294), ELSEVIER.2025

[14] Ahmed, M. T., Rashel, M.R., Al-Wadud, M. A., Hoque,T.T., Janeiro,F.M., Tlemcani,M. Mathematical Modeling, Parameters Effect, and Sensitivity Analysis of a Hybrid PVT System. Energies, 17(12), pp (2887), mdpi.com.2024

[15] Ahn, J.G., Yu, J.S., Boafo, F. E., Kim, J.H., & Kim, J.T. Simulation and Performance Analysis of Air-Type PVT Collector with Interspaced Baffle-PV Cell Design. Energies, 14(17), pp (5372), mdpi.com.2021

[16] Nešović, A., Lukić, N., Kowalik, R., Janaszek, A., Taranović, D., & Kozłowski, T. Experimental and numerical comparison of glass tube collector with relative single-axis tracking and flat-plate collector without tracking during cloudy-sky days. Solar Energy, 291, pp (113412), ELSEVIER.2025

[17] Dannemand,M., Mikkelsen,S.E., Nielsen,E., &Furbo,S. How does the thermal characteristics of PVT panels influence the performance of PVT heat pump systems. In Proceedings of EuroSun 2024, pp (772-778), International Solar Energy Society.2024

[18] Zhou, J., Ke, H., & Deng, X. Experimental and CFD investigation on temperature distribution of a serpentine tube type photovoltaic/thermal collector. Solar Energy, 174, pp (735–742).2018

[19] Naghdbishi, A., Yazdi, M. E., & Akbari, G. Numerical study on the performance of a glazed photovoltaic thermal system integrated with phase change material (GPVT/PCM): on the contribution of PCM volumetric fraction and environmental temperature. arXiv preprint arXiv,2105, pp (14827), arxiv.org.2021

[20] Abdullah, A. L., Misha, S., Tamaldin, N., Rosli, M. A.M., & Sachit, F.A. Numerical Analysis of Solar Hybrid Photovoltaic Thermal Air Collector Simulation by ANSYS. CFD Letters, 11(2), pp (1–11), akademiabaru.com.2021

[21] Karaaslan, İ., & Menlik, T. Numerical study of a photovoltaic thermal (PV/T) system using mono and hybrid nanofluid. Solar Energy, 224, pp (1260–1270), ELSEVIER.2021

[22] Ishak, M. A. A. B., Ibrahim, A., & Din, S.I.U. Energy and exergy analysis of a reversed circular flow jet impingement bifacial PVT collector: CFD simulation and experimental study. Thermal Science and Engineering Progress ,62, pp (103602), ELSEVIER.2025

[23] Liu, N., Jiang, D., Liu, H., Sun, K., & Bai, S. Experimental and simulation study on a novel photovoltaic-thermal (PVT) system with enhanced combined thermal

and electrical efficiency. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects ,47(1), pp (12059-12076), Taylor & Francis.2025

[24] Satpute, J., Srinidhi, C., Rathore, S.S., Yadav, S.M., Kumar, A., Gajbhiye, A., Channapattana, S.V., & Aithal, K.Parametric influence and efficiency assessment of water-cooled photovoltaic thermal PV/T absorber designs. Energy, 320, pp (135218).2025

[25] Mahdavi, A., Niloofari, P., Gorji-Bandpy,M., & Mahmoudi, A. Numerical simulation of a PVT-PCM system by altering fluid tube positioning adding nanoparticles and embedding a porous medium. Alexandria Engineering Journal, 115, pp (30-46), ELSEVIER.2025

[26] Kalkan, C., Ezan, M. A., Duquette, J., Balaman, Ş. Y., & Yilanci, A. Numerical study on photovoltaic/thermal systems with extended surfaces. International Journal of Energy Research, 43(10), pp (5213–5229), Wiley Online Library.2019

[27] Prasetyo, S. D., Budiana, E. P., Prabowo, A. R., & Arifin, Z. Modeling Finned Thermal Collector Construction Nanofluid-based Al2O3 to Enhance Photovoltaic Performance. Civil Engineering Journal, 8(6), pp (1192–1203), academia.edu.2022

[28] Kong, X., Zhang, Y., Wu, J., & Pan, S. Numerical Study on the Optimization Design of Photovoltaic/Thermal (PV/T) Collector with Internal Corrugated Channels. International Journal of Photoenergy, 2022, pp (8632826), Wiley Online Library.2022

[29] Ajel, M.G., Gedik, E., abdul Wahhab, H.A., & Shallal,B.A. (2023). Performance Analysis of an Open-Flow Photovoltaic/Thermal (PV/T) Solar Collector with Using a Different Fins Shapes. Sustainability, 15(5), pp (3877), mdpi.com.2023

[30] Alqatamin, A., & Jinzhan, S. Numerical Analysis and Design of Photovoltaic-thermal (PVT) System with Novel Water-Cooling Channel Structure Integrated

with Perforated V-Shape Fins. Renewable Energy ,243, PP (122587) ELSEVIER,.2025

[31] Liu, H., & Zhu, W. Optimisation analysis by numerical simulation of adding internal fins in photovoltaic/thermal system based on Taguchi method. Applied Thermal Engineering ,266, pp (125635), ELSEVIER.2025

[32] NEZAM, A. M., MAHMOOD., M.K., KARIM, S.M., & ADDAWE, A. Evaluation of Incremental Conductance MPPT Algorithm Under Varying Conditions. 21st International Multi-Conference on Systems, pp (98-103), Signals & Devices (SSD).2024

[33] Tahir, Z.U.R., Kanwal, A., Asim, M., Bilal, M., Abdullah, M.F., Saleem, S., Abbas, M.M., Veza, I., & Mousa, M. Effect of temperature and wind speed on efficiency of five photovoltaic module technologies for different climatic zones. Sustainability ,14.23, pp (15810), mdpi.com.2022

[34] Abou akroush, M., Faraj, J., Hachem, F., Castelain, C., & Khaled, M. A comprehensive review and comparison of cooling techniques for photovoltaic panels: An emphasis on experimental setup and energy efficiency ratios. International Journal of Thermofluids,23, pp (100774), ELSEVIER.2024

[35] Alsaqoor, S., Alqatamin, A., Alahmer, A., Nan, Z., Al-Husban, Y., & FREng,H.J. The impact of phase change material on photovoltaic thermal (PVT) systems: A numerical study." International Journal of Thermofluids ,18, pp (100365), ELSEVIER.2023

[36] Abdalla, A.N. Jing, W., Nazir, M.S., Jiang, M., & Tao, H. Socio-economic impacts of solar energy technologies for sustainable green energy: A review. Environment, Development and Sustainability ,25(12), pp (13695-13732), Springer.2023

[37] Nasri, H., Riahi, J., Oueslati, H., TAGHOUTI, H., & Vergura, S. Performance Analysis and Optimization of a Channeled Photovoltaic Thermal System with

Fin Absorbers and Combined Bi-Fluid Cooling.Computation ,12, pp (188), researchgate.net.2024

[38] Ahmed, S., Ali, A., Ansari, J.A., Qadir, S.A., & Kumar, L. A Comprehensive Review of Solar Photovoltaic Systems: Scope, Technologies, Applications, Progress, Challenges and Recommendations. IEEE Access,13, pp (69723-69750), ieeexplore.ieee.org .2025

[39] VODAPALLY, S.N., & Ali, M.H. A comprehensive review of solar photovoltaic (PV) technologies, architecture, and its applications to improved efficiency. Energies ,16(1) pp (319) mdpi.com.2022

[40] Nazir, S., Ali, A., Aftab, A., Abdul Muqeet, H., Mirsaeidi, S., & Zhang, J.M. Techno-economic and environmental perspectives of solar cell technologies: a comprehensive review. Energies 16(13) pp (4959), mdpi.com.2023

[41] Shao, N., Ma, L., Zhou, C., & Zhang, D. Experimental study on the heat transfer performance of the PVT ventilated roof as heat exchanger for heat pump system. Renewable Energy, 187, pp (995-1008), ELSEVIER.2022

[42] Ahmed, M.T., Rashel, M.R., Islam, M., Hoque, T.T., Tlemcani, M., & Janeiro, F.M. Characterization, Performance, and Efficiency Analysis of Hybrid Photovoltaic Thermal (PVT) Systems. Energies,18(5), pp (19961073), search.ebscohost.com. 2025

[43] Diwania, S., Siddiqui, A.Z., Agrawal, S., & Kumar, R. Modeling and assessment of the thermo-electrical performance of a photovoltaic-thermal (PVT) system using different nanofluids. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 43, pp (1-18) Springer.2021

[44] Ansys, A. N. Ansys engineering simulation software. 20 November 2025. https://www.ansys.com/. 2025

[45] Global, S. A. Global Solar Atlas. 20 November 2025. https://globalsolaratlas.info/map?c=11.523088,8.173828,3. 2025