

INVESTIGATION AND ANALYSIS OF FLUID BASED ABSORPTION FILTERS FOR SOLAR PVT SYSTEM

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Mechanical Engineering

by

Pushparaj Ramesh Jiwanapurkar

199999919557

under supervision of

Dr. Hiteshkumar A Bhargav



GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

October – 2026

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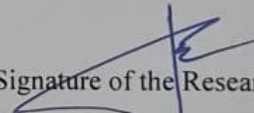
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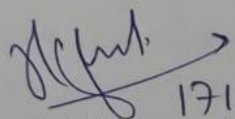
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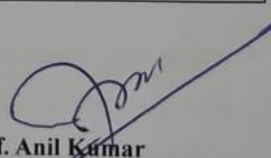
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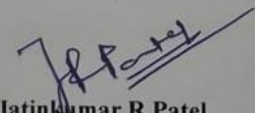
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ABSTRACT

The fast depletion of fossil fuels and the growing demand for energy around the world have made it necessary to switch to more sustainable sources, with solar energy emerging as a premier, clean, and inexhaustible alternative. While silicon (Si) solar cells currently dominate 95% of the global market, they face significant operational hurdles in outdoor environments. Specifically, module temperatures often exceed 60°C, triggering thermal degradation that severely reduces electrical efficiency.

To address this, Photovoltaic-Thermal (PVT) systems were developed to extract heat directly from panels using transfer fluids. However, conventional PVT designs suffer from a fundamental trade-off: they cannot maximize electrical and thermal efficiencies simultaneously, as thermal output must be kept low to prevent the PV module from overheating.

Spectral Beam Splitting (SBS) technology offers a solution to this conflict. By separating the solar spectrum into specific wavelength ranges, the system can direct the responsive range of silicon cells (751 nm to 1126 nm) toward the PV receiver while diverting the remaining thermal radiation to a secondary absorber. Liquid-based SBS systems are particularly effective as they offer tenable optical properties and cost-efficiency.

Despite extensive numerical and laboratory-based research, there remains a critical gap in experimental validation under natural solar conditions. This study addresses this gap by developing a compact, portable experimental platform designed for year-round outdoor testing. The research focuses on the fabrication and analysis of a fluid-based absorption filter integrated with a PVT system, capable of testing various fluids to optimize radiation filtering.

Following a comprehensive review of organic and nanofluid-based SBS filters, this work identifies water-based Titanium Dioxide nanofluid as a high-potential candidate for commercial implementation. Spectroscopic analysis of 12 samples (TiO₂ and ZnO at concentrations of 0.01% to 0.05%) determined that a 0.04% concentration of TiO₂ is the most effective for BSPVT systems, as it balances high transmissivity with effective UV and infrared attenuation.

The experimental setup features a modular, adjustable support structure for precise tilt orientation, a 10W crystalline silicon PV module, and high-precision instrumentation including pyranometers and thermocouples. By systematically comparing three configurations i.e. standalone PV (Case 1), PV with an empty filter (Case 2), and PV with circulating nanofluid (Case 3) the study isolates the thermal and optical impacts of the filter.

Testing at variable volumetric flow rates (52, 58, and 70 LPH) revealed that 58 LPH provides the optimal balance, maintaining a stable 7.4% electrical efficiency and 66% thermal efficiency, totalling 73% overall efficiency. Ultimately, this research validates the TiO_2 -based spectral beam-splitting approach as a superior method for total energy harvesting, transforming waste heat into a valuable secondary energy stream and providing a more comprehensive solution than traditional solar systems.

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List of Abbreviations

AM	- Air Mass
ASTM	- American Society for Testing and Materials
CNT	- Carbon Nanotubes
PVT	- Photovoltaic-Thermal
BSPVT	- Beam-Splitting Photovoltaic-Thermal
CPVT	- Concentrated Photovoltaic-Thermal
ENF	- Electrolyte Nanofluid
ITO	- Indium Tin Oxide
LPH	- Liters Per Hour (Unit for volumetric flow rate)
IR	- Infrared
NIR	- Near-Infrared (750 nm to 2500 nm)
PG	- Propylene Glycol
PU	- Polyurethane
PV	- Photovoltaic
PV/OF	- Photovoltaic-Optical Filter
PVT	- Photovoltaic-Thermal
PMMA	- Poly Methyl Methacrylate
RTE	- Radiative Transport Equation
SBS	- Spectral Beam Splitting
SDS	- Sodium Dodecyl Sulfate
STC	- Standard Test Conditions (1000 W/m ² , AM 1.5, 25 °C)
TESPI	- Thermal Electric Solar Panel Integration
UV	- Ultraviolet (300 nm to 400 nm)
VIS	- Visible Spectrum (400 nm to 750 nm)

List of Symbols

A_{filter}	Area of Filter (m^2)
A_{pv}	Area of PV panel (m^2)
Cp_f	Specific heat of water ($J/kg \cdot K$)
Cp_p	Specific heat of Nanoparticle (TiO_2) ($J/kg \cdot K$)
Cp_{nf}	Specific heat of Nanofluid ($J/kg \cdot K$)
E_L	elevation of the location above sea level (km)
f_c	Normalizing factor
G	Solar radiation on the PVT (W/m^2)
G_a	Solar radiation above the filter (W/m^2)
G_b	Solar radiation below the filter (W/m^2)
$\bar{H}_g$	Monthly average of daily global radiation on horizontal surface (kJ/m^2 -day)
$\bar{H}_o$	Monthly average of daily extraterrestrial radiation (kJ/m^2 -day)
$\bar{H}_d$	Monthly average of daily diffused radiation on horizontal surface (kJ/m^2 -day)
I_{sc}	Extraterrestrial radiation (kW/m^2)
$\bar{I}_g$	Monthly average of instantaneous global radiation in horizontal surface at $\omega = 0$ (W/m^2)
$\bar{I}_o$	Monthly average of instantaneous extraterrestrial radiation in horizontal surface at $\omega = 0$ (W/m^2)
$\bar{I}_d$	Monthly average of instantaneous diffused radiation in horizontal surface at $\omega = 0$ (W/m^2)
I_T	Flux falling on Tilted surface (W/m^2)
I_b	Beam component of flux falling on Tilted surface (W/m^2)
I_d	Diffused component of flux falling on Tilted surface (W/m^2)
I_{mp}	maximum rated power current of PV panel (amp)
$I_{sc(pv)}$	short-circuit current of PV panel (amp)
k_f	Thermal Conductivity of fluid (water) ($W/m \cdot K$)
k_p	Thermal Conductivity of Nanoparticle (TiO_2) ($W/m \cdot K$)
k_{nf}	Thermal Conductivity Nanofluid ($W/m \cdot K$)
$\bar{K}_t$	monthly average clearness index
$\dot{m}_{nf}$	Mass flow rate of nanofluid (Kg/sec)
n	day of the year
P_{max}	Maximum power of solar panel (W)
P_{STC}	Rated power of solar panel (W)
P_{drop}	Power drop due to temperature rise of PV Panel (W)
Q_{th}	Heat Gain by the filter (W)

r_b	Tilt Factor for beam radiation on tilted surface
r_d	Tilt factor for diffused radiation on tilted surface
r_r	radiation shape factor for tilted surface
$\bar{S}$	Monthly average of sunshine hours per day at the location (h)
$\bar{S}_{max}$	Monthly average of maximum possible sunshine hours per day / day length (h)
S_T	Incident solar radiation on PV panel (W/m ²)
T_{cp}	Temperature drop coefficient (W/°C)
T_{STC}	Temperature of Solar Panel at STC (°C)
T_{pv}	Temperature of solar panel during operation (°C)
T_{amb}	Ambient temperature (°C)
T_{in}	fluid inlet temperature (°C)
T_{out}	fluid outlet temperature (°C)
ΔT	Temperature Difference (°C)
V_{oc}	Open Circuit Voltage (V)
V_{mp}	maximum rated power voltage of PV panel (V)
V_{nf}	Volume of nanofluid collected in beaker in t sec (m ³)

Greeks

ω_p	Mass fraction (g/kg(nf))
ρ_f	Density of base fluid (water) (kg/m ³)
ρ_p	Density of Nanoparticle (TiO ₂) (kg/m ³)
ρ_{nf}	Density of Nanofluid (Kg/m ³)
φ	Volume fraction
γ	Azimuth angle of the setup (Degree)
ω	Hour angle (Degree)
δ	Declination angle (Degree)
ϕ	Latitude of the location (Degree)
β_{opt}	Optimum tilt angle at the location (Degree)
τ	Transmissivity
α	Absorptivity
ρ	Diffused reflectivity
ω_s	Hour angle at sunrise /Sunset (maximum day length) (degree)
η_{ele}	Electrical Efficiency
η_{th}	Thermal Efficiency
$\eta_{overall}$	Overall efficiency of PVT system

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CHAPTER 1

Introduction

1.1 Preamble

The fast depletion of conventional fossil fuels with the increasing energy demand globally have driven a major transition toward sustainable and renewable energy resources. Among the various available alternatives, solar energy has emerged as the most abundant, clean, and inexhaustible source. The solar photovoltaics technology converts sunlight to electrical energy directly using semiconductor materials through the photoelectric effect, and owing to its simplicity, modularity, and decreasing cost trend, it has become one of the fastest-growing renewable technologies worldwide [1]. When photons strike a semiconductor junction, electrons are excited to higher energy states, generating an electric current.

Over the past few decades, PV systems have emerged as one of the fastest expanding renewable energy technologies due to their modularity, low maintenance requirements, and continually declining installation costs [1], [2]. Among existing PV technologies, silicon (Si) solar cells dominate with a global market share of over 95 %, mainly due to their maturity, stability, and availability. [3].

Under STC (Standard Test Conditions) i.e. the solar irradiance of 1000 W/m^2 , air mass 1.5, and 25°C operating temperature: typical Si modules exhibit efficiencies between 15-20 %. However, in outdoor operation, module temperature frequently rises above 60°C , particularly in tropical climates, resulting in substantial efficiency loss. The semiconductor band-gap energy decreases with temperature, which lowers the open-circuit voltage (V_{oc}) and hence a decrease in power output. The average power loss is approximately 0.45-0.5 % per $^\circ\text{C}$ rise beyond STC [4], [5], [6], [7]. Thus, managing temperature rise is crucial for improving overall PV performance and reliability.

To mitigate this thermal degradation, the Photovoltaic-Thermal (PVT) concept was introduced, in which a working fluid such as air, water, or a nanofluid is circulated over or beneath the PV module in direct contact to extract the excess heat. The recovered heat is utilized for water heating, space heating, or industrial purposes, thereby producing both electrical and thermal energy simultaneously from the same

surface [8]. Such systems offer improved overall energy utilization compared to standalone PV or solar-thermal collectors.

Nevertheless, conventional PVT systems illustrated in Figure 1.1 suffer from an inherent trade-off between electrical and thermal efficiencies [9].

When the fluid temperature is kept low to cool the PV surface, the electrical efficiency improves but the thermal output decreases; conversely, higher fluid temperatures enhance thermal yield but cause overheating of the PV module, reducing electrical output. Hence, it is challenging to maximize both simultaneously within traditional PVT configurations.

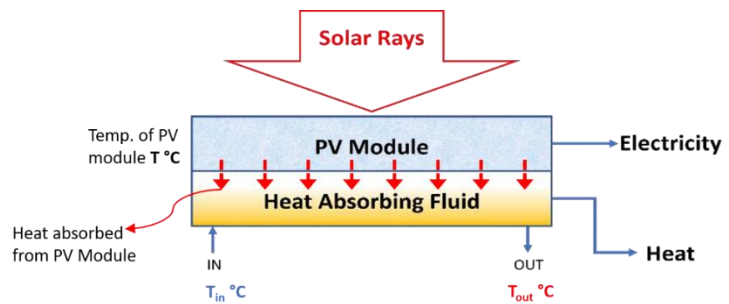


Figure 1.1 Conventional PVT System

1.2 Problem Statement

Conventional Photovoltaic–Thermal (PVT) systems (figure 1.1) attempt to address the heating issue by circulating a fluid to cool the PV surface by direct contact while recovering thermal energy. However, these systems face a fundamental limitation:

“The electrical and thermal efficiencies cannot be maximised simultaneously in conventional PVT systems because the thermal output is restricted to lower temperature to maintain the efficiency of PV module and prevent overheating.”

At lower fluid temperatures, although electrical efficiency improves, the recovered heat is of limited quality. Conversely, extracting high-temperature heat reduces cooling effectiveness and leads to PV overheating. This inherent thermo-optical conflict prevents PVT systems from achieving their full energy potential.

1.3 Spectral Beam Splitting

A potential approach to overcome this limitation involves Spectral Beam Splitting (SBS) technology illustrated in figure 1.2 [10], [11]. For the first time in 1955, Jackson proposed the idea of harvesting solar energy by dividing the solar spectrum and directing each band to the effective converter [12]. While Imenes and Mills [13] provided a comprehensive review of spectral beam splitting up to 2003, the field has since evolved significantly to achieve much higher conversion efficiencies and greater

design flexibility. The solar spectrum reaching the Earth comprises ultraviolet (UV), visible (VIS), and near-infrared (NIR) parts, wavelength ranging from 300 to 2500 nm [14], [15]. The solar cell uses only some part of solar spectrum to effectively convert into electricity, this wavelength range is called responsive range, while other wavelengths mainly contribute to heating[16] [17]. Different solar cell materials have different responsive ranges.

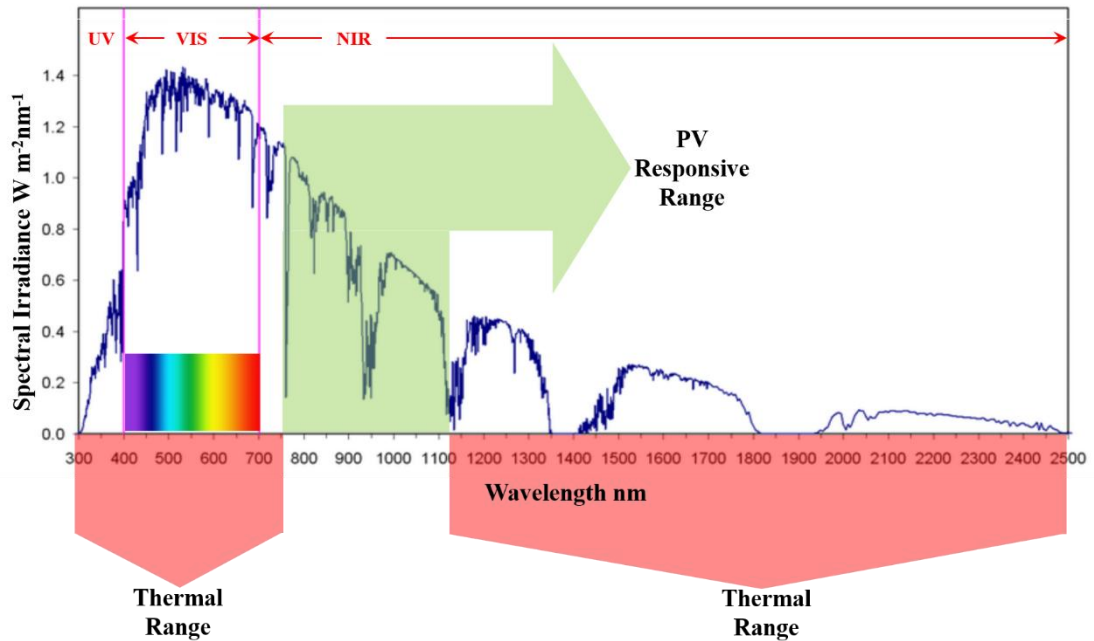


Figure 1.2 Spectral Beam Splitting concept showing C-Si Responsive range and thermal range.

Figure 1.3 shows different solar cells responsive ranges. The responsive range of a silicon solar cell is between 751 nm and 1126 nm, indicating that the silicon solar cell converts only the incident wavelengths within this range into electrical energy [17]. Beam-splitting systems aim to separate the useful (responsive range) part of the spectrum and divert the remaining thermal range to a secondary absorber (figure 1.2). This enables the PV cell to operate at a lower temperature while simultaneously harvesting the otherwise wasted energy as heat.

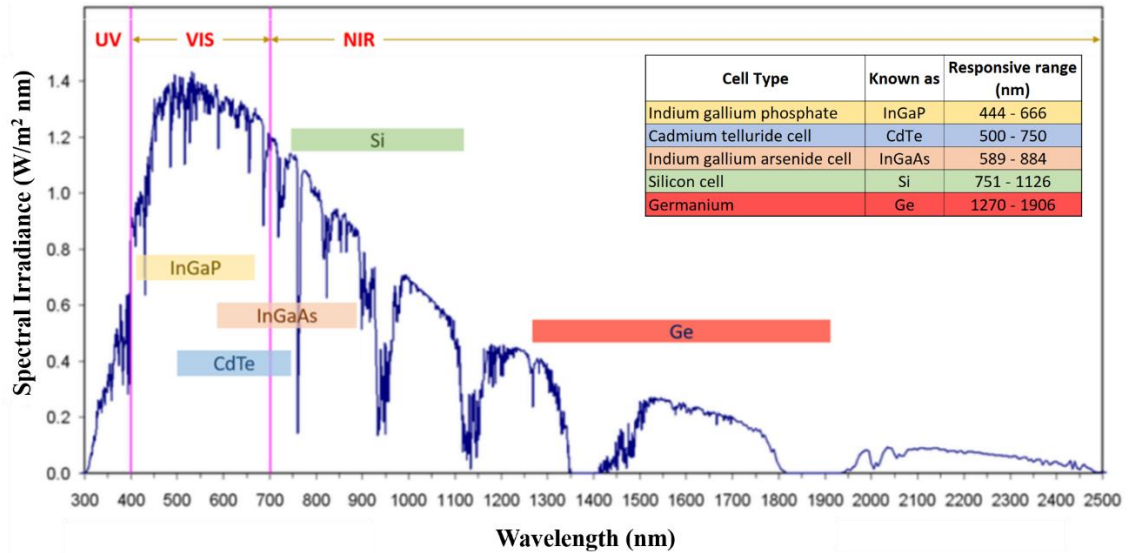


Figure 1.3 Responsive wavelength ranges of different photovoltaic materials plotted on ASTM G-173 graph

Compared to conventional glass or solid beam splitters, liquid-based systems are more cost-effective, and offer tuneable optical and thermal properties. An advanced implementation of this

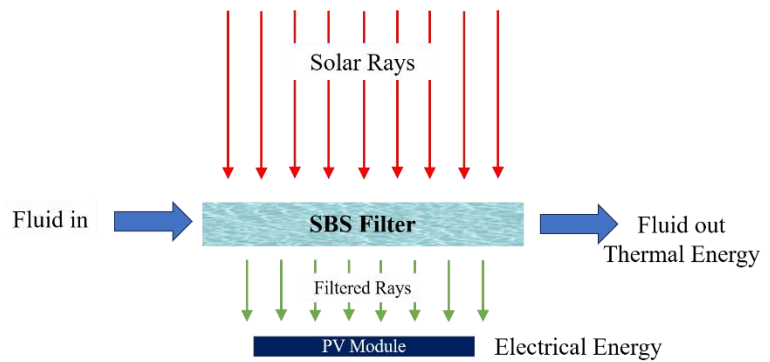


Figure 1.4 Concept Visualization of the fluid-based (SBS) filter above PV module to filter out the heating waves.

concept is the fluid-based spectral beam-splitting (SBS) system introduced by Powell [18], wherein a fluid filter is positioned before the photovoltaic (PV) module to selectively absorb the thermal portion of the solar spectrum while allowing only the responsive wavelengths to transmit and reach the PV module. Figure 1.4 illustrates the conceptual visualization of this arrangement. In this technique, the fluid-based spectrum filter acts as an intermediary layer between the incident solar radiation and PV surface. The filter absorbs the thermal range of the solar spectrum and transmits the useful portion that contributes to electrical power generation. Consequently, the unwanted heating effect on the PV cell is minimized, improving electrical performance while enabling simultaneous heat extraction from the fluid.

Heat can be extracted from absorption filter and electricity from PV cell without raising the temperature of the cell. One of the benefits of using the fluid-based absorption filter is that the optical and thermal properties are tuneable and it can be pumped in and out for effective extraction of heat[17]. Figure 1.5 shows the concept of an ideal fluid filter for a silicon cell.

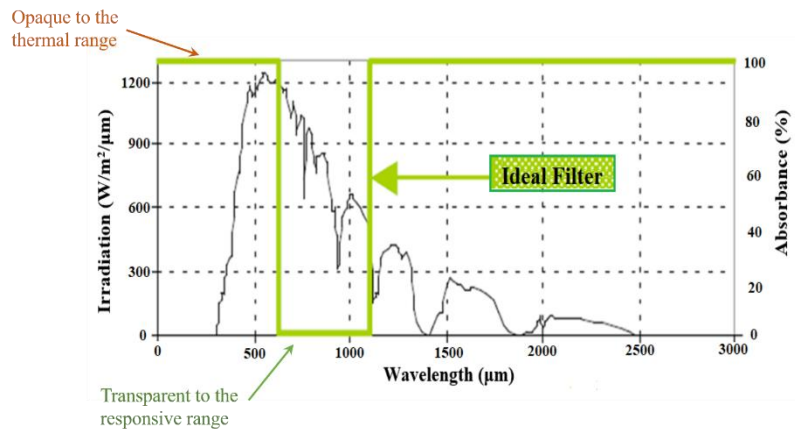


Figure 1.5 Optical characteristics of Ideal Filter for a Si Solar Cell

1.4 Research Motivation

The motivation for this research stems from the need to develop a low-cost, tuneable, and practical spectral-splitting system that can simultaneously cool the PV module, improve its electrical output, and recover usable heat under real outdoor conditions. Despite several numerical and simulator-based studies reported in literature, there remains a lack of experimental authentication of fluid-based SBS systems under natural solar irradiance.

Accordingly, the present work focuses on the development, fabrication and experimental analysis of a fluid-based absorption filter integrated with a solar PVT system. The research aims to design a portable and adjustable test setup capable of operating under field conditions, evaluate the performance of various nanofluid concentrations and flow rates, and determine their impact on the thermal-electrical performance coupling. The outcomes are expected to contribute toward realizing a high-efficiency hybrid solar collector that effectively utilizes the entire solar spectrum for enhanced renewable energy conversion.

1.5 Objectives of the Research

1. **To identify suitable fluid for Spectral Beam Splitting (SBS) filter for solar PVT system.**
 - a. Identify potential nano particle and base fluid for spectral beam splitting filter.

- b. To perform spectroscopic analysis of nanofluids to identify optimal concentrations for spectral selectivity.

2. Development of Beam Split Photovoltaic-Thermal (BSPVT) system for experiment in natural and real operating environment.

- a. To design and fabricate a portable, adjustable, and cost-effective experimental setup for evaluating the PVT system with fluid-based absorption filters.
- b. To develop a filter housing to circulate an optically selective nanofluid over the PV panel for effective spectrum separation and heat absorption.

3. Performance analysis of the system developed and feasibility for sustainable commercial operation.

- a. To carry out theoretical performance estimation of the BSPVT system.
- b. To experimentally investigate the system under different configurations.
- c. To assess the feasibility and potential of the fluid-based SBS for complete solar energy utilization

1.6 Thesis Organization

The thesis is organized into 8 distinct chapters, following a logical progression from theoretical motivation and literature review to experimental validation and final conclusions.

Chapter 1: Introduction

This chapter provides the preamble to the research, discussing the global energy crisis and the importance of solar energy. It introduces the "thermo-optical conflict" in photovoltaic systems where solar radiation not only generates electricity but also causes efficiency-killing heat. The chapter concludes by defining the specific research problem, objectives, and the scope of this study.

Chapter 2: Literature Review

A systematic review of existing solar technologies is presented here, focusing on the evolution of Photovoltaic-Thermal (PVT) systems. It examines previous studies on spectral beam splitting and the emerging role of nanofluids in solar engineering. This chapter identifies the research gap that this thesis aims to fill, particularly the need for outdoor experimental validation BSPVT systems.

Chapter 3: Selection, Preparation and Testing of Nanofluid

This chapter details the selection criteria for the candidate nanofluids and the subsequent identification of the most effective nanoparticles for the system. Through rigorous spectrometric analysis, the transmissivity of each fluid is evaluated to determine its optical performance. Based on these findings, the most suitable nanofluid is selected to proceed with the comprehensive analysis of the BSPVT system.

Chapter 4: Theoretical Estimation of Performance

This chapter outlines the mathematical framework used to predict the electrical as well as thermal performance of the proposed system. The theoretical investigation confirms that the integration of a liquid spectrum filter in a BSPVT system significantly enhances overall system performance by enabling simultaneous electrical and thermal energy generation.

Chapter 5: Design of Experimental Setup

This chapter presents the visualization, design and fabrication of a modular, adjustable support structure that serves as a robust experimental platform. It details the integration of the fluid circuit, the specific geometry of the nanofluid filter, the PV mounting mechanisms, and the diagnostic instrumentation utilized for data acquisition.

Chapter 6: Experimental Methodology

This chapter details the "how-to" of the research. It describes the experimental site in Daman, India, and defines the three experimental cases (PV with no filter, PV with empty filter, and Integrated BSPVT) used for comparative analysis. Method of data acquisition is discussed to collect data for rigorous analysis. A robust comparative framework to evaluate the performance of BSPVT system in real-world outdoor conditions is shown.

Chapter 7: Observation, Results and Discussion

This chapter presents the experimental findings. It provides a detailed comparison of the three cases, highlighting how the BSPVT system reduced panel temperatures by. It discusses the impact of varying volumetric flow rates and identifies the optimal point for overall system efficiency.

Chapter 8: Conclusion and Future Scope

The final chapter recapitulates the Key Findings of this research, outcomes and contribution of the research, comparison with similar previous researches, and future scope of research.

CHAPTER 2

Literature Review

The contents presented in this chapter have been published in a review article: Jiwanapurkar, P.R., Bhargav, H.A., and Ramani, B. (2023). “*Fluid-based solar spectral beam splitters for hybrid photovoltaic thermal systems: A review.*” International Journal of Renewable Energy Technology, 14(3), 241–258. [9]

A comprehensive review showing the development in fluid-based spectral beam-splitting (SBS) filters utilizing organic fluids as well as nanofluids over the past decade has been presented in this chapter. Various pure/organic fluids and nanofluids were investigated as potential SBS filter media have been explored. Among organic fluids; silicone oil, coconut oil and water were recognized as promising candidates for effective solar spectrum filtering. Mathematical estimations indicated achievable electrical and thermal efficiencies of approximately 14% and 79%, respectively. Furthermore, the highest overall efficiencies of 56% and 62% for photovoltaic-thermal (PVT) systems employing fluid-based SBS filters were reported when using crystalline-silicon (C-Si) and gallium arsenide (GaAs) solar cells, respectively, in combination with gold (Au) nanofluids. However, it was also noted that the price of nanofluids must be justified by a corresponding upgrading in the system’s overall efficiency.

2.1 Study based on organic/inorganic fluids as SBS filter.

Several pure fluids and their blends have been investigated for their effectiveness as spectral beam-splitting (SBS) filters. An appropriate selection of fluid is essential, not only for its optical selectivity but also for its favourable thermal properties, ensuring that the absorbed heat can be efficiently transferred to the desired medium.

Maiti et al. [19] examined a mixture of propylene glycol, ethylene glycol, and glycerol in a volumetric ratio of 1:1:3 as a potential filtering medium. The performance of a 0.13 m² silicon PV module was evaluated under outdoor conditions, both with and without the use of a concentration mechanism and filter. It was reported that the average electrical performance doubled when the solar concentration was increased fivefold.

However, in the absence of a filter, the PV module temperature increased uncontrollably, adversely affecting its performance.

In another study, Vijayaraghavan et al. [20] investigated the use of copper sulphate (CuSO_4) solution as a spectral attenuation medium under concentrated

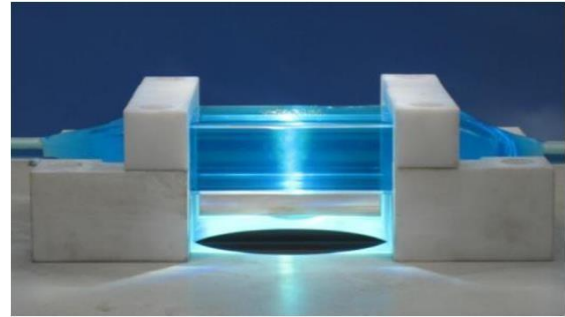


Figure 2.1 Borosilicate volumetric absorber with copper sulphate solution.

sunlight achieved through a Fresnel lens. The system utilized a 2 cm optical path length in a borosilicate volumetric absorber, as shown in Figure 2.1. The results revealed that a CuSO_4 concentration of 40 g/L absorbed approximately 67% of the solar spectrum, while an increase to 60 g/L resulted in a marginal improvement to 69% absorption. Moreover, flow rate variations were found to have negligible influence on thermal efficiency, indicating that the concentration ratio of the CuSO_4 solution played a more dominant role in determining spectral attenuation characteristics.

Joshi et al. [21] investigated the performance of a crystalline silicon (C-Si) solar cell under a solar simulator using thirteen different fluids as potential spectral beam-splitting (SBS) filters. Figure 2.2 presents the experimental setup employed for the study. Among the tested liquids, coconut oil, silicone oil, and water were identified as the most effective optical filters for C-Si cell-based photovoltaic–thermal (PVT) systems. It was further observed that the usage of processed coconut oil resulted in a notable enhancement in the solar cell's electrical performance, demonstrating its suitability as an optically selective and thermally stable fluid medium.

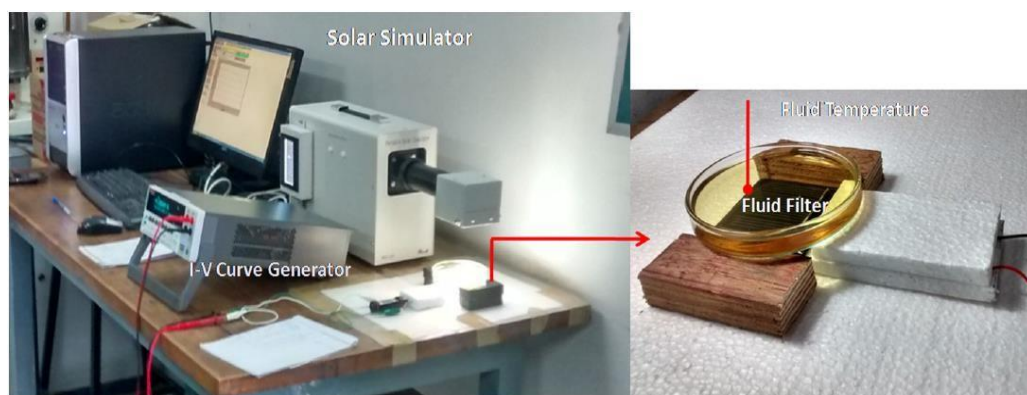


Figure 2.2 Fluid tested under a solar simulator [21]

Water has been widely explored as an optical filtering medium to reduce the thermal load on photovoltaic (PV) modules under natural sunlight. Al-Shohani et al.[22], [23] investigated the effect of water path length on the cell temperature, as well as the performance of PV modules. Their study demonstrated that the thickness of the water layer significantly affects system performance, with an optimum layer thickness of 4 cm yielding the best results. However, the gap between the water filter and the PV module was found to have no significant influence on the overall performance.

Building on this approach, Ramdani et al. [24] proposed a novel conceptual design in which a water layer is directly superimposed on a PV module, allowing water to function simultaneously as a direct absorber and an SBS filter. Through simulation-based analyses, the authors investigated the influence of intrinsic and extrinsic parameters on the overall energetic and exergetic performance of the PVT system. Their findings revealed that the proposed design outperformed conventional PVT systems, both in energy yield and efficiency.

Chemisana et al. [25] identified the fundamental optical, thermal, and electrical properties that an effective fluid-based SBS filter should possess. Based on these criteria, a selection of pure and blended liquids was evaluated. Among the tested candidates, a blend of isopropyl alcohol + deionized water exhibited the most favourable balance of optical transmission and thermal stability, making it the optimum choice for SBS applications.

Further experimental investigations were conducted by Joshi et al. [26], [27], [28], who recorded the optical attenuation characteristics of water, coconut oil, and silicone oil, and subsequently determined their transmissivity-absorptivity ($\tau\alpha$) product using Snell's and Bouguer's laws. Mathematical estimations indicated thermal and electrical efficiencies of approximately 79% and 14%, respectively. The feasibility of employing a silicone oil 1 cm-thick layer as an optical solar filter for an Si PV module was evaluated under natural sunlight in Nagpur, India, over a one-year period. On average, a 10 W PV module achieved a 27 W thermal gain, while its electrical performance improved marginally with the silicone oil SBS filter. It was further reported that approximately 239 W/m² of the undesired solar spectrum was effectively attenuated by the filter. The study also examined the long-term optical stability of silicone and coconut oils under prolonged solar exposure. It was observed that coconut

oil exhibited enhanced optical properties with aging, whereas silicone oil showed degradation, highlighting the importance of stability considerations for sustained SBS filter performance.

For a comprehensive understanding of SBS fluid behaviour, it is essential to analyse the optical transmittance of the fluid to determine wavelength-specific transmission characteristics. Maiti et al. [19] conducted one of the earliest such studies, evaluating the optical transmittance of a propylene glycol-ethylene glycol-glycerol mixture (1:1:3). The results indicated that the transmissivity of the blend closely aligned with the spectral responsive range of silicon PV cell.

The optical transmittance of eighteen commercial heat transfer fluids was experimentally characterized, alongside an assessment of their photostability under prolonged UV exposure by Looser et al. [29]. Among these, Duratherm G, Duratherm 600, pink-dyed propylene glycol, Royco 782, and industrial propylene glycol demonstrated superior optical stability and transmission characteristics. However, these fluids were found to be expensive and environmentally non-friendly, rendering them unsuitable for large-scale or sustainable applications.

In a subsequent study, Han et al. [30] evaluated the optical characteristics and filtering performance of several fluids using a 10 mm path length spectrophotometer setup for both GaAs and monocrystalline silicon solar cells. Their analysis revealed that Valvoline oil, inorganic aqueous salts, and copper salts significantly enhanced the commercial value of Si and GaAs cells by 20% and 34%, respectively as compared to stand-alone PV operation. In a concentrated PVT configuration, valvoline oil exhibited the maximum merit function, with the absorbed thermal energy playing a vital role in the system's overall energy output.

Further progress was made by Rosa et al. [31], [32], who developed the Thermal Electric Solar Panel Integration (TESPI) system. In this design, water flows through a serpentine channel positioned above the PV surface to filter unwanted solar radiation and reduce module temperature. The serpentine flow channel and actual photo of TESPI is shown in figure 2.3. Although the electrical efficiency of the PV module declined slightly, the overall combined efficiency of the TESPI system was significantly improved, demonstrating the advantage of hybrid configurations for improved energy utilization.

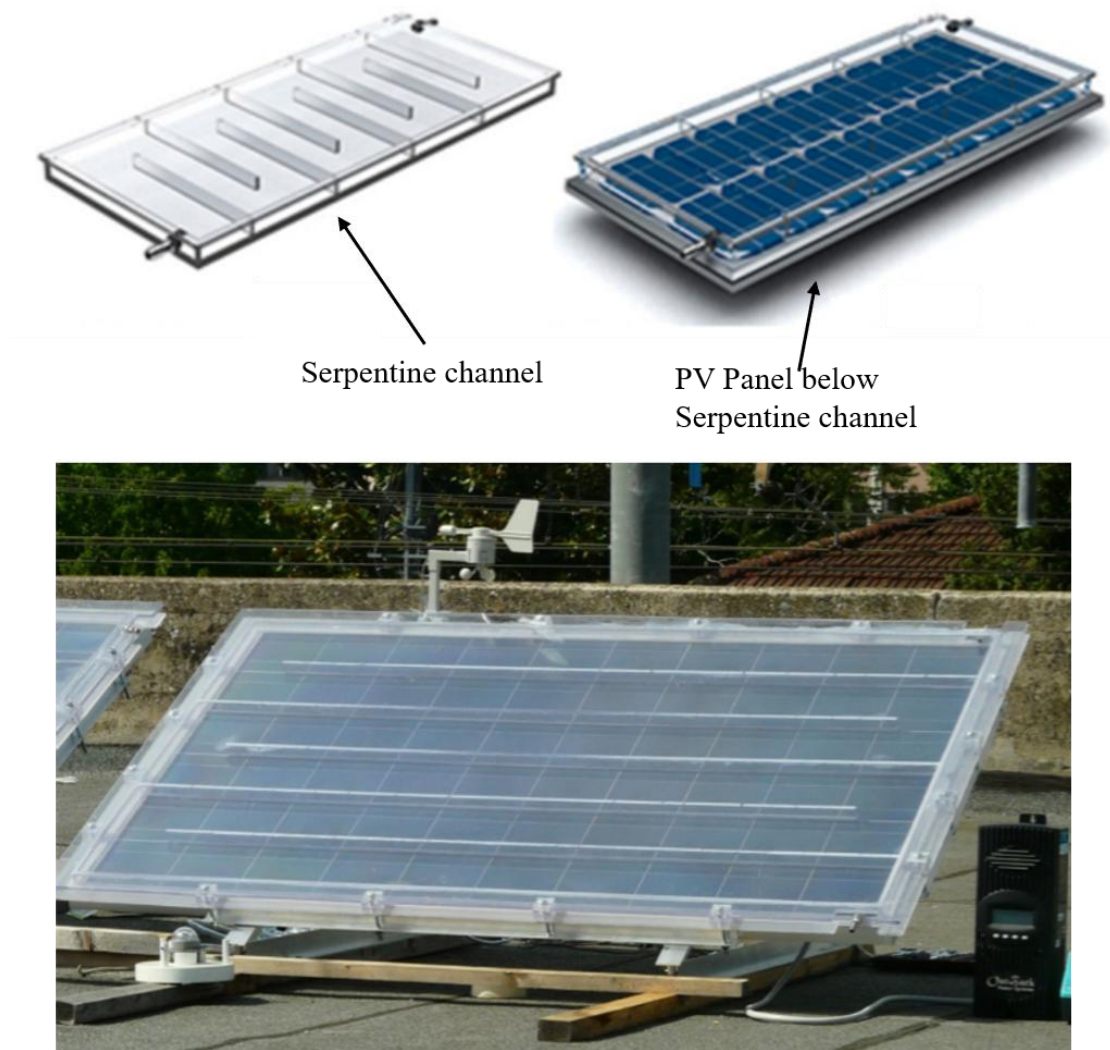


Figure 2.3 Thermal Electric Solar Panel Integration (TESPI) system [31] [32]

2.2 Study based on Nano Fluids as SBS filter.

The application of nanofluids for direct heat absorption and enhanced thermal performance has become increasingly popular in photovoltaic–thermal (PVT) systems, with numerous studies reporting promising results [33], [34]. In recent years, nanomaterials and nanofluids have also gained significant attention within the domain of spectral beam-splitting (SBS) technology, owing to their tuneable optical and thermal characteristics. The principal advantage of nanofluids lies in their ability to be engineered to exhibit desired spectral selectivity and enhanced heat transfer properties, thereby improving the overall performance of hybrid PVT collectors [17].

Taylor et al. [17] demonstrated that by manipulating the particle type, concentration, and size, the spectral absorption characteristics of nanofluids can be tailored to achieve optimal beam-splitting behaviour. Building upon this concept,

several mathematical and theoretical models were developed to assess the performance of precious metal-based nanofluids, particularly gold (Au) and silver (Ag), despite their high cost.

Saroha et al. [35] proposed a nanofluid-based hybrid PVT collector and performed numerical modelling to analyse the system's performance with primary and secondary fluid circulation loops. The study focused on Ag and Au nanofluids integrated with a crystalline silicon (C-Si) solar cell, comparing theoretical and experimental findings. The results, illustrated in Figures 2.4 & 2.5, showed a strong correlation between simulation and experimental outcomes. Among the tested fluids, the Ag (silver) nanofluid exhibited the highest photovoltaic, thermal and overall efficiency. The authors concluded that continued research into nanofluid composition and PV cell compatibility could lead to combinations that closely approximate the characteristics of an ideal optical filter, thereby maximizing both electrical and thermal energy conversion efficiencies.

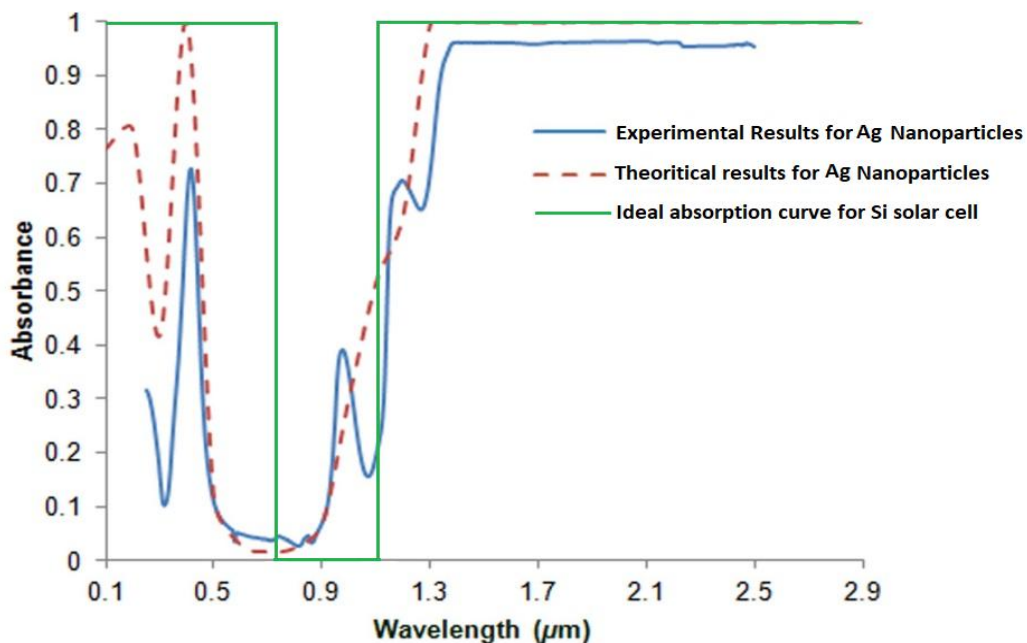


Figure 2.4 Theoretical and experimental comparison between absorbance for silver nanoparticles imposed on ideal SBS filter absorbance curve for C-Si solar cell [35]

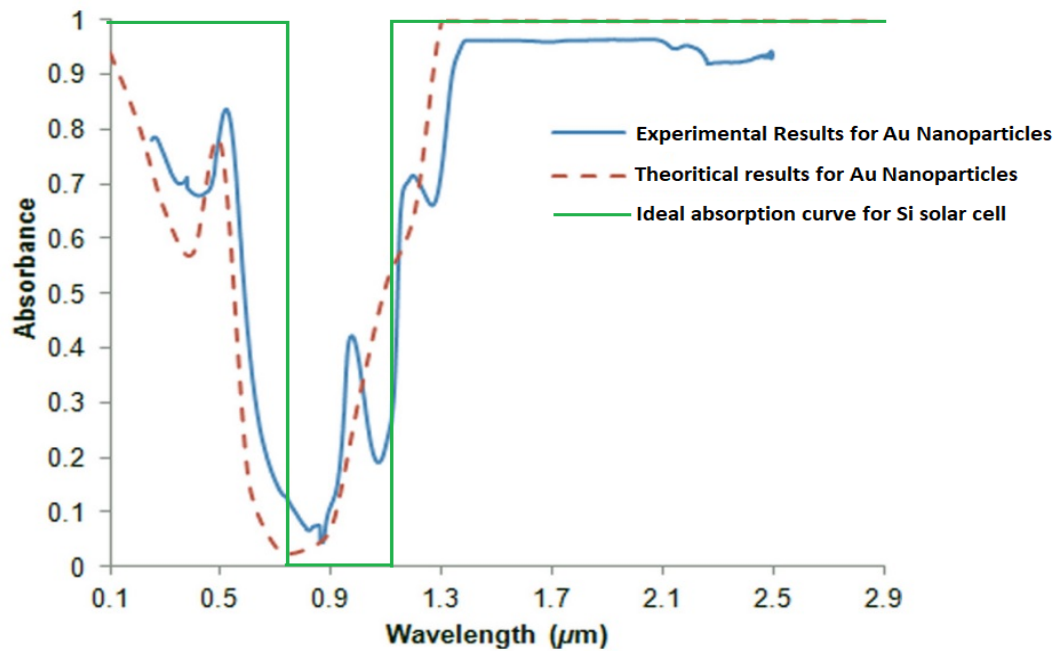


Figure 2.5 Theoretical and experimental comparison between absorbance for gold nanoparticles imposed on ideal SBS filter absorbance curve for C-Si solar cell [35]

Jing et al. [36] developed a two-dimensional (2D) numerical model to analyse the performance of a SiO₂/water nanofluid filter under varying solar concentration levels up to 100 suns. The simulation results indicated that the optimal performance was achieved at 40 suns solar concentration and a filter fluid velocity of 0.015 m/s. For a nanoparticle size of 5 nm and a volumetric fraction of 2%, the thermal conductivity of the fluid was enhanced by approximately 20%, while the optical transmissivity remained at 97% of that of pure water, demonstrating a favourable balance between optical transparency and thermal enhancement.

Experimental investigations were also conducted on nanofluids under both laboratory and outdoor conditions. Cui and Zhu [37] examined the performance of a MgO/H₂O nanofluid filter placed above a 25 W photovoltaic module operating under natural sunlight. The study revealed that the optical transmittance of the nanofluid reduced with increasing mass fraction of nanoparticles, resulting to a corresponding decrease in the electrical performance of the solar cell. This decline was attributed to the increased opacity of the nanofluid at higher particle concentrations, which impeded light transmission to the PV surface. Despite this, the thermal efficiency of the nanofluid-based PVT system was significantly higher than that of a conventional PV module, compensating for the marginal electrical losses. As summarized in Table 2.1,

the aggregate (electrical + thermal) efficiency of the system exceeded 60% under optimized parameters, demonstrating the potential of nanofluid filters for hybrid solar energy conversion.

Table 2.1 Performance of PV and PVT modules under MgO/water nanofluid [37]

Parameter	PVT with a 2 mm thick liquid film	PVT with a 4 mm thick liquid film	PV module
T_{pv} (°C)	27.3	27.8	23.1
ΔT (°C)	7.5	5.1	--
η_{ele}	14.7%	14.0%	15.9%
η_{th}	47.2%	32.0%	--
$\eta_{overall}$	61.9%	46.0%	15.9%

Wei An et al. [38] experimentally investigated the performance of a Cu₉Ss/oleylamine-based optical filter integrated with a concentrated photovoltaic–thermal (PVT) collector under natural sunlight using a Fresnel lens for optical concentration. The system achieved a peak efficiency of 34.2%, making a 17.9% improvement over the non-filtered configuration. The highest fluid temperature attained was 100 °C. In preliminary trials utilizing polypyrrole nanofluids, it was found that excessive particle concentration negatively affected the photovoltaic (PV) efficiency, indicating that an optimum nanoparticle concentration must be determined to achieve a balance between electrical and thermal performance.

The concept of multi-particle nanofluids was subsequently explored by several researchers. DeJarnette et al. [39] developed a nanofluid optical filter composed of gold nanoparticles and indium tin oxide (ITO) nanocrystals. The radiative transport equation (RTE) was applied to assess the optical characteristics of the composite fluid based on the properties of the individual nanoparticles. The filter efficiency was reported as 56% for a crystalline silicon (c-Si) cell and 62% for gallium arsenide (GaAs) PV cells. Otanicar et al. [40] also investigated a Duratherm S-based nanofluid containing a mixture of gold and ITO nanoparticles, evaluating its performance in a prototype concentrated PVT system operating above 100 °C. Under 14× solar concentration, the system achieved 4% electrical efficiency and 61% thermal efficiency, indicating an optimal operating point for hybrid systems.

In another study, Han et al. [41] inspected the optical and electrical performance of an Ag/CoSO₄–water nanofluid filter integrated with a PVT system. The Merit Function of the system was found to peak at an Ag concentration of 37 ppm, outperforming an Ag/water nanofluid filter. Furthermore, the researchers prepared nanofluids using Ag nanoparticles dispersed in a hybrid base fluid composed of CoSO₄ and propylene glycol (PG) and tested them with c-Si PV cells. The total system efficiency of the hybrid base fluid nanofluid filter was observed to be 9% greater than that of the Ag/CoSO₄-H₂O nanofluid filter system.

The core-shell Ag@SiO₂ nanoparticles have gained significant attention due to their tuneable visible-light absorption and high optical selectivity. Hjerrild et al. [42] investigated a multiparticle nanofluid filter consisting of Ag@SiO₂ nanodiscs and carbon nanotubes (CNTs) dispersed in water, combining both experimental and theoretical analyses. The Ag@SiO₂ nanodiscs were engineered to absorb visible wavelengths while transmitting the spectrally responsive region for silicon solar cells, whereas CNTs enhanced the heating rate of the nanofluid. Compared with a pure water filter, the Ag@SiO₂/water nanofluid (0.026 wt%) improved the overall PVT system efficiency by 30%. Subsequently, in a follow-up study, Hjerrild et al.[43] examined three PV materials c-Si, GaAs, and Ge paired with Ag@SiO₂ nanoplates and Au/Au–CuSiO₂-based nanofluids under 1 sun and air mass (AM) 1.5 solar simulation. The combination of c-Si PV cell and Ag@SiO₂/water nanofluid exhibited the peak overall efficiency (40%), validating the potential of this filter design for solar spectrum management.

Similarly, Felipe et al. [11] utilized core-shell Ag-SiO₂ nanoparticles dispersed in water to filter solar radiation optimally for silicon PV cells. They developed and validated a combined optical-thermal transmission model using experimental data obtained from a prototype subjected real outdoor conditions. The system demonstrated a 12% higher energy output compared to a standalone PV module, highlighting its industrial applicability for co-generation of heat and power.

Huang Ju et al. [44] synthesized Ag@SiO₂ nanoparticles with controlled shell thickness and suspended them in a propylene glycol-CoSO₄ hybrid base fluid. At 25.4 mg/L concentration, the filter efficiency reached 63.3%, accompanied by an economic performance index of 67.8%, showing promise for cost-effective PVT applications. Li

et al. [45] further explored Ag@TiO₂/water nanofluid as a beam-splitting medium for PVT systems, reporting high transmittance in the silicon cell's responsive range and strong absorption within the visible spectrum, thereby improving overall energy utilization.

Abdelrazik et al. [46] highlighted that the performance of fluid-based SBS filters is strongly influenced by ambient temperature. Their photovoltaic-optical filter (PV/OF) system, employing Ag-water nanofluid, exhibited superior operation at elevated temperatures, achieving an overall efficiency of approximately 75% at 45 °C.

In an innovative approach, Jin et al. [47], [48] proposed a magnetic electrolyte nanofluid (ENF) for use as a fluid optical filter in BSPVT applications. The transmittance characteristics were analysed using UV-Vis spectrophotometry and a solar simulator (1 sun). The ENF demonstrated better optical control and cost efficiency compared to conventional core-shell nanofluid filters, making it a potential low-cost alternative.

Likewise, Liang et al. [48] investigated a ZnO/glycol-based nanofluid, reporting a 47% increase in photothermal efficiency as the concentration of nanoparticle rose from 11.2 ppm to 89.2 ppm. The study emphasized that ZnO/glycol nanofluids offer a significantly lower-cost solution compared to noble-metal-based fluids such as Ag and Au.

Despite these advancements, a major challenge in implementing nanoparticle-based SBS filters remains their high production cost, particularly associated with fabricating nanoparticles of small and uniform size. Ongoing research efforts are directed toward developing economical synthesis techniques and optimizing nanoparticle volumetric concentrations to achieve desirable optical and thermal characteristics, enabling high-performance yet cost-effective BSPVT systems.

2.3 Discussion

In recent years, noteworthy research efforts have been focused towards the development of fluid-based spectral beam-splitting (SBS) filters aimed at achieving higher overall efficiencies in hybrid photovoltaic-thermal (PVT) systems. These systems function by separating the photovoltaic and thermal components of solar energy conversion, thereby maximizing both electrical and thermal yields simultaneously. The primary focus of current research lies in identifying or formulating

an ideal working fluid whose optical absorption characteristics align closely with the spectral response of solar cells.

Numerous studies have explored both pure fluids and nanofluids for their suitability as SBS filters. For optimal performance, the fluid must exhibit a balanced combination of optical and thermal properties that is, high thermal conductivity and heat capacity to facilitate efficient heat transfer, coupled with selective optical absorption and transmission to achieve the desired spectral filtering effect. Consequently, the development of a fluid that can be tuned for specific absorptivity and transmissivity characteristics remains a major objective. To this end, multi-fluid blends have been prepared and experimentally tested to enhance spectral selectivity and heat transfer capability.

Researchers have investigated a wide range of pure fluids, fluid mixtures, and nanofluid formulations, assessing their performance under various operating conditions. In the case of nanofluids, the impact of parameters such as particle concentration, size, and scattering effects on the optical and thermal behaviour has been extensively examined. For instance, J. Tan et al. [49] analysed the scattering phenomena in TiO₂-based nanofluids, highlighting its impact on the optical characteristics relevant to SBS applications.

A major challenge in this domain is the high cost of noble-metal nanoparticles, particularly silver (Ag) and gold (Au), and their core-shell derivatives, despite their promising spectral selectivity. To address this limitation, researchers are increasingly exploring low-cost alternatives. For example, Liang et al. [48] reported a 47% enhancement in photothermal efficiency using a ZnO/glycol-based nanofluid, as the particle concentration raised from 11.2 ppm to 89.2 ppm, demonstrating its potential as an economical substitute for Ag or Au nanofluids.

A chronological summary of the various fluids and nanofluids tested for SBS filter applications in the past decade is presented below.

2.4 Summary of pure fluids and their blends (without nanoparticles)

The table 2.2 shows summary of studies based on organic/inorganic fluids as SBS filter in chronological order as discussed in section 2.1.

Table 2.2 Study based on organic/inorganic fluids as SBS filter.

Year	Author	Fluids examined	Comments
2010	Maiti et. al. [19]	1. 1-butyl-3-methyl imidazolium tetrafluoro borate 2. Mohr's salt 3. Glycerol 4. Ethylene glycol:propylene glycol:glycerol (1:1:3) (thiophenediyl benz- oxazole class 4ppm)	• Unsuitable due to oxidation stability issues • Highly viscous • In the wavelength range corresponding to the silicon responsive range, the liquid was completely transparent, although it absorbed considerably in the infrared.
2013	Vijayaraghavan et.al. [20]	Copper sulphate solution (CuSO ₄)	• An increasing amount of concentration did not have a significant effect
2016	Joshi et.al. [21]	1. Tap water 2. Distilled water 3. Saline water 4. Ethylene glycol 5. Glycerin 6. Transformer oil 7. Coconut oil 8. Rice bran oil 9. Al ₂ O ₃ nanofluid 10. Glycerin + water 11. Rice bran oil & transformer oil	• Coconut oil, Transformer oil and water were found as potential fluid for the SBS filter. • The solar cell's performance was improved by using processed coconut oil.

Year	Author	Fluids examined	Comments
2016	Al Shohani et.al. [22], [23]	Water as SBS Filter tested for the effect of thickness of a layer on performance	• Optimum Thickness 3 CM
2020	H. Ramdani et. al. [24]	Water is used as direct absorption and SBS filter simultaneously Modelled and Numerically simulated on ANSYS Fluent software	The novel PVT was found to be superior to the existing conventional PVT system
2018	D Chemisana et. al. [25]	Direct immersion of Solar cell in 1. Deionized water 2. Isopropyl alcohol 3. Isobutyl alcohol 4. Dimethyl sulfoxide 5. Glycerol 6. A few mixes with different volumetric fractions (IPA / GLY, IPA / DIW, DMSO / DIW and DMSO / IPA)	• Direct contact increase heat dissipation • Deionized water with isopropyl alcohol and deionized water with dimethyl sulfoxide were found to be the most effective. • Possible oxidation of components • Freezes above 0°C so not feasible for cold climates
2018	Joshi S [26]	Silicone oil (Transformer oil) is researched as a spectrum filter and heat absorber for C-Si solar cells.	• Significant heat gain is possible in a larger unit

Year	Author	Fluids examined	Comments
2018	Joshi S [27]	Ageing effect on water, silicone oil, and coconut oil as SBS filter for C–Si solar photovoltaic system	• Degradation of silicone oil is significant in a short time the Oil turns Yellow. • The electrical performance of the solar cell is reduced as silicone oil ages, but the electrical performance of the solar cell is increased when coconut oil ages.
2018	Joshi S [28]	Water, silicone oil, and coconut oil were tested for transmissivity range for C–Si solar photovoltaic systems	• The wavelength window for C-Si solar cells is compatible with these liquids. • Performance of solar cell to be verified physically
2014	R. Looser [29]	18 combinations of Glycols: industrial Propylene Glycol, Duratherm G, pink dyed Propylene Glycol (PG), Synthetic oils: Royco 782, Mineral oils: Duratherm 600.	• Propylene Glycol & Duratherm G were found optimum among other liquids • The PVT MCT system must be modelled with an emphasis on the number of heating cycles and combined heat exposure time.
2019	Xinyue Han et.al. [30]	Five groups of 17 liquids, i.e. glycol, synthetic oil, silicone oil, mineral oil and inorganic aqueous salt.	• With the CPVT system, the Valvoline oil filter has the highest merit function value, and the thermal energy produced plays an essential role in the system's combined energy production.

2.5 Summary of fluids with nanoparticles

The table 2.2 shows summary of studies based on Nano Fluids as SBS filter in chronological order as discussed in section 2.2.

Table 2.3 Summary of Studies based on Nano Fluids as SBS filter

Year	Author	Nanofluids examined	Comments
2012	Qunzh Zhu [37]	MgO/water nanofluid	• The fluid becomes more opaque with increased concentration of nanoparticles • Electrical efficiency becomes lower but overall efficiency increases
2015	Siddharth Saroha et.al [35]	Gold and Silver Nanofluids	• Results showed the feasibility of nanofluids as SBS filters. • Future research should focus on nanofluid filter and PV combinations that approach the optimum filter while improving electrical and thermal efficiency.
2015	Jing et.al. [36]	Silicon Dioxide/ water nanofluid	• Optimum at 40 suns solar concentration and filter fluid velocity 0.015 m/s.
2016	Wei An et.al. [38]	Oleylamine solution of 41 Cu ₉ S ₅ nanoparticle	• The heat-to-electricity ratio in PVT systems can be adjusted by adjusting the nanoparticle concentration to match the needs of various applications.
2016	DeJarnette et.al. [39]	Au (Gold) nanoparticles and nanocrystals of ITO (Indium tin oxide)	• The optical characteristics of the filter were based on individual nanoparticle properties, with 56 percent efficiency for nanofluid optimised for C-Si cells and 62 percent for GaAs cells.

Year	Author	Nanofluids examined	Comments
2017	Felipe et.al. [11]	Core-shell Ag-SiO ₂ nanoparticles in water	- Compared to a stand-alone PV system under the same illumination, this PVT prototype can produce 12% higher value (weighted energy output). - This technology can be used in industrial applications for combined heat and power generation.
2017	Jin et.al. [47]	Magnetic electrolyte nanofluid (ENF) was proposed.	For SBS PVT systems, ENFs can be effective low-cost optical liquid filters.
2018	Todd Otanicar et.al. [40]	Gold and indium tin oxide in base fluid Duratherm S	- Electrical efficiency of 4% and thermal efficiency of 61 percent were reached under 14X concentration, which was optimal. - A low-cost substitute for gold nanoparticles is to be found.
2019	Han et.al [41]	- Ag/CoSO₄-water nanofluid - Ag nanoparticles in fused base fluid (CoSO₄ +PG)	- Ag/CoSO₄-water nanofluid was superior than Ag/water nanofluid. - Total efficiency of Ag with fused base fluid was 9% greater.
2016	Natasha E. H. et.al. [42]	Core-shell Ag@SiO ₂ nanodiscs and carbon nanotubes in water	- Compared to a water filter alone, Ag@SiO₂/water nanofluids increased total efficiency by 30%. - Carbon nanotubes boosted the nanofluid's heating rate.

Year	Author	Nanofluids examined	Comments
2019	Natasha E. Hjerrild et.al. [43]	Ag@SiO ₂ nanoplates and Au/AuCu-SiO ₂ Nanofluids	• Highest overall efficiency was 40%
2019	Li et.al. [45]	Ag@TiO ₂ nanoparticles in water	• Nanoparticles exhibited strong absorptivity in visible light wavelengths and good transmittance in the silicon photovoltaic cell's spectral response range.
2020	Liang H [48]	ZnO in glycol base fluid	• The ZnO/Glycol nanofluid is very cost-effective than Ag and Au nanofluids
2021	Huang Ju et.al. [44]	Ag@SiO ₂ /CoSO ₄ -PG nanofluid	• A 25.4 mg/L Ag@SiO ₂ /CoSO ₄ -PG nanofluid filter showed a spectrum match with a silicon concentrator solar cell.
2021	Abdelrazik et. al. [46]	Ag-water as base fluid	• A hybrid PV/OF system is an excellent alternative to a single PV system.

2.6 Outcomes of the Literature Review

Based on the extensive review of existing literature on fluid-based BSPVT systems, the following key outcomes have been identified:

- Significant research has focused on developing fluid-based SBS filters to enhance hybrid photovoltaic-thermal (PVT) system efficiency.
- SBS filters enable spectral separation of solar energy, maximizing both electrical and thermal outputs simultaneously.
- The ideal SBS fluid requires a balance of high thermal conductivity, high heat capacity, and selective optical absorption/transmission properties.
- Pure fluids such as water, coconut oil, and silicone oil have been identified as probable SBS filter candidates.
- Among pure fluids, water is the most practical due to its abundance, low cost, and environmental friendliness.
- Nanofluids offer tuneable optical and thermal characteristics by varying nanoparticle type, size, and concentration.
- Scattering effects in nanofluids (e.g., TiO₂-based) significantly influence optical performance in SBS applications.
- Noble-metal nanofluids (Ag, Au) exhibit strong spectral compatibility with crystalline silicon solar cells.
- High cost of noble-metal nanoparticles limits large-scale commercialization of such nanofluids.
- Low-cost alternatives like ZnO-based nanofluids have shown substantial improvement in photothermal efficiency.
- Multi-fluid blends have been explored to enhance both spectral selectivity and heat transfer performance.
- Development of cost-effective, high-performance SBS fluids remains crucial for commercial scalability of BSPVT systems.

2.7 Conclusion

The reviewed literature establishes that fluid-based SBS filters hold great promise for improving the overall efficiency of photovoltaic-thermal systems by enabling spectral separation and simultaneous recovery of electrical and thermal energy. While noble-metal nanofluids offer superior optical performance, their high-

cost limits scalability. In contrast, low-cost alternatives such as ZnO-based nanofluids and optimized pure fluids like water present a practical path toward commercial implementation. Therefore, ongoing research should focus on developing economically viable, spectrally selective, and thermally efficient SBS fluids to ensure the widespread adoption of high-efficiency hybrid solar energy systems.

CHAPTER 3

Selection, Preparation and Testing of Nanofluid

The content presented in this chapter has been published as a study: Jiwanapurkar, P. R and Bhargav, H. A (2025). “Spectroscopic Analysis of Water-Based TiO₂ and ZnO Nanofluid for Fluid-Based Beam Split Photovoltaic-thermal System” *Journal of Solar Energy Research*, 10 (Emerging Trends in Photothermal Conversion for Solar Energy Harvesting), 45-55. [50]

Traditional photovoltaic-thermal (PVT) systems face a fundamental limitation in achieving simultaneous enhancement of electrical and thermal efficiencies, primarily due to temperature-induced degradation of photovoltaic (PV) performance and incomplete utilization of the solar spectrum. Although nanofluid-based direct absorption techniques have been proposed to improve heat recovery, these systems lack spectral selectivity, often resulting in elevated cell temperatures and reduced electrical efficiency.

To overcome these limitations, this research focuses on the development of a fluid-based SBS system for improved spectral management in PVT applications. The system aims to selectively absorb the non-useful thermal portion of solar radiation while allowing the responsive wavelengths to reach the solar cell. This approach enables both the thermal and electrical collectors to operate within their respective optimal ranges, thereby improving overall energy conversion efficiency.

This chapter details the selection criteria for the base fluid and nanoparticles, the methodology for preparing stable nanofluids at varying concentrations, and the testing procedures adopted for evaluating their optical characteristics. The experimental outcomes form the basis for identifying an optimal nanofluid composition suitable for SBS filter applications in hybrid PVT systems.

3.1 Characteristic requirements of spectral beam splitting fluid

The performance of a fluid-based SBS depends largely on the thermal, optical and physical properties of the working fluid medium. The fluid should effectively transmit the wavelength range corresponding to the photovoltaic cell's response while absorbing the non-useful portion of the solar spectrum for thermal conversion. In addition, it must maintain thermal and chemical stability under continuous solar

exposure. Table 3.1 outlines the fundamental requirements and optimal properties required for a fluid to function effectively as a spectral beam splitter for hybrid PVT system.

Table 3.1 Requirements and Characteristics of a Fluid for Spectral Beam Splitting (SBS) Applications

Parameter	Requirement / Desired Property	Justification
Optical Transparency	High transmittance in the PV-active wavelength range (e.g., 751–1126 nm for Si cells)	Allows maximum photon transmission for photovoltaic conversion
Selective Absorptivity	Absorbs thermal range and transmits responsive range. (751–1126 nm for Si solar cell)	Enables effective spectral splitting for thermal and electrical utilization
Optical Stability	Stable transmittance and absorptance under prolonged solar exposure	Maintains consistent spectral performance during long-term operation
Low Scattering and Turbidity	Minimal light scattering and high clarity	Ensures uniform optical filtering without energy losses
Thermal Conductivity	High	Enhances heat transfer efficiency to the thermal collector
Specific Heat Capacity	High	Allows higher heat storage and prevents excessive temperature rise
Viscosity	Low	Reduces pumping power and facilitates easy fluid circulation
Thermal and Chemical Stability	Stable under varying temperatures and solar exposure	Prevents degradation and maintains long-term system reliability
Volatility and Flammability	Non-volatile and non-flammable	Ensures operational safety under concentrated sunlight
Corrosion Tendency	Non-corrosive to system materials	Increases equipment lifespan and prevents contamination
Availability and Cost	Easily available and low-cost	Enables large-scale and economically viable applications
Environmental Impact	Non-toxic and eco-friendly	Promotes sustainability and safe disposal
Compatibility with Nanoparticles	Allows stable dispersion without agglomeration	Facilitates preparation of tuneable nanofluids for improved performance

3.2 Selection of base fluid and nanoparticles for making nanofluid

Based on the detailed literature review presented in Chapter 2, several pure fluids such as refined coconut oil, transformer oil, and water have been acknowledged as promising candidates for spectral beam splitting due to their favourable optical characteristics and spectral compatibility with the operational wavelength ranges of solar cells, as demonstrated by Joshi et al. [21]. Among these, water emerges as the most suitable base fluid owing to its exceptional physical and chemical properties. Water is a universal solvent with a high specific heat capacity, low viscosity, non-flammability, and environmental friendliness. Its optical transmissivity within the visible to near-infrared region makes it particularly beneficial for SBS applications.

The absorption spectrum of water, as illustrated in Figure 3.1, indicates negligible absorbance in the wavelength range of approximately 751-1126 nm, which aligns with the responsive region of silicon (Si) solar cells [27]. This transparency allows efficient transmission of the useful solar spectrum for photovoltaic conversion. Beyond 1126 nm, water exhibits a steep rise in absorbance within the infrared (IR) region, indicating its capacity to absorb thermal radiation effectively. This dual behaviour makes water a highly tailorable base fluid that can serve simultaneously as spectral filter and thermal energy absorber, thereby enhancing the overall energy yield of beam-splitting PVT systems.

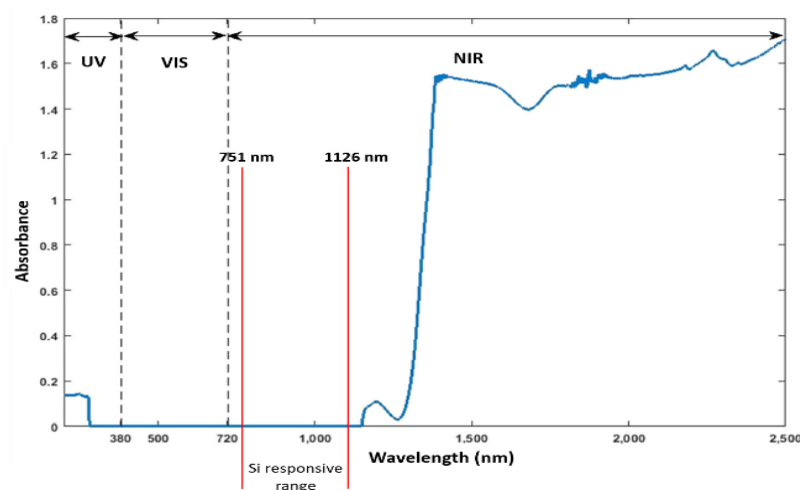


Figure 3.1 Spectroscopic analysis of water plotted absorbance against wavelength[27]

While other fluids such as propylene glycol, Valvoline oil, and silicone oil have also shown promising optical and thermal properties, their relatively higher cost and limited availability render them less practical for large-scale or low-cost system

development. Water, on the other hand, is abundant, inexpensive, and readily available globally, making it the most viable option for the current study. Furthermore, its compatibility with a wide range of nanoparticles enables the creation of nanofluids with enhanced optical and thermal properties, tailored specifically for BSPVT applications.

In addition to selecting a suitable base fluid, the choice of nanoparticles is equally crucial. Titanium dioxide (TiO_2) and zinc oxide (ZnO) have been identified as the most suitable nanoparticle materials for the present research. Both TiO_2 and ZnO are semiconducting metal oxides known for their strong absorption characteristics in the UV region and partial absorption in the visible region, making them effective in filtering the undesired portion of the solar spectrum while allowing transmission of wavelengths corresponding to the responsive region of silicon solar cells. These materials are non-toxic, chemically stable, and exhibit excellent dispersion stability in aqueous media. Moreover, TiO_2 and ZnO nanoparticles are widely available at a relatively low cost compared to precious metal nanoparticles such as gold (Au) and silver (Ag), which, although effective, are prohibitively expensive for large-scale implementation.

TiO_2 and ZnO are extensively used in cosmetic and coating industries for UV protection due to their superior radiation absorption characteristics [51], [52]. Their inclusion in water-based nanofluids can therefore yield a cost-effective, efficient, and environmentally sustainable optical filtering medium for BSPVT systems. The integration of these nanoparticles with water as the base fluid ensures a balance between spectral control, heat absorption, and economic feasibility, which is essential for developing scalable, high-performance hybrid solar energy systems.

In summary, water has been selected as the base fluid due to its favourable optical transparency, high specific heat capacity, non-flammability, low cost, and global availability. Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles have been selected as the dispersed phase for their excellent optical absorption characteristics, stability, and affordability. Together, these materials form an ideal foundation for developing tuneable, low-cost nanofluid-based SBS systems that augment overall efficiencies in photovoltaic-thermal applications.

3.3 Preparation of nanofluid

A total of twelve nanofluid samples were prepared using water as the base fluid with titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles as the dispersed phases. To ensure a homogeneous dispersion and overcome the high cohesive forces between nanoparticles, a probe sonicator was employed, as it provides superior cavitation energy compared to ultrasonic baths [53]. Furthermore, Sodium Dodecyl Sulfate (SDS) was added as an anionic surfactant to provide electrostatic stabilization, effectively preventing agglomeration and ensuring long-term suspension stability [54]

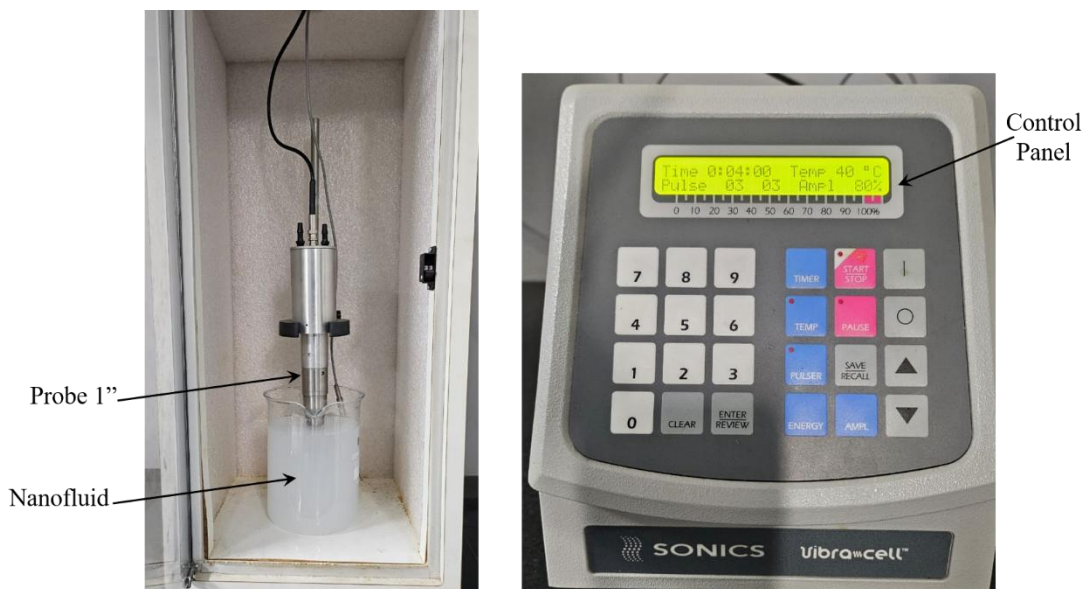


Figure 3.2 Setup for nanofluid preparation featuring a Sonics Vibra-Cell™ probe sonicator.

The nanofluid samples were synthesized by dispersing the required amount of nanoparticles in deionized water according to the desired weight concentration, followed by ultrasonication using a probe sonicator operated at 80% amplitude for a total duration of one hour, with intermittent 3-minute on-off cycles to maintain uniform temperature. The process was carried out at ambient conditions with a 1-inch probe. Figure 3.2 shows a Sonics Vibra-Cell probe sonicator during the process of preparation of nanofluids.

In total, twelve nanofluid compositions were developed shown in figure 3.3, and listed in Table 3.2. These included five samples of TiO_2 /water nanofluids, five samples of ZnO /water nanofluids, and two hybrid nanofluids containing both ZnO and TiO_2

nanoparticles. The nanoparticle concentration was varied within a range of 0.01 wt% to 0.05 wt% to study the effect of nanoparticle loading on optical and thermal properties.

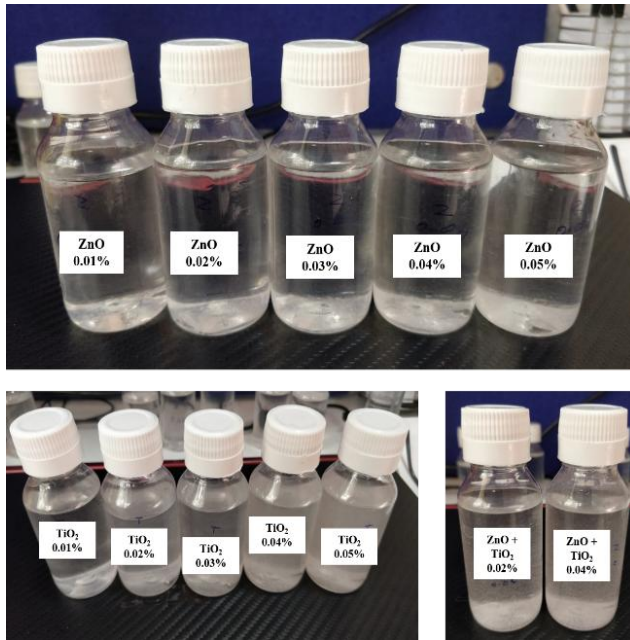


Figure 3.3 Photograph of fluids sample showing ZnO (0.01 to 0.05%), bottom left TiO₂ (0.01 to 0.05%) and bottom right ZnO+TiO₂ (0.02 & 0.04%)

Table 3.2 Composition and concentration levels of the prepared nanofluid samples.

Sr. No.	Composition
1	H ₂ O + TiO ₂ (0.01%)
2	H ₂ O + TiO ₂ (0.02%)
3	H ₂ O + TiO ₂ (0.03%)
4	H ₂ O + TiO ₂ (0.04%)
5	H ₂ O + TiO ₂ (0.05%)
6	H ₂ O + ZnO (0.01%)
7	H ₂ O + ZnO (0.02%)
8	H ₂ O + ZnO (0.03%)
9	H ₂ O + ZnO (0.04%)
10	H ₂ O + ZnO (0.05%)
11	H ₂ O + ZnO + TiO ₂ (0.02%)
12	H ₂ O + ZnO + TiO ₂ (0.04%)

Thus, twelve nanofluid samples were successfully synthesized through controlled probe sonication to achieve uniform dispersion and consistent optical characteristics suitable for spectral beam splitting (SBS) photovoltaic–thermal (PVT) applications.

3.3.1 Spectroscopic analysis of the prepared nanofluids

The optical properties of the synthesized nanofluids were experimentally characterized using a high-performance UV-VIS-NIR spectrophotometer (LAMBDA 1050+, Perkin Elmer, USA) to determine their transmissivity and absorbance characteristics across the solar spectrum. The spectrometric analysis of the samples was carried out at the Sophisticated Instrumentation Centre for Applied Research and Testing (SICART). This facility is sponsored by the Department of

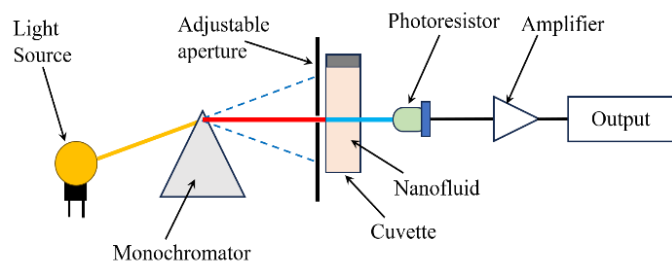


Figure 3.4 Operational layout of the spectrophotometer, illustrating the light path from the source through the monochromator and the nanofluid-filled cuvette to the output.

Science and Technology (DST), Govt. of India, New Delhi, and is located in Anand, Gujarat, India. The spectral analysis was conducted across a wavelength range of 200-2500 nm, encompassing the terrestrial solar irradiance (300-2500 nm)[14][15]. Figure 3.4 presents the working principle of the spectrophotometer employed in this study.

Before commencing the measurements, the spectrophotometer was calibrated by allowing it to warm up for 30 minutes as per manufacturer recommendations. All quartz cuvettes were thoroughly cleaned with distilled water followed by ethanol to remove any residual contaminants that could affect measurement accuracy. Each quartz cuvette was carefully filled with the nanofluid, ensuring the elimination of air bubbles, and a 10 mm path length was maintained during all tests.

The spectrophotometer was configured to scan from 200 nm to 2500 nm at a steady scanning rate i.e. 600 nm/min and 1.0 nm data interval. All measurements were performed at ambient laboratory temperature. During each trial, the quartz cuvette was securely positioned in the sample holder, as illustrated in Figure 3.5, and the scanning process was initiated to record transmissivity and absorbance data for each nanofluid sample.

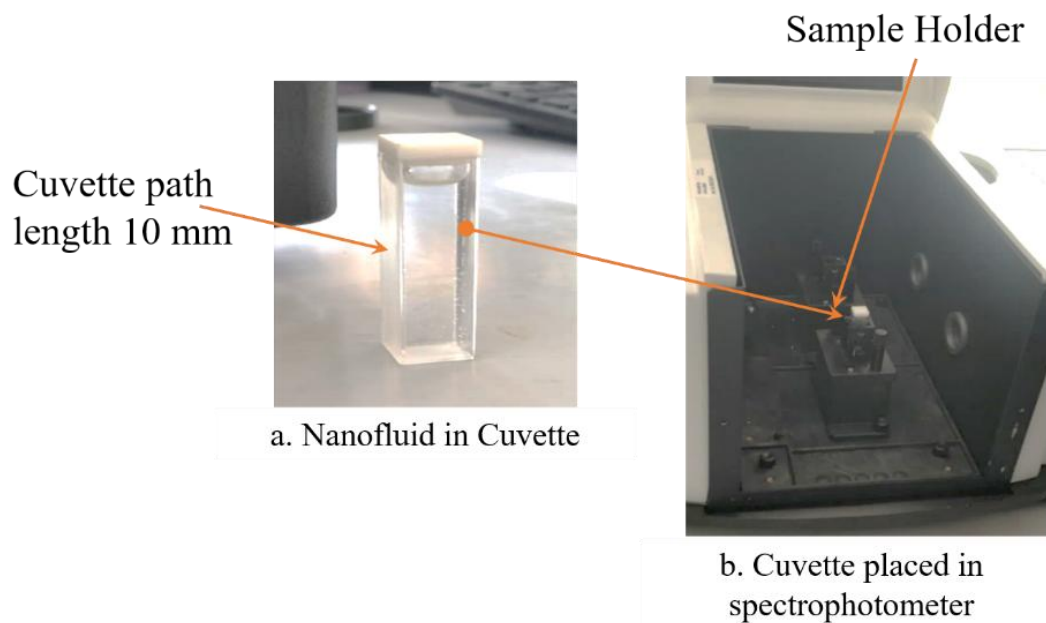


Figure 3.5 (a) Nanofluid sample contained in a cuvette with a 10mm path length; (b) Placement of the cuvette within the spectrophotometer sample holder for spectral transmittance measurements.

Numerical values of transmissivity corresponding to each wavelength were automatically obtained from the spectrophotometer and subsequently used for further analysis of the optical behaviour of the nanofluids.

This systematic procedure ensured accurate and repeatable measurement of the optical properties of $\text{TiO}_2/\text{H}_2\text{O}$, $\text{ZnO}/\text{H}_2\text{O}$, and $\text{ZnO-TiO}_2/\text{H}_2\text{O}$ nanofluids, which are essential for evaluating their potential as fluid-based SBS filters in hybrid PVT systems.

3.4 Results of Spectrophotometric analysis

A plot of transmissivity (%) versus wavelength (nm) was generated to analyse the wavelength-dependent transmissivity behaviour of the prepared nanofluid samples.

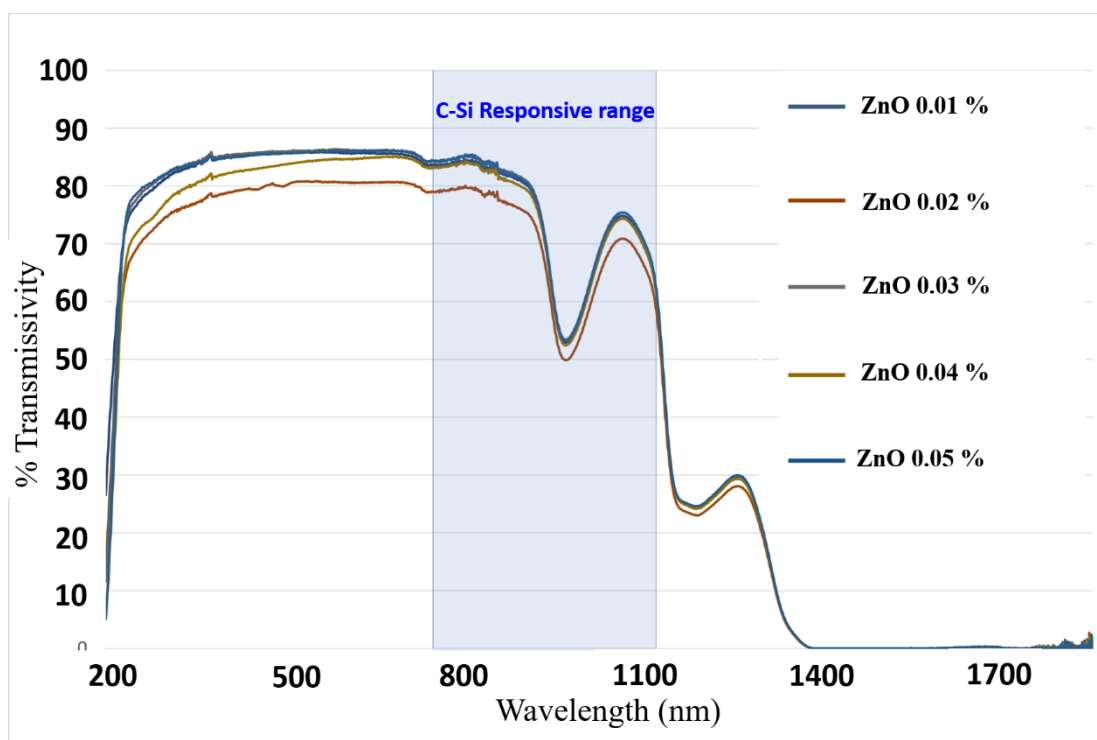


Figure 3.6 Spectral transmissivity of $\text{H}_2\text{O}/\text{ZnO}$ nanofluids (0.01%–0.05% concentration) highlighting the c-Si responsive bandwidth.

Figure 3.6 illustrates the variation of transmissivity with wavelength for $\text{H}_2\text{O}/\text{ZnO}$ nanofluids prepared at concentrations ranging from 0.01% to 0.05%. The transmissivity curve corresponding to the 0.03% ZnO concentration exhibits a maximum transmissivity of approximately 86%, which is the highest among all tested samples. Conversely, the 0.02% concentration demonstrates the lowest transmissivity, particularly within the c-Si responsive wavelength range (751–1126 nm). A noticeable reduction in transmissivity is observed in the ultraviolet (UV) region as the nanoparticle concentration increases. This trend can be attributed to the enhanced light scattering

effect caused by increased nanoparticle density. Beyond a concentration of 0.02%, the multiple scattering phenomena within the nanofluid result in increased transmissivity within the visible range, suggesting complex optical interactions between the dispersed ZnO particles and incident solar radiation.

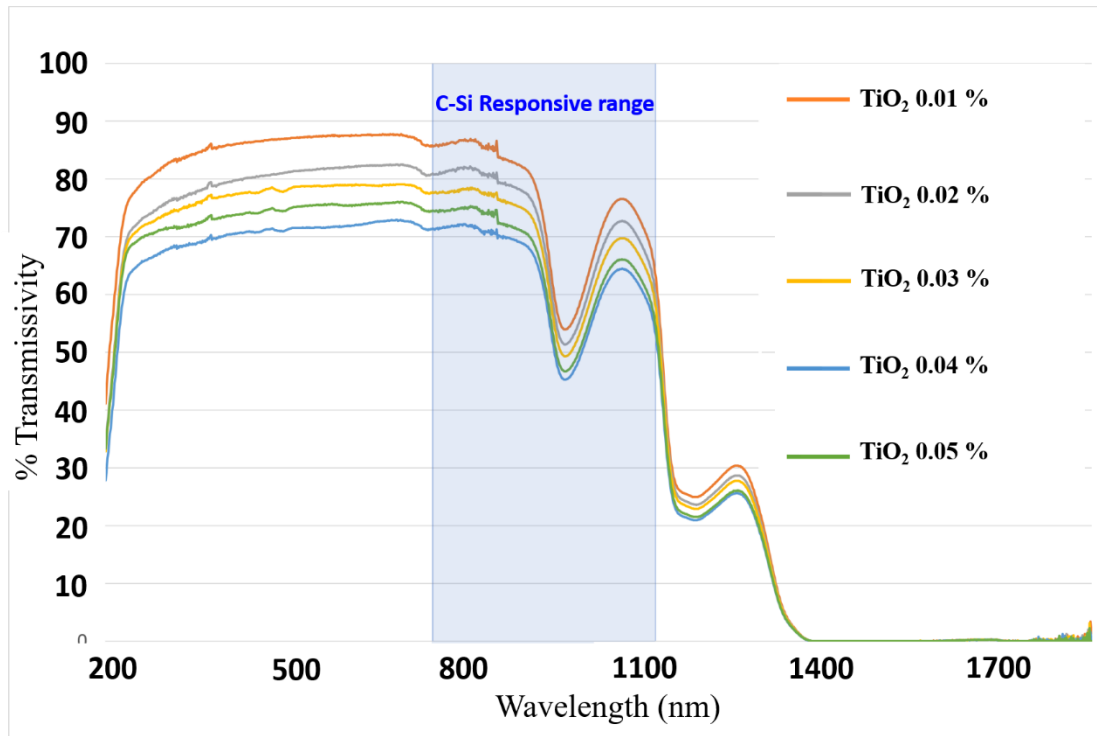


Figure 3.7 Spectral transmissivity of $\text{H}_2\text{O}/\text{TiO}_2$ nanofluids (0.01%-0.05% concentration) highlighting the c-Si responsive bandwidth.

Figure 3.7 depicts the variation of transmissivity with wavelength for $\text{H}_2\text{O}/\text{TiO}_2$ nanofluids prepared at five concentrations ranging from 0.01% to 0.05%. It can be observed that transmissivity is highest (~87%) at 0.01% concentration and gradually decreases with increasing nanoparticle loading, reaching a minimum of approximately 72% at 0.04% within the c-Si responsive wavelength range (751-1126 nm). This behaviour reflects enhanced light absorption as the nanoparticle concentration increases. A slight rise in transmissivity at 0.05% concentration is attributed to nanoparticle agglomeration and scattering phenomena, which disrupt the uniform interaction between light and the suspended particles, thereby reducing effective absorption. Consequently, a concentration of 0.04% can be considered optimal for achieving maximum spectral filtering efficiency while maintaining nanofluid stability.

In comparison to ZnO nanofluids, TiO_2 nanofluids exhibit consistently lower transmissivity across the entire wavelength range at equivalent concentrations. While

ZnO demonstrates a more pronounced drop in transmissivity within the UV region due to its strong UV-blocking capability, TiO_2 provides a more uniform and sustained absorption extending from the UV to the near-infrared regions. Additionally, the transmissivity variation between 0.02% and 0.03% TiO_2 concentrations is minimal, suggesting a point of diminishing optical enhancement beyond 0.02%. Nevertheless, the 0.04% TiO_2 nanofluid proves to be the most effective in filtering the non-useful portion of the solar spectrum, which is critical for enhancing the thermal efficiency of BSPVT systems.

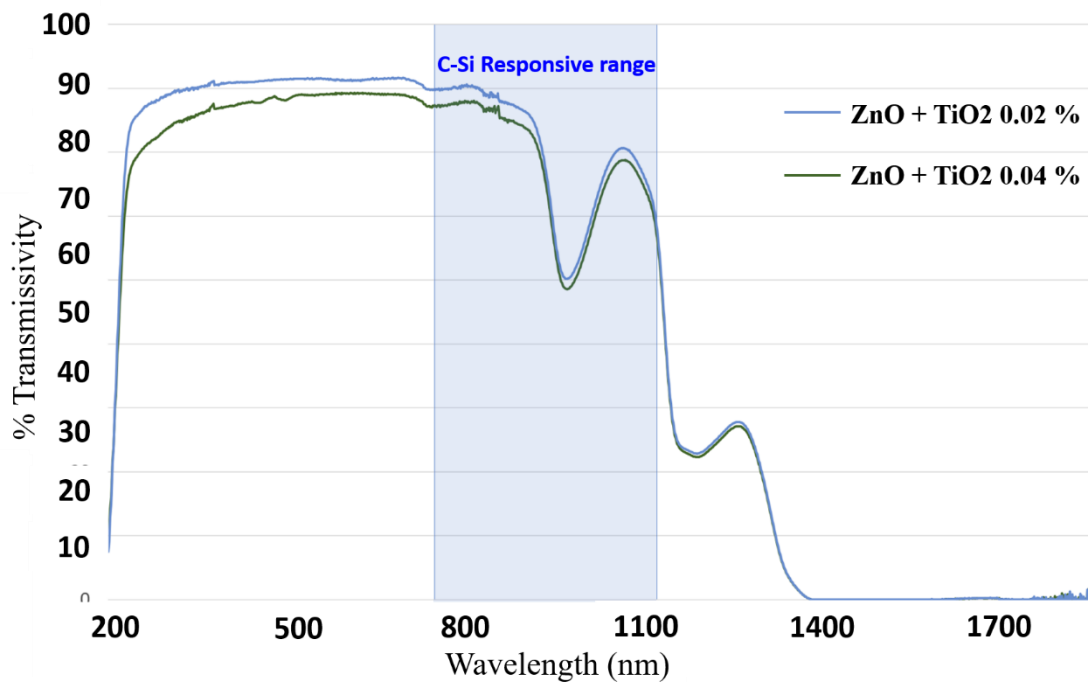


Figure 3.8 Spectral transmissivity of $\text{H}_2\text{O}/\text{ZnO}+\text{TiO}_2$ nanofluids (0.02 & 0.04% concentration) highlighting the c-Si responsive bandwidth.

Figure 3.8 presents the spectral transmissivity characteristics of H_2O -based TiO_2 + ZnO nanofluid blends at concentrations of 0.02% and 0.04%. It is observed that the 0.02% blend exhibits lower transmissivity compared to the 0.04% blend, particularly within the c-Si responsive wavelength range (751–1126 nm). However, across the visible and near-infrared (NIR) regions, the 0.04% mixture demonstrates relatively higher transmissivity, which may be attributed to non-uniform particle dispersion or increased scattering effects resulting from higher nanoparticle loading.

While both blends exhibit a comparable spectral trend, the 0.04% sample demonstrates superior overall spectral filtering performance. Nevertheless, neither of the blends achieves the sharper filtering characteristics observed in pure TiO_2 nanofluid

at 0.04% concentration. This indicates that, although combining nanoparticles introduces greater tunability in optical response, it may also lead to a reduction in peak performance. These findings suggest that binary nanofluid blends provide a balanced compromise between spectral selectivity and material compatibility; however, further optimization is required to surpass the efficiency of the best-performing single-component nanofluids.

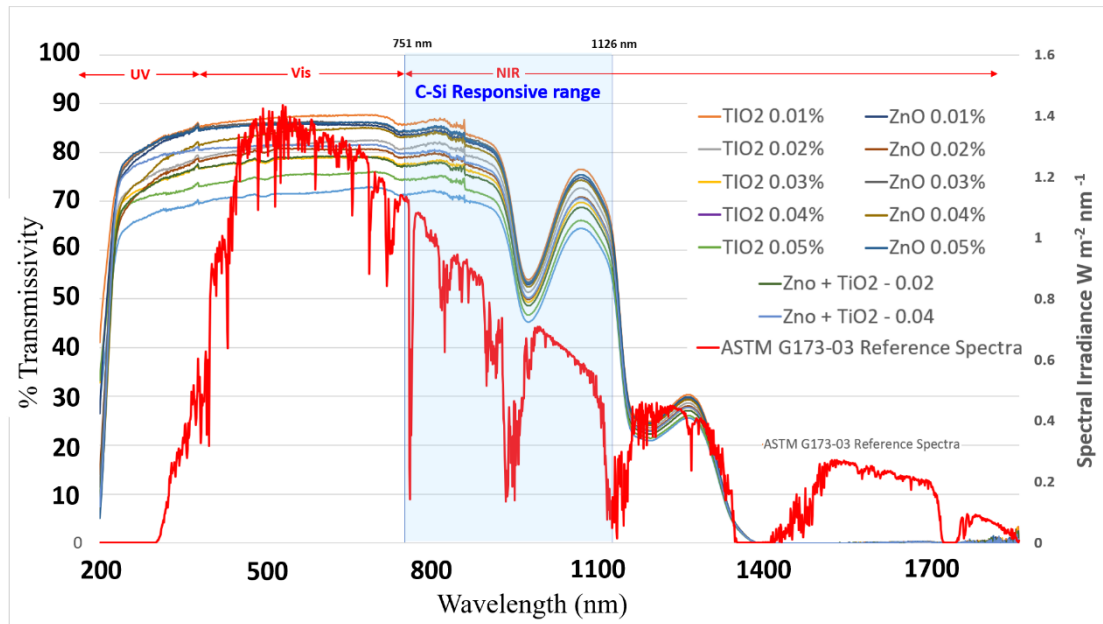


Figure 3.9 Spectral transmissivity of $\text{H}_2\text{O}/\text{ZnO}$, $\text{H}_2\text{O}/\text{TiO}_2$, and $\text{ZnO}+\text{TiO}_2/\text{H}_2\text{O}$ nanofluids superimposed on the standard ASTM G173-03 solar spectral irradiance.

Figure 3.9 presents the variation of transmissivity with wavelength for $\text{H}_2\text{O}/\text{ZnO}$, $\text{H}_2\text{O}/\text{TiO}_2$, and their blended nanofluids at concentrations ranging from 0.01% to 0.05%, plotted alongside the ASTM G173-03 Reference Solar Spectrum ($\text{W m}^{-2} \text{ nm}^{-1}$). The ASTM G173-03 standard provides benchmark solar irradiance data, essential for evaluating the spectral performance of photovoltaic and thermal systems.

A pronounced reduction in transmissivity, reaching up to 45.5%, is observed across all nanofluid types within the wavelength range of 900-1070 nm, followed by a gradual recovery beyond 1070 nm. Although all nanofluids display a similar overall spectral trend, their absolute transmissivity values differ notably.

Table 3.3 presents a comparative summary of twelve nanofluid samples composed of TiO_2 , ZnO , and their binary combinations across varying concentrations, highlighting their average, minimum, and maximum transmissivity within the 751-1126 nm range corresponding to the responsive range of silicon solar cells. The tested

nanofluids are arranged in ascending order of average transmissivity, thereby illustrating their relative spectral filtering capabilities. Lower transmissivity values indicate higher absorption and improved potential for thermal energy capture. Among all samples, the TiO₂ nanofluid at 0.04% concentration exhibits the lowest average and minimum transmissivity, confirming its superior filtering performance in blocking unwanted infrared radiation. This makes it the most promising candidate for efficient spectral beam-splitting photovoltaic-thermal (BSPVT) applications. In contrast, TiO₂ at 0.01% and all ZnO-based nanofluids exhibit higher transmissivity, signifying reduced spectral filtering effectiveness.

Table 3.3 Comparative analysis of the average, minimum, and maximum spectral transmissivity for TiO₂, ZnO, and TiO₂-ZnO nanofluids within the 751 - 1126 nm bandwidth.

Nanofluid Sample	Average Transmissivity (%)	Minimum Transmissivity (%)	Maximum Transmissivity (%)
TiO ₂ 0.04%	63.19	45.25	72.22
TiO ₂ 0.05%	65.31	46.69	75.28
ZnO + TiO ₂ 0.02%	67.89	48.59	78.02
TiO ₂ 0.03%	68.69	49.3	78.48
ZnO 0.02%	69.71	49.85	80.05
ZnO + TiO ₂ 0.04%	70.01	50.17	80.62
TiO ₂ 0.02%	71.59	51.36	82.18
ZnO 0.04%	73.27	52.44	84.29
ZnO 0.01%	73.81	52.91	84.56
ZnO 0.05%	74.37	53.2	85.34
ZnO 0.03%	74.45	53.46	85.48
TiO ₂ 0.01%	75.51	53.94	86.98

The transmissivity characteristics of the nanofluids reveal that H₂O/TiO₂ at a 0.01% concentration exhibits the highest transmissivity, whereas the same fluid at 0.04% concentration shows the lowest transmissivity across the visible and near-infrared (NIR) regions. In contrast, H₂O/ZnO nanofluids display their minimum transmissivity at 0.02% concentration, followed by a gradual increase with further rise

in concentration up to 0.05%. However, within the ultraviolet (UV) region, the transmissivity of ZnO-based nanofluids decreases progressively with increasing concentration. For TiO₂-based nanofluids, transmissivity decreases consistently as concentration increases, reaching its minimum value at 0.04%.

A comparative evaluation of twelve different nanofluid samples indicates that TiO₂ at 0.04% concentration achieves the lowest average transmissivity (63.19%), along with a moderate maximum transmissivity (72.22%). Conversely, nanofluids such as TiO₂ at 0.01% and all ZnO-based blends exhibit higher transmissivity levels, allowing greater infrared radiation to pass through and thereby demonstrating lower spectral filtering effectiveness for BSPVT applications.

These observations establish TiO₂ (0.04%) as the most suitable nanofluid for spectral beam-splitting filters. Its higher absorption capability, as reflected by lower transmissivity, enables efficient capture and conversion of non-useful solar radiation into heat, thereby enhancing thermal output and improving the overall efficiency of BSPVT systems. Although the reduction in transmissivity within the photovoltaic response range may slightly reduce electrical output, this effect is offset by the corresponding increase in thermal energy gain. Moreover, at 0.04% concentration, TiO₂ nanofluid offers an optimal balance between enhanced thermal conductivity and suspension stability, minimizing the risks of nanoparticle agglomeration or sedimentation that can occur at higher concentrations.

Therefore, the TiO₂-H₂O nanofluid at concentration 0.04% is identified as optimal working fluid for fluid-based BSPVT systems, combining superior optical filtering, improved heat transfer performance, and long-term stability.

3.5 Validation of results

The findings of the current study are consistent with those reported by Mohit Barthwal [55], who developed an optical theoretical model based on Rayleigh scattering to predict the transmittance and absorbance characteristics of ZnO, Fe₃O₄, and SiO₂ nanofluids across the solar spectrum (300–2500 nm). The transmittance–wavelength relationship for ZnO/H₂O nanofluid obtained from his

theoretical model exhibits a trend comparable to the experimental observations presented in this work. Figure 3.10 illustrates the transmittance behaviour of ZnO-based nanofluid as predicted by the Rayleigh scattering model.

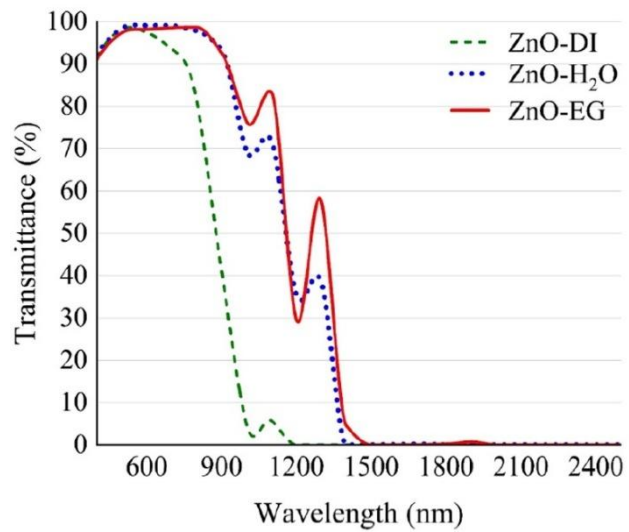


Figure 3.10 Transmittance behaviour of ZnO-based nanofluid as predicted by the Rayleigh scattering model [55]

The study conducted by Rashid et al. [56] examined the optical characteristics of ZnO, TiO₂, and ZnO:TiO₂ composite thin films using UV-Vis spectroscopy within the wavelength range of 250–700 nm. Their results revealed that the

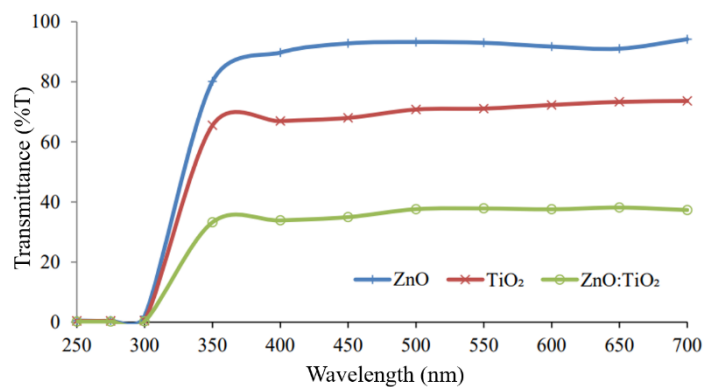


Figure 3.11 transmittance-wavelength behaviour of ZnO, TiO₂, and ZnO:TiO₂ composite thin films across the 250–700 nm spectral range. [56]

transmittance trend up to 700 nm aligns closely with the findings of the present investigation. Figure 3.11 illustrates the transmittance-wavelength behaviour of ZnO, TiO₂, and ZnO:TiO₂ composite thin films across the 250–700 nm spectral range.

3.6 Conclusion

To ensure high precision in evaluating the optical properties of the prepared nanofluid samples, the spectrometric analysis was conducted at the “Sophisticated

Instrumentation Centre for Applied Research and Testing (SICART)”, sponsored by the Department of Science and Technology (DST), Govt. of India, New Delhi, and is located in Anand, Gujarat, India. The test certificate of each sample is attached in appendix A.

Experimental findings identify TiO₂ nanofluid with a concentration of 0.04% as the most suitable working fluid for BSPVT systems. The transmissivity analysis revealed that, overall, transmissivity decreases with increasing nanoparticle concentration, especially in the ultraviolet (UV) region. However, both TiO₂ and ZnO exhibited distinct optimal concentrations where transmissivity peaks were observed. For TiO₂, the highest transmissivity in the visible spectrum occurred at 0.03%, while ZnO achieved maximum transmissivity at 0.01%. Beyond these concentrations, increased particle scattering led to a decline in transmissivity.

Comparative evaluation between H₂O/TiO₂ and H₂O/ZnO nanofluids indicated that at lower concentrations (0.01%), TiO₂ offers higher transmissivity, whereas ZnO demonstrates superior performance in the UV range at higher concentrations. The TiO₂–ZnO blended nanofluids also displayed concentration-dependent transmissivity trends, highlighting the potential for tailored optical behavior through nanoparticle mixing.

In summary, TiO₂ nanofluid at 0.04% concentration emerged as the optimal fluid for BSPVT applications due to its superior balance of optical absorption, thermal performance, and stability. The study emphasizes that precise control over nanoparticle concentration is crucial for achieving optimal solar spectral management. Future work should focus on real-world experimental validation of the 0.04% TiO₂ nanofluid in an operational BSPVT setup to test its long-term performance, stability, and energy conversion efficiency under variable environmental conditions.

3.7 Properties of the selected Nanofluid [57], [58]:

3.7.1 Specific heat per unit mass (mass-weighted) [58]

Values

- Mass fraction of TiO₂ nanoparticles: $\omega_p = 0.04\% = 0.00004 \text{ g/kg(nf)}$
- Specific heat of water (C_{p_f}): 4180 J/kg·K
- Specific heat of TiO₂ (C_{p_p}): 695 J/kg·K [57]
- Density of water (ρ_f): 997 kg/m³
- Density of TiO₂ (ρ_p): 3467.5 kg/m³ [57]

The specific heat of the nanofluid (Cp_{nf}) using mass-weighted average method

$$Cp_{nf} = \omega_p Cp_p + (1 - \omega_p) Cp_f \quad \text{Eq 3.1}$$

$$Cp_{nf} = 0.0004 \times 695 + .9996 \times 4180$$

$$Cp_{nf} = 4178.6 \text{ J/kg K}$$

3.7.2 Convert mass fraction to volume fraction

- mass fraction $\omega_p = 0.0004$ (0.04 wt%)
- ρ_p (TiO₂) = 4230 kg/m³
- ρ_f (water, 25°C) = 997 kg/m³

Volume fraction φ

$$\varphi = \frac{\frac{\omega_p}{\rho_p}}{\frac{\omega_p}{\rho_p} + \frac{1 - \omega_p}{\rho_f}} \quad \text{Eq 3.2}$$

$$\varphi \approx 9.42 \times 10^{-5} \quad (\approx 0.00942\%)$$

3.7.3 Density of Nanofluid (rule of mixtures)

$$\rho_{nf} = \frac{1}{\frac{\omega_p}{\rho_p} + \frac{1 - \omega_p}{\rho_f}} \quad \text{Eq 3.3}$$

$$\rho_{nf} \approx 997.30 \text{ kg/m}^3$$

3.7.4 Thermal conductivity - Maxwell's Model

A common theoretical model for dilute suspensions is Maxwell's model:

$$k_{nf} = k_f \frac{k_p + 2k_f - 2\varphi(k_f - k_p)}{k_p + 2k_f + \varphi(k_f - k_p)} \quad \text{Eq 3.4}$$

- k_f (water, 25°C) $\approx 0.60 \text{ W/m K}$
- k_p (TiO₂, typical bulk) $\approx 8.4 \text{ W/m K}$
- $\varphi \approx 9.42 \times 10^{-5}$

$$k_{nf} \approx 0.60013 \text{ W/m K}$$

3.7.5 Summary of properties of H₂O/TiO₂ 0.04%.

The following table 3.4 shows the calculated values of thermophysical properties of the best selected nanofluid H₂O/TiO₂ 0.04%. These values are calculated in section 3.7. [57], [58]

Table 3.4 Summary of properties of H₂O/TiO₂ 0.04% nanofluid.

Sr. No.	Property	Value
1.	Volume fraction ϕ	9.42×10^{-5}
2.	Density ρ_{nf}	997.30 kg/m^3
3.	Specific heat Cp_{nf}	4178.6 J/kg K
4.	Thermal conductivity k_{nf}	0.60013 W/m K

CHAPTER 4

Theoretical Estimation of Performance of BSPVT

This chapter presents the theoretical estimation of the output parameters of the Beam-Splitting Photovoltaic-Thermal system. The estimation aims to predict the electrical, thermal and overall performances of the system under standard solar radiation conditions. The analysis includes the evaluation of incident solar radiation, evaluating the optimum tilt angle, and assessment of solar flux received and transmitted through the optical filter and nanofluid. Theoretical modelling serves as a foundation for comparison with the experimental results discussed in subsequent chapters.

4.1 Assumptions

For the purpose of theoretical estimation, several simplifying assumptions have been made to ensure analytical tractability and consistency in performance evaluation. To simplify the analytical modelling and ensure tractability, the following assumptions are adopted:

- The incident solar irradiation on the collector surface is assumed to be uniformly distributed across the entire aperture area.
- The analysis assumes clear-sky conditions with negligible effects of atmospheric scattering, shading, and cloud interference.
- The system is oriented due south ($\gamma = 0$) with analysis conducted at solar noon (*hour angle* $\omega = 0^\circ$) to represent peak radiation conditions.
- The optical, thermal, and electrical properties of the PV module, optical filter, and nanofluid are considered constant and independent of temperature or wavelength variations within the analysed range.
- The BSPVT system is assumed to operate under steady-state thermal conditions, with no transient temperature fluctuations during the period of observation.
- Convective and radiative heat losses from the system boundaries are considered minimal and are therefore neglected in the theoretical calculations.
- The heat transfer process between the filter surface, and working fluid is assumed to occur predominantly in one dimension i.e. perpendicular to the surface ignoring lateral losses.

- Only beam radiation is considered for simplification.
- The heat absorbed by the fluid-based spectrum filter is considered as the thermal yield of the system.
- The electrical output of the PV module is modelled as function of operating temperature of the module.
- The other auxiliary losses in the PV system are neglected.
- The radiation energy that remains unconverted into electricity by photovoltaic process is dissipated as heat within the PV module.
- Steady state energy transfer is assumed.
- The thermal capacity of the filter housing material is negligible.
- The material properties are considered constant.

4.2 Estimation of Incoming Solar Radiation

To evaluate the solar energy input on the PVT, the incoming radiations were estimated considering both beam and diffuse components. These components were determined using the Gopinathan and Soler model [59], which provides empirical correlations based on atmospheric transmissivity and solar geometry parameters.

The analysis is conducted for Daman, India (Latitude: 20.41° N, Longitude: 72.86° E). Monthly average values are calculated using representative days as per Klien recommendation [60].

The solar declination angle is calculated according to the empirical relation proposed by Cooper [61] Eq 4.1

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad \text{Eq 4.1}$$

Where,

n = day of the year

The Gopinathan Correlation [62] (Eq 4.2) is used to predict the Monthly average of daily global radiation on horizontal surface at the location.

$$\frac{\bar{H}_g}{\bar{H}_o} = a_1 + b_1 \left[\frac{\bar{S}}{\bar{S}_{max}} \right] \quad \text{Eq 4.2}$$

Monthly average of daily extraterrestrial radiation is given by eq 4.3 [63]

$$H_o = \frac{24}{\pi} I_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) (\omega_s \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega_s) \quad \text{Eq 4.3}$$

I_{sc} = Extraterrestrial radiation 1.367 kW/m²

Monthly average of sunshine hours per day ($\bar{S}$ hours) at the location is based on traditional Indian astronomical, or Panchang data, specifically integrated with the Gregorian calendar. Monthly average of maximum possible sunshine hours per day ($\bar{S}_{max}$ hours) at the location / day length is given by eq 4.4.

$$\bar{S}_{max} = \frac{2}{15} \omega_s = \frac{2}{15} \cos^{-1}(-\tan \phi \tan \delta) \quad \text{Eq 4.4}$$

The Gopinathan constants a_1 & b_1 are calculated using equation 4.5 & 4.6

$$a_1 = -0.309 + 0.539 \cos \phi - 0.0693 E_L + 0.290 \left[\frac{\bar{S}}{\bar{S}_{max}} \right] \quad \text{Eq 4.5}$$

$$b_1 = 1.527 - 1.207 \cos \phi + 0.0926 E_L - 0.359 \left[\frac{\bar{S}}{\bar{S}_{max}} \right] \quad \text{Eq 4.6}$$

The ratio $\frac{\bar{H}_g}{\bar{H}_o}$ is denoted by $\bar{K}_t$ called as monthly average clearness index

The table 4.1 shows declination angle, daylengths, Gopinathan constants and monthly average of global and extraterrestrial radiations values calculated for 12 months using equations 4.1 to 4.6.

Table 4.1 Calculated values of declination angle, daylengths, Gopinathan constants and monthly average of global and extraterrestrial radiations for 12 months

Month	Declination angle δ°	$\bar{S}$ hrs	$\bar{S}_{max}$ hrs	a_1	b_1	$\bar{H}_o$ (kJ/m ² -day)	$\bar{H}_g$ (kJ/m ² -day)
January	-20.90	10.89	10.89	0.485	0.208	26556	18391
February	-12.91	11.28	11.33	0.484	0.209	30410	21042
March	-2.36	11.86	11.88	0.484	0.208	34582	23945
April	9.47	12.47	12.48	0.485	0.208	37882	26236
May	18.83	12.97	12.98	0.485	0.208	39374	27266
June	23.10	13.23	13.23	0.485	0.208	39674	27475
July	21.15	13.12	13.12	0.485	0.208	39372	27269
August	13.39	12.69	12.68	0.485	0.208	38255	26498
September	2.13	12.10	12.10	0.485	0.208	35596	24652
October	-9.68	11.51	11.50	0.485	0.208	31471	21797
November	-18.97	11.00	11.00	0.485	0.208	27355	18946
December	-23.07	10.76	10.76	0.485	0.208	25347	17555

The diffused component of the monthly average of daily global radiation on horizontal surface is given by the Gopinathan and Soler model [59] Eq 4.7

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.87813 - 0.33280 \bar{K}_t - 0.53039 \left[\frac{\bar{S}}{\bar{S}_{max}} \right] \quad \text{Eq 4.7}$$

Monthly average of instantaneous global radiation is given by Eq 4.8 suggested by Collarees-Pereira and Rabl and modified by Gueymard [64], [65]

$$\frac{\bar{I}_g}{\bar{H}_g} = \frac{\bar{I}_o}{\bar{H}_o} (a + b \cos \omega) / f_c \quad \text{Eq 4.8}$$

Instantaneous value of $\bar{I}_o$ at $\omega = 0$ [63]

$$I_o = I_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad \text{Eq 4.9}$$

$$a = 0.409 + 0.5016 \sin(\omega_s - 60)$$

$$b = 0.6609 + 0.4747 \sin(\omega_s - 60)$$

$$\text{Normalizing factor } f_c = a + 0.5b \left[\frac{\frac{\pi \omega_s}{180} - \sin \omega_s \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \right]$$

Monthly average of hourly diffused radiation is given by Eq 4.10 suggested by Lieu & Jordan [66]

$$\frac{\bar{I}_d}{\bar{H}_d} = \frac{\bar{I}_o}{\bar{H}_o} \quad \text{Eq 4.10}$$

$\bar{I}_d$ = Monthly average of instantaneous diffused radiation in horizontal surface at $\omega = 0$ (W/m²)

The estimation of solar radiation on a horizontal surface provides the fundamental basis for energy availability at the given location. However, for practical applications, photovoltaic-thermal systems are installed at a specific inclination to maximize solar energy capture. Therefore, it is essential to determine the optimum tilt angle that enhances the incident solar radiation on the collector surface.

4.3 Optimum tilt angle (β_{opt}) at the location

The optimum tilt angle for the solar PVT, ensuring maximum incident radiation over the year, is calculated using the relation (Eq 4.11) developed by Kacira et al. [67].

$$\beta_{opt} = \tan^{-1} \left[\frac{\sum_{k=1}^{12} H_b \tan(\varphi - \delta)}{\sum_{k=1}^{12} H_b} \right] \quad \text{Eq 4.11}$$

To maximize annual energy yield, the optimum tilt angle was obtained by following the methodology of Kacira et al.[67]. For the coordinates of Daman (20.41°N), the optimal inclination was determined to be approximately 20° from horizontal.

$$\beta_{opt} = 19.96^\circ \approx 20^\circ$$

The next step involves evaluating the actual solar radiation incident on the inclined surface. This requires transforming the horizontal radiation components into their corresponding values on the tilted plane using appropriate geometric and empirical relations.

4.4 The solar radiation falling on tilted surface [63]

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \quad \text{Eq 4.12}$$

Where,

I_T = Flux falling on Tilted surface (W/m²)

I_b = Beam component of flux falling on Tilted surface (W/m²)

I_d = Diffused component of flux falling on Tilted surface (W/m²)

r_b = Tilt Factor for beam radiation on tilted surface with slope $\beta = \beta_{opt}$

$$r_b = \frac{\cos \theta}{\cos \theta_z} = \frac{\sin \delta \sin(\phi - \beta) + \cos \delta \cos \phi \cos(\phi - \beta)}{\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega}$$

r_d = Tilt factor for diffused radiation on tilted surface with slope $\beta = \beta_{opt}$

$$r_d = (1 + \cos \beta)/2$$

r_r = radiation shape factor for tilted surface with slope β_{opt}

$$r_r = \rho(1 + \cos \beta)/2$$

ρ = Diffused reflectivity

Since the reflected radiation does not contribute much to the total, it can be neglected so Eq 4.12 reduces to

$$I_T = I_b r_b + I_d r_d \quad \text{Eq 4.13}$$

Table 4.2 shows the calculated values of solar radiation falling on tilted surface for 12 months at $\beta_{opt} = 20^\circ$

Table 4.2 Calculated values of the solar radiation falling on tilted surface for 12 months

Month	$\bar{H}_g$ (kJ/m ² -day)	$\bar{H}_d$ (kJ/m ² -day)	$\bar{H}_b$ ($\bar{H}_g - \bar{H}_d$)	I_o W/m ²	I_g W/m ²	I_d W/m ²	I_b ($I_g - I_d$)	I_T W/m ²
January	18391	2159	16233	1055	796	86	710	967
February	21042	2524	18518	1164	879	97	782	1007
March	23945	2826	21120	1269	960	104	856	1030
April	26236	3079	23158	1330	1007	109	898	1011
May	27266	3211	24056	1335	1010	109	901	963
June	27475	3229	24247	1323	1001	108	893	931
July	27269	3195	24075	1323	1002	108	894	943
August	26498	3098	23401	1324	1003	108	895	985
September	24652	2895	21758	1285	972	105	867	1017
October	21797	2553	19245	1189	899	97	802	1009
November	18946	2223	16724	1076	813	88	725	973
December	17555	2058	15499	1018	768	83	685	949

Although the total radiation incident on the tilted surface (I_T W/m²) represents the available energy, not all of it reaches the photovoltaic module in a BSPVT system. A portion of the radiation is selectively absorbed or attenuated by the liquid spectrum filter. Hence, it becomes necessary to quantify the transmitted radiation reaching the PV module after filtering.

4.5 Flux available on PV after filtering in the fluid filter.

The radiation flux falling on the PV module after attenuating by the liquid spectrum filter is calculated using Eq 4.14 (neglected reflected radiation component) [2]

$$S_T = I_b r_b (\tau\alpha)_b + I_d r_d (\tau\alpha)_d \quad \text{Eq 4.14}$$

Value of $(\tau\alpha)_b$ & $(\tau\alpha)_d$ is taken from Joshi S [28]

Table 4.3 shows Calculated values of the solar radiation available on PV surface and percentage reduction in filter for 12 months.

Table 4.3 Calculated values of the solar radiation available on PV surface and percentage reduction in filter for 12 months.

Month	I_T W/m ²	I_b W/m ²	r_b	I_d W/m ²	r_d	S_T W/m ²	Absorbed in Filter	% reduction in solar radiation due to filter
January	967	710	1.243094	86	0.969846	804	163	16.86
February	1007	782	1.166859	97	0.969846	838	169	16.78
March	1030	856	1.08517	104	0.969846	858	172	16.70
April	1011	898	1.007476	109	0.969846	843	168	16.62
May	963	901	0.950735	109	0.969846	804	159	16.51
June	931	893	0.92525	108	0.969846	778	153	16.43
July	943	894	0.936878	108	0.969846	787	156	16.54
August	985	895	0.983447	108	0.969846	822	163	16.55
September	1017	867	1.054442	105	0.969846	847	170	16.72
October	1009	802	1.140036	97	0.969846	840	169	16.75
November	973	725	1.223109	88	0.969846	809	164	16.86
December	949	685	1.267075	83	0.969846	789	160	16.86

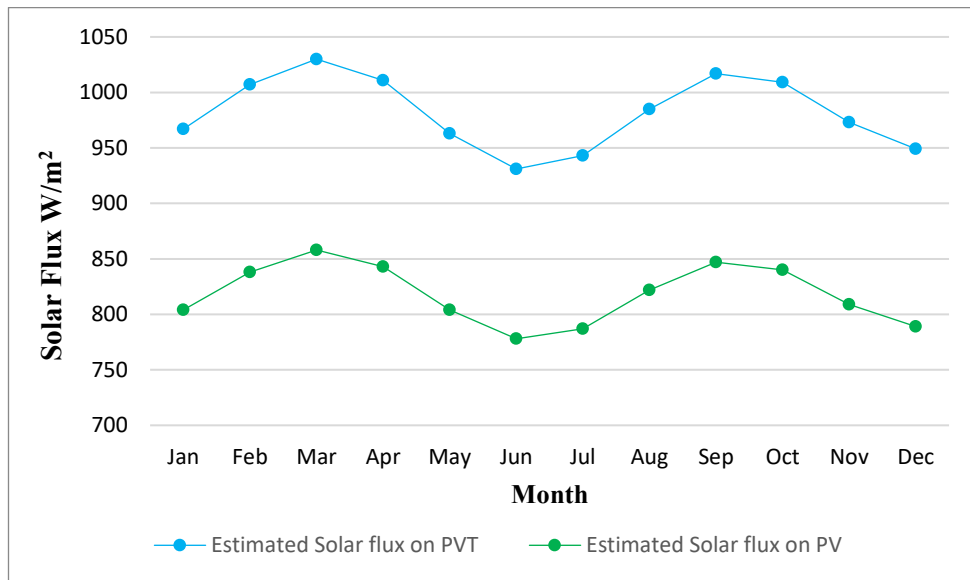


Figure 4.1 Monthly variation of estimated solar flux incident on the tilted PVT collector and the transmitted flux available at the PV module

Figure 4.1 illustrates the theoretical solar flux distribution for the BSPVT system located in Daman, India, throughout a calendar year. The blue series represents the total instantaneous solar radiation falling on the tilted surface (I_T), which reaches its maximum in March at approximately 1030 W/m². The green series represents the flux available at the photovoltaic module (S_T W/m²) after passing through the liquid

spectrum filter. The consistent gap between the two curves indicates that the optical filter and nanofluid attenuate the incident radiation by approximately 16.4% to 16.9%. This filtered portion is not lost but is instead absorbed as thermal energy by the fluid medium, facilitating the hybrid functionality of the system. The seasonal peak in March vs. the June minimum is attributed to the interplay between the higher declination angle and the optimized 20° tilt of the collector.

4.6 Performance analysis of the PVT system

The electrical performance of a PV module is highly influenced by its operating temperature. The spectral filter attenuates a portion of the incoming solar radiation, which helps in maintaining a lower operating temperature of the PV module. As a result, the thermal load on the module is reduced, contributing to improved electrical performance.

4.6.1 Electrical Performance of the PV module

For a crystalline silicon (C-Si) solar cell, the relationship between module temperature, solar radiation intensity, and ambient temperature is expressed by Eq. (4.15). [68]. The value of ambient temperature was taken from historical data of meteorological department IMD.

$$T_{pv} = 30 + 0.0175(S_T - 300) + 1.14(T_{amb} - 25) \quad \text{Eq 4.15}$$

Where,

T_{pv} = Temp of solar panel

S_T = Incident solar radiation on PV panel (W/m²)

T_{amb} = ambient temperature

Using eq (4.15) the temperature of PV panel with and without filter can be estimated using the solar flux falling on the tilted surface eq(4.13) and on PV after filtering by fluid filter eq (4.14).

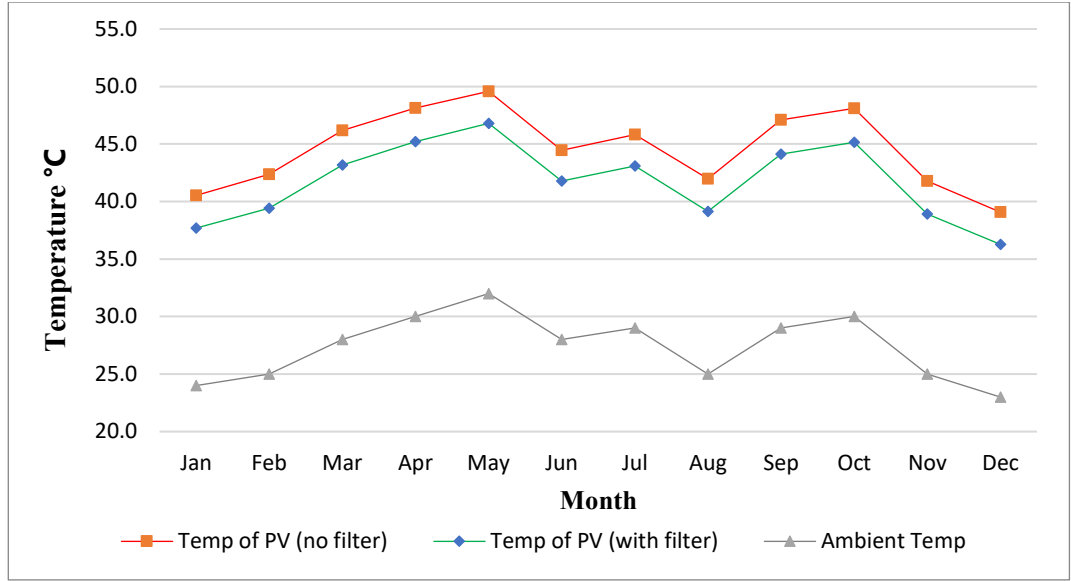


Figure 4.2 Comparison of Monthly Average Ambient and Photovoltaic Module Temperatures (with filter and without filter cases)

The theoretical analysis of the BSPVT system demonstrates a significant correlation between ambient conditions and the operating temperature of the photovoltaic module across all months shown in figure 4.2. By utilizing the Lasnier and Ang model, it is observed that without spectral filtering, the PV module temperature (T_{pv}) reaches a peak of 49.6°C in May, driven by high solar flux and an ambient temperature of 32°C. However, the integration of the liquid spectrum filter effectively attenuates a portion of the incoming radiation, resulting in a consistent reduction in the thermal load on the crystalline silicon cells. This cooling effect manifests as a temperature decrease of approximately 2.5°C to 3°C, representing a relative reduction of 5.6% to 7.2% compared to the unfiltered state. Such mitigation of the module's operating temperature is critical for enhancing electrical performance, as it directly reduces the thermal degradation typically associated with standard PV installations.

4.6.2 Estimation of electrical power output [2]

The values are calculated considering a 100-Watt C-Si solar panel. Area of panel 0.615 m² (Standard area of a 100 W Solar panel)

The drop in power output is calculated by eq (4.16)

$$P_{drop} = T_{cp} \times (T_{pv} - T_{STC}) \quad \text{Eq 4.16}$$

Maximum power output is calculated by eq (4.17)

$$(P_{max})_{T_{pv}} = P_{STC} - P_{drop} \quad \text{Eq 4.17}$$

4.6.3 Thermal Performance of the PVT

As per the assumptions made in section 4.1, The heat absorbed by the liquid spectrum filter is considered as the thermal output of the system.

Therefore

$$Q_{th} = (I_T - S) \times A_{filter} \quad \text{Eq 4.17}$$

4.7 Efficiency of the PVT System

4.7.1 Electrical Efficiency

The area of the PV panel is considered the solar radiation capture area for electrical efficiency, as the solar radiation, after passing through the optical filter, is absorbed exclusively by the PV panel surface.

$$\eta_{ele} = \frac{(P_{max})_{T_{pv}}}{A_{pv} \times I_T} \quad \text{Eq 4.18}$$

4.7.2 Thermal Efficiency

The area of the filter is considered the solar radiation capture area for thermal efficiency, as the solar radiation, is absorbed by the entire filter surface.

$$\eta_{th} = \frac{Q_{th}}{A_{filter} \times I_t} \quad \text{Eq 4.19}$$

Assuming the collector (filter) area same as PV module area.

4.7.3 Overall Efficiency

$$\eta_{overall} = \eta_{th} + \eta_{ele} \quad \text{Eq 4.20}$$

Table 4.4 Temperatures, Power and % increase in output of PV due to temperature reduction for 12 months.

Month	Ambient Temp °C	Temp of PV (no filter) °C	Temp of PV (with filter) °C	% reduction in temperature of PV	P _{max} without filter Watt	P _{max} with filter Watt	% increase in PV output
January	24	40.5	37.7	7.04	92.23	94.80	2.78
February	25	42.4	39.4	6.98	91.31	94.09	3.04
March	28	46.2	43.2	6.52	89.40	92.54	3.51
April	30	48.1	45.2	6.11	88.43	91.72	3.72
May	32	49.6	46.8	5.61	87.71	91.06	3.82
June	28	44.5	41.8	6.02	90.27	93.12	3.16
July	29	45.8	43.1	5.96	89.59	92.59	3.34
August	25	42.0	39.1	6.79	91.51	94.20	2.95
September	29	47.1	44.1	6.32	88.95	92.16	3.61
October	30	48.1	45.2	6.15	88.45	91.74	3.72
November	25	41.8	38.9	6.87	91.61	94.30	2.93
December	23	39.1	36.3	7.17	92.96	95.38	2.60

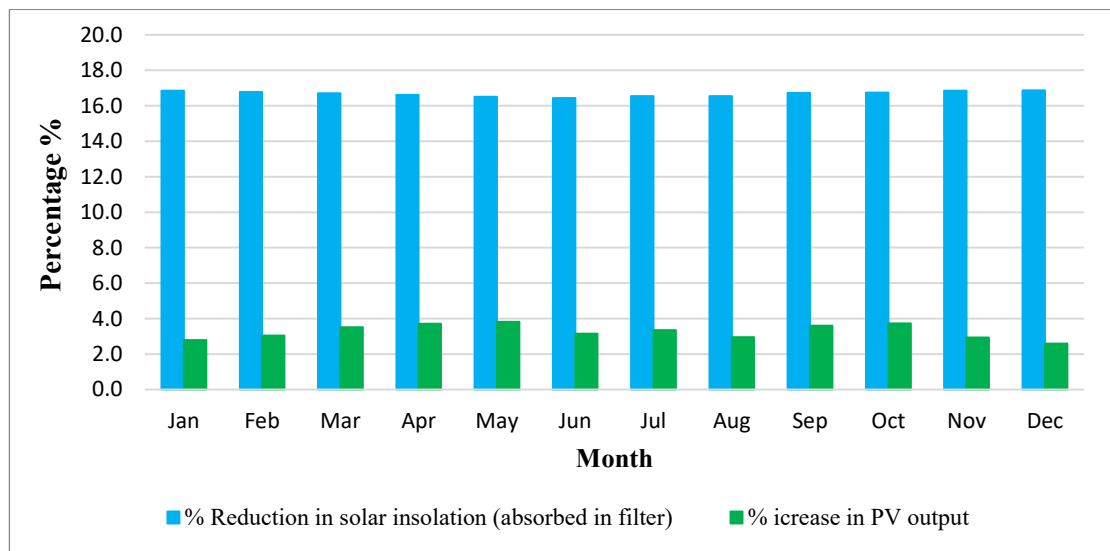


Figure 4.3 Impact of Spectral Filtering on Solar Irradiation and Photovoltaic Power Output.

The theoretical evaluation of the BSPVT system highlights a strategic trade-off between optical attenuation and electrical enhancement as shown in Table 4.4 and Figure 4.3. As demonstrated by the performance data, the liquid spectrum filter causes a near-uniform reduction in solar radiation ranging between 16.43% and 16.86% across all months which is effectively absorbed as the system's primary thermal input. This intentional reduction in incident flux leads to a direct decrease in the PV module's operating temperature by approximately 5.6% to 7.2%. Consequently, the cooling

benefit provided by the spectral filter triggers a measurable increase in electrical power output, varying from a minimum of 2.60% in December to a maximum of 3.82% in May. This indicates that the thermal mitigation of the crystalline silicon cells successfully compensates for the decrease in incident radiation, allowing the system to achieve higher relative electrical efficiency while simultaneously generating useful thermal energy. The overall system efficiency, which ranges from 31.31% to 33.20%, underscores the advantage of this hybrid energy utilization strategy.

4.8 Theoretical efficiencies of the system

Table 4.5 Theoretical Monthly Efficiencies of the BSPVT System

Month	Efficiency of PV without Filter	Efficiency of PV With Filter	% increase in efficiency of PV due to reduction in temperature	Thermal Efficiency	Overall Efficiency
January	15.51	15.94	2.78	16.86	32.80
February	14.74	15.19	3.04	16.78	31.98
March	14.11	14.61	3.51	16.70	31.31
April	14.22	14.75	3.72	16.62	31.37
May	14.81	15.38	3.82	16.51	31.89
June	15.77	16.26	3.16	16.43	32.70
July	15.45	15.96	3.34	16.54	32.51
August	15.11	15.55	2.95	16.55	32.10
September	14.22	14.73	3.61	16.72	31.45
October	14.25	14.78	3.72	16.75	31.53
November	15.31	15.76	2.93	16.86	32.61
December	15.93	16.34	2.60	16.86	33.20

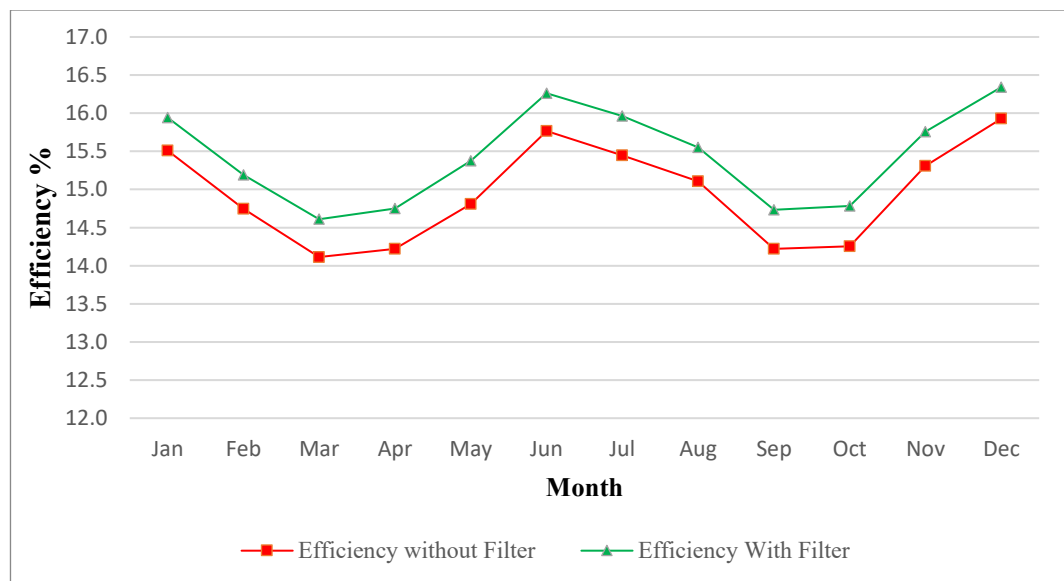


Figure 4.4 Comparison of PV Electrical Efficiency with and Without Spectral Filtering.

The theoretical investigation of the BSPVT system demonstrates that the integration of a liquid spectrum filter significantly enhances the overall energy conversion efficiency. As shown in the comparative data Table 4.5, while the spectral filter reduces the total incident radiation reaching the photovoltaic cells, the corresponding decrease in the module's operating temperature leads to a measurable improvement in electrical efficiency. Specifically, as depicted in figure 4.4 the electrical efficiency of the PV module improves from a range of 14.11%-15.93% in the unfiltered state to 14.61%-16.34% with the filter, representing a relative increase of 2.60% to 3.82% due to thermal mitigation. Furthermore, as shown in the table 4.5 the system achieves a consistent thermal efficiency between 16.43% and 16.86% by effectively harnessing the filtered portion of the solar spectrum as useful heat. When these components are combined, the overall system efficiency ranges from 31.31% to 33.20%, confirming the effectiveness of spectral beam-splitting in optimizing total solar energy utilization.

4.9 Discussion

The solar radiation analysis indicates that the monthly average global radiation varies from approximately 25,347 kJ/m²-day in December to 39,674 kJ/m²-day in June, reflecting seasonal variations in solar intensity. After accounting for diffuse components and tilt angle correction, the average instantaneous solar radiation at 12:00 noon (Peak radiation time of the day) on the tilted surface ranges between ~931 W/m² (June) and ~1030 W/m² (March).

The incorporation of the liquid spectrum filter results in a reduction of incident radiation on the PV module by approximately 16.4% to 16.9% throughout the year, with an average transmitted radiation of about 780-860 W/m². The absorbed portion of this radiation is effectively utilized as thermal energy.

Due to this attenuation, the operating temperature of the PV module decreases by approximately 5.6% to 7.2%, corresponding to an average temperature reduction of about 2.5°C to 3°C compared to the unfiltered condition. This reduction in temperature leads to an enhancement in electrical performance.

The electrical power output of the PV module increases from approximately 87.7-92.9 W (without filter) to 91.0-95.4 W (with filter), resulting in an enhancement

of 2.6% to 3.8% in power output. Similarly, the electrical efficiency improves from ~14.1%-15.9% to ~14.6%-16.3%, representing a relative increase of 2.6% to 3.8%.

The thermal performance analysis shows that the system achieves a thermal efficiency of approximately 16.5% to 16.8% across different months. When combined with electrical efficiency, the overall system efficiency ranges from 31.31% to 33.2%, demonstrating the advantage of hybrid energy utilization.

4.10 Conclusion

The theoretical investigation confirms that the integration of a liquid spectrum filter in a BSPVT system significantly enhances overall system performance by enabling simultaneous electrical and thermal energy generation. Although the filter reduces the incident radiation reaching the photovoltaic module, the corresponding decrease in operating temperature leads to a measurable improvement in electrical efficiency. Furthermore, the absorbed portion of radiation is effectively harnessed as useful thermal energy, resulting in a substantial increase in overall system efficiency exceeding 33%. These findings demonstrate the effectiveness of spectral beam-splitting in optimizing solar energy utilization and provide a strong foundation for experimental validation and further system optimization.

CHAPTER 5

Design of Experimental Setup

This chapter discusses the design, development, and experimental evaluation of a fluid-based BSPVT system employing a $\text{TiO}_2\text{-H}_2\text{O}$ nanofluid filter. The system was conceptualized and fabricated to enable simultaneous harvesting of electrical and thermal energy through spectral separation of incident solar radiation. A modular test rig was designed, consisting of a mild steel frame to support the PV panel and nanofluid filter assembly, a fluid circulation unit for maintaining regulated flow conditions, and a comprehensive instrumentation system for monitoring electrical and thermal parameters under outdoor solar exposure. The TiO_2 0.04% w/w nanofluid, as discussed in Chapter 3, was selected, making it an effective spectral filter for hybrid PV-thermal applications.

As discussed in Chapter 2, extensive research has been carried out to identify suitable working fluids capable of matching the bandgap of PV modules for improved spectral utilization in spectral beam-splitting (SBS) configurations. However, most prior studies were limited to laboratory-scale experiments using solar simulators under controlled conditions and short exposure durations. Only a few have investigated the long-term stability and performance of fluids under real-time solar outdoor conditions, which is crucial for understanding their durability, optical stability, and overall system reliability.

Several notable efforts have explored innovative BSPVT configurations. Huang et al. [69] developed a tubular oil-filled optical concentrator combined with PV cells (Figure 5.1a), where silicone oil acted as a selective photothermal absorber, seizing IR radiation while focusing visible light towards the PV surface. Vijayaraghavan et al. [20] investigated a borosilicate volumetric absorber using CuSO_4 solution, achieving 67% spectral absorption in the desired range (Figure 5.1b). Crisostomo et al. [11] introduced a hybrid PVT collector employing Ag-SiO_2 nanofluid, resulting in a 12% rise in weighted energy output as compared to a conventional PV system (Figure 5.1c). Similarly, Joshi et al. [26] evaluated a 10 mm silicone oil layer as a spectrum filter

above a silicon PV module, highlighting the viability of optical filtering for spectral control (Figure 5.1d).

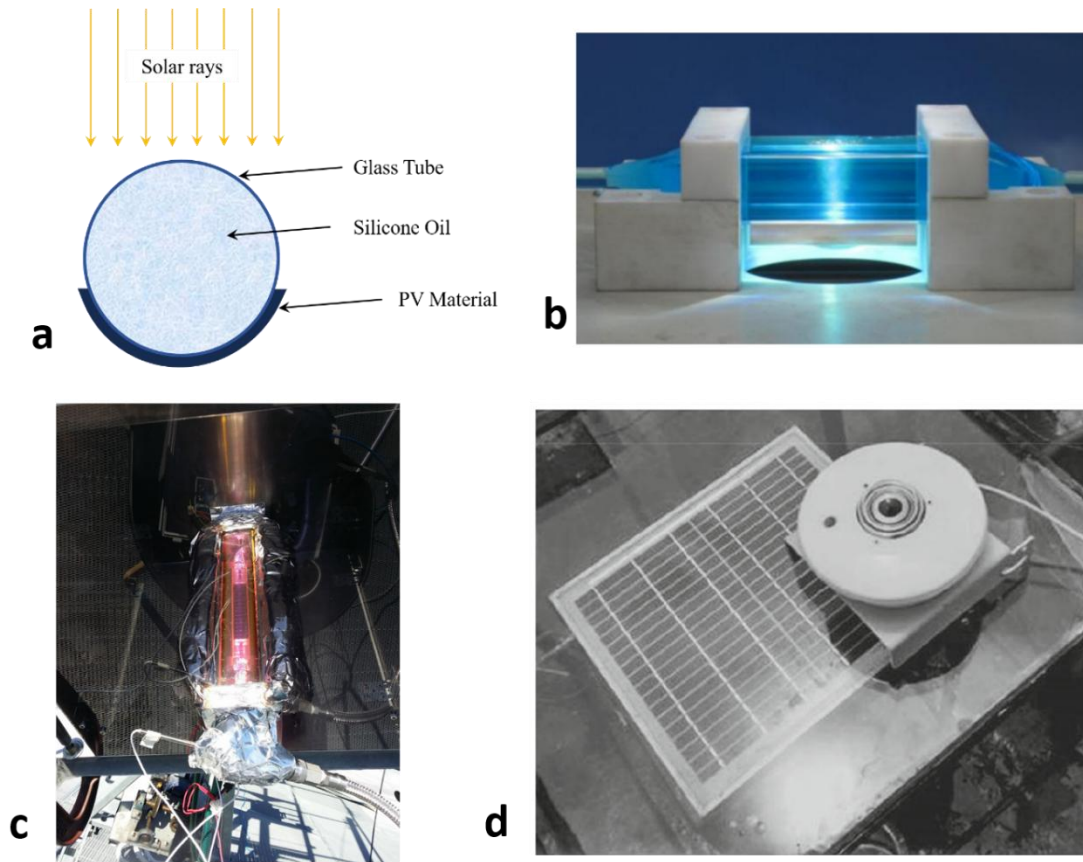


Figure 5.1 a) Oil filled tube concentrator BSPVT [69], b) a borosilicate volumetric absorber CuSO_4 solution [20], c) Transparent nanofluid channel placed above silicon PV cells [11], d) Silicone oil spectrum filter 10mm layer above Si PV module [26]

Long-term testing is essential to assess how continuous sunlight exposure affects the optical, thermal, and chemical stability of the fluid, as well as the integrity of structural materials like glazing, coatings and adhesives that may degrade with time.

Hence, this chapter focuses on the design, fabrication, and outdoor performance assessment of a fluid-based absorbance filter tested under natural solar exposure. The developed setup serves as a robust experimental platform for evaluating the optical, thermal, and electrical characteristics of several working fluids, determining their suitability as beam-splitters, and providing practical insights for the real-world applicability of BSPVT systems for efficient solar energy conversion.

5.1 Experimental Setup Overview

Keeping in mind the concept of the fluid-based spectral beam splitter discussed and visualized in Chapter 1, the system requires a controlled flow of fluid over the

surface of a PV module, maintaining a uniform gap between the two. To achieve this, a transparent housing was designed to contain the working fluid and ensure a consistent flow path across the module surface. A small-scale filter unit with an incident area of 500×500 mm was conceptualized for experimental evaluation.

A cage-like frame is developed to house both the fluid filter and the PV module, ensuring mechanical stability and proper alignment. This cage assembly is hinged with a mild steel frame, permitting tilt angle adjustment through an adjustment screw mechanism to optimize solar incidence based on location and time. The fluid circulation requirement is met using a pump, while a reservoir tank serves as the storage and supply unit for the nanofluid. Temperature sensors are strategically within the system to monitor fluid inlet and outlet temperatures, PV surface temperature, and ambient conditions. A PV analyser is used to record and evaluate the electrical performance of the module in real-time.

The design and configuration of each essential component including the frame, fluid channel, circulation system and instrumentation are discussed in detail in the subsequent sections of this chapter. A schematic illustration of the experimental setup is shown in the figures 5.2 & 5.3.

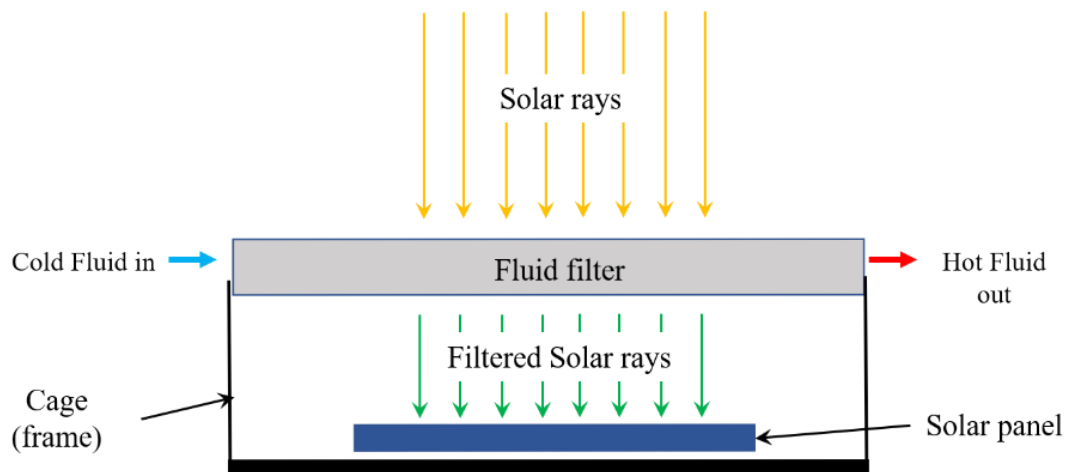


Figure 5.2 Schematic of cage to accommodate filter above PV module

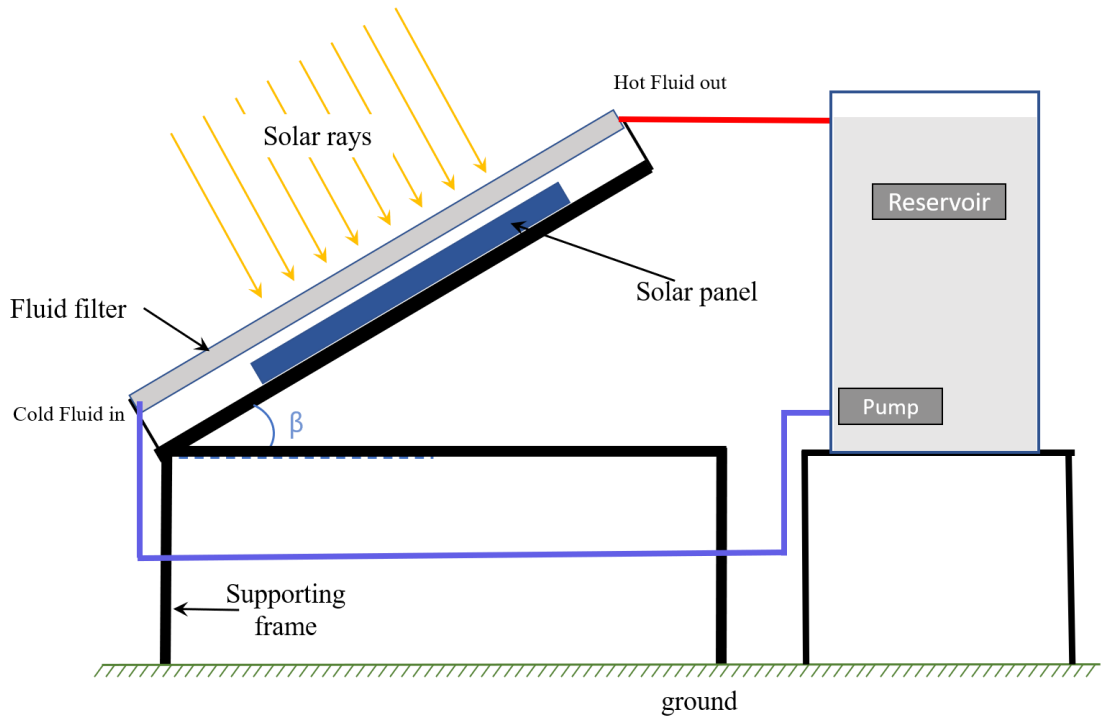


Figure 5.3 Schematic illustration of the experimental setup.

5.2 Solar Panel

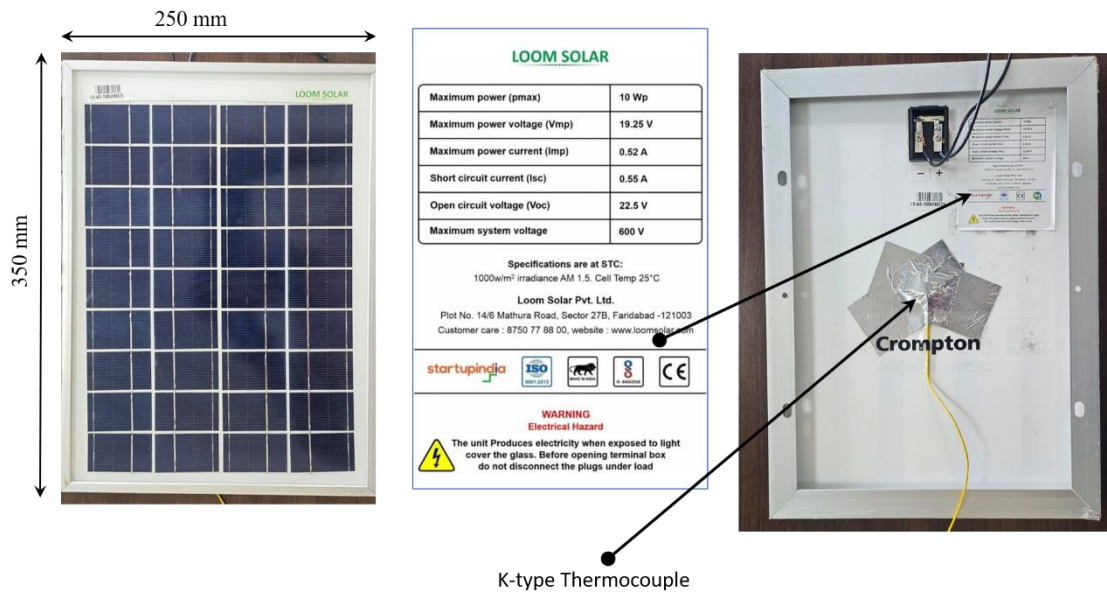


Figure 5.4 A 10 W C-Si photovoltaic module with a K-type thermocouple attached to the rear surface using heat-resistant aluminium tape for real-time temperature monitoring.

A 10 W silicon (Si) solar photovoltaic (PV) module, as shown in Figure 5.4, was used for the experimental investigation. The module has an active area of 250 mm × 350 mm, and its specifications under STC are:

- maximum power output of 10 W
- maximum power voltage (V_{mp}) of 19.25 V
- maximum power current (I_{mp}) of 0.52 A
- short-circuit current ($I_{sc(pv)}$) of 0.55 A
- open-circuit voltage (V_{oc}) of 22.5 V

To monitor the thermal behaviour of the PV module during operation, a K-type thermocouple was mounted at the rear surface of the panel using thermally conductive adhesive, as illustrated in Figure 5.4. This sensor continuously records the back-surface temperature, enabling evaluation of the cooling performance of the fluid-based spectral filter placed above the module.

5.3 Filter with circulating fluid

5.3.1 Requirements of Filter

For the effective functioning of a fluid-based BSPVT system, the design of the fluid filter must satisfy specific structural, optical, and operational requirements. The following considerations were established during the design phase to ensure optimal performance and durability of the filter under outdoor conditions:

- The filter material should be highly transparent ($\approx 100\%$) to solar radiation in the visible range to allow maximum light transmission to the PV surface.
- The filter should be lightweight to facilitate easy installation, adjustment, and maintenance.
- It must have adequate mechanical strength to withstand hydrostatic pressure, wind load, and other outdoor mechanical stresses.
- The filter dimensions should cover the entire surface area of the PV module, ensuring uniform spectral filtering and consistent optical exposure.
- The design should be simple, modular, and easily fabricated using commercially available materials to reduce cost and complexity.
- The filter assembly should be easy to handle during assembly, testing, and maintenance operations.
- Inlet and outlet vents must be incorporated to allow smooth and continuous circulation of working fluid.

- The system should allow accurate measurement of the working fluid temperatures at both inlet and outlet points for performance evaluation.
- Leak-proof joints and seals must be ensured throughout the assembly to prevent fluid leakage during operation.
- The flow of the fluid should be easily controllable using valves and flow regulation mechanisms, maintaining uniform distribution over the PV surface.

These requirements guided the design, selection of materials, and fabrication approach for the transparent filter unit used in the BSPVT experimental setup.

5.3.2 Filter Design

Considering the above design requirements, the fluid filter was conceptualized as a sandwiched transparent enclosure that allows the working fluid to flow uniformly over the PV module. A fluid layer of 10 mm thickness was selected to ensure adequate spectral filtering and thermal

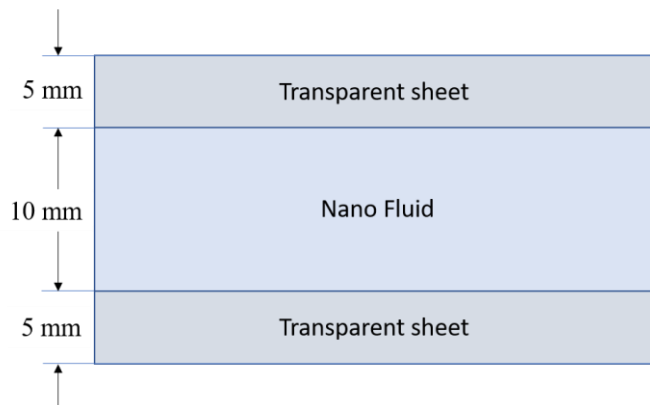


Figure 5.5 Filter Cross-section, nanofluid sandwiched between two transparent sheet with 10 mm gap.

exchange while minimizing optical losses and hydrostatic load. The filter assembly consists of two transparent sheets of dimensions 500×500 mm 5 mm thick, forming the bottom and top surfaces of the enclosure. The flowing nanofluid layer is confined between these sheets using sealing gaskets and spacer supports along the edges to maintain a uniform gap and prevent leakage. The entire filter unit is positioned above the PV module within the cage assembly, ensuring proper alignment and full coverage of the active PV area. The cross-section view of the designed filter is illustrated in the accompanying figure 5.5, showing the arrangement of the transparent plates and fluid layer that together form the integral structure of the fluid-based spectral beam-splitting filter.

5.3.3 Material of filter casing

The first candidate considered to meet the high-transmissivity requirement was glass. Previous evaluations of optical transmissivity for transparent materials used in solar flat-plate collectors indicate that low-iron glass provides excellent transmission ($\approx 92\%$) across the responsive range of silicon solar cells [70]. This makes low-iron glass an attractive option for maximizing visible-light throughput to the PV module while allowing the fluid layer to absorb the infrared portion of the spectrum. Despite its favourable optical properties, glass presents several practical disadvantages for the proposed fluid-filter assembly:

- Heavy weight, which increases the overall structural load on the frame and complicates handling and mounting.
- Brittleness and susceptibility to breakage upon impact, reducing field robustness.
- Difficulty in machining (drilling/cutting), complicating the fabrication of inlet/outlet ports and custom features.
- Low impact resistance, increasing the risk of damage during installation or operation.
- Susceptibility to thermal-stress cracking under rapid temperature fluctuations experienced outdoors.
- Challenges in achieving reliable, long-term leak-proof seals at glass interfaces.
- Limited reparability: damaged panes are difficult to repair on-site and typically require full replacement.
- Safety hazards from sharp fragments if breakage occurs, which raises maintenance and occupational safety concerns.

Given these limitations, glass while optically excellent may impose significant constraints on system weight, durability, manufacturability, and maintenance.

The spectral transmission of solar radiation through various plastic materials was analysed and compared to that of conventional glass [70], [71]. The results demonstrated that Poly methyl methacrylate (PMMA) exhibits optical transmission characteristics nearly identical to glass across the solar spectrum. This makes PMMA a

highly suitable substitute for use as a transparent enclosure material for fluid-based filter.

A mirror-finished PMMA sheet offers several distinct advantages over glass, combining good optical performance with enhanced mechanical and handling properties. The key advantages of PMMA are as follows:

- Lightweight, reducing the overall system weight and structural load.
- Higher impact resistance than glass, making it less prone to shattering under mechanical stress.
- Ease of fabrication, as it can be readily cut, drilled, or machined for inlet and outlet vents.
- Better flexibility, which minimizes the risk of cracking due to stress or temperature variations.
- High optical transparency (~92%), ensuring efficient transmission of solar radiation to the PV surface.
- Improved sealing capability, facilitating leak-proof joints for fluid containment.
- Enhanced safety, since PMMA does not form sharp fragments upon breakage.
- Cost-effectiveness and availability, with customizable sizes and thicknesses.
- Thermoformability, allowing it to be molded or curved into desired shapes for experimental or field setups.

Given these advantages, PMMA was selected as the transparent material for the fluid filter design, offering an ideal balance between optical efficiency, mechanical strength, and ease of fabrication and maintenance. The material's excellent light transmission and mechanical resilience make it particularly well-suited for repeated experimental use in outdoor conditions.



Figure 5.6 Filter material

Product Detail	
Material:	PMMA
Thickness:	5 mm
Color:	Transparent
Size:	500 X 500 mm ²
Finish:	Mirror Finish

A 5 mm thick PMMA sheet was employed for constructing the transparent housing to prevent sagging or deformation under the hydrostatic pressure of the contained fluid. In order to prevent any shadowing effects and ensure that the entire active area of the PV module (250×350 mm) is uniformly exposed to filtered solar radiation, the filter dimensions were chosen to completely cover the PV surface. Accordingly, a filter of size 500 mm $\times$ 500 mm was designed, providing adequate margin for mounting, sealing, and structural support. The cross-section configuration of the filter is depicted in Figure 5.7, while the detailed design layout is presented in Figure 5.8.

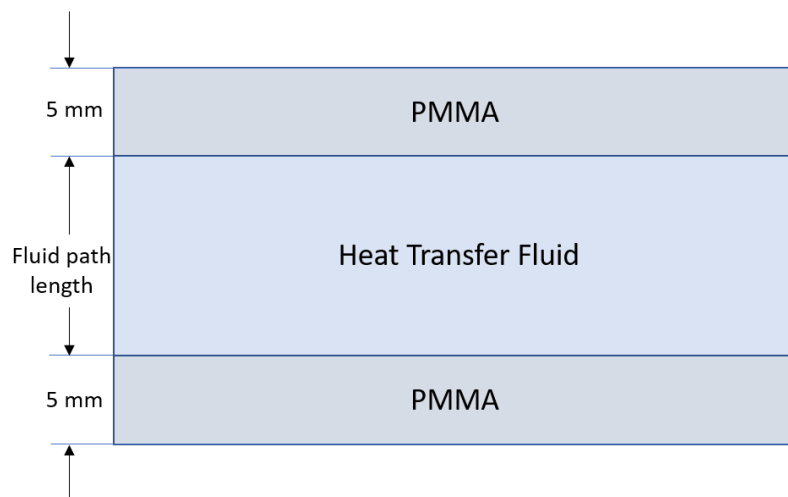


Figure 5.7 The cross-section configuration of the filter

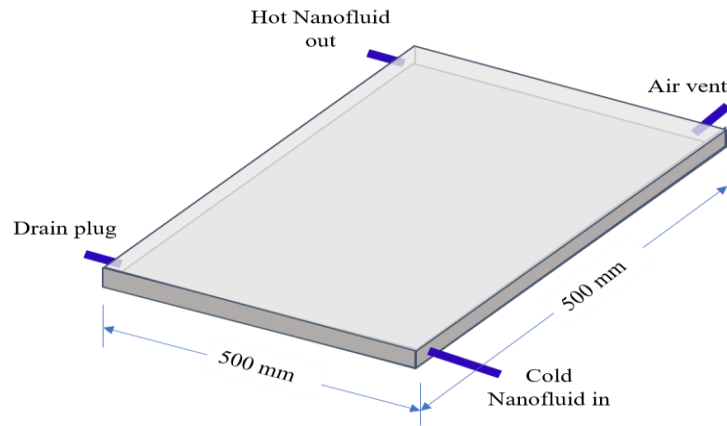


Figure 5.8 Design layout visualization of the filter 500 x 500 mm.

The filter casing is equipped with 10 mm nozzle valves at the inlet and outlet to facilitate smooth fluid entry and discharge. An air vent is incorporated at the top of the filter to eliminate trapped air during the startup phase, ensuring stable flow conditions. Additionally, a drain valve is provided at the lowest point of the system to allow complete drainage of the fluid when required for maintenance or replacement. The arrangement and positioning of these valves are illustrated in Figure 5.8.

To ensure experimental flexibility, the design allows for the fabrication of interchangeable filters with varying optical path lengths, enabling comparative testing under identical conditions. For the present experimentation, a 1 cm (10 mm) fluid path length was selected, providing an effective balance between spectral absorption and optical transmission to the PV surface. The filter assembly incorporates inlet and outlet vents for smooth fluid circulation, a drain valve and an air breathing vent to ensure complete draining and prevent air blocking during operation. The modular and adaptable design enhances the setup's durability, serviceability, and suitability for long-term experimental evaluations.

Unlike TESPI Design [31], [32] serpentine heat extraction geometry or separate internal cooling circuit is omitted based on optical, fluidic, and manufacturing constraints, like causing shading on the solar PV panel, hydraulic resistance and head losses, nanoparticles may get trapped, and non-uniform gradients on the PV panel may form.

5.3.4 Fluid flow circuit through the filter

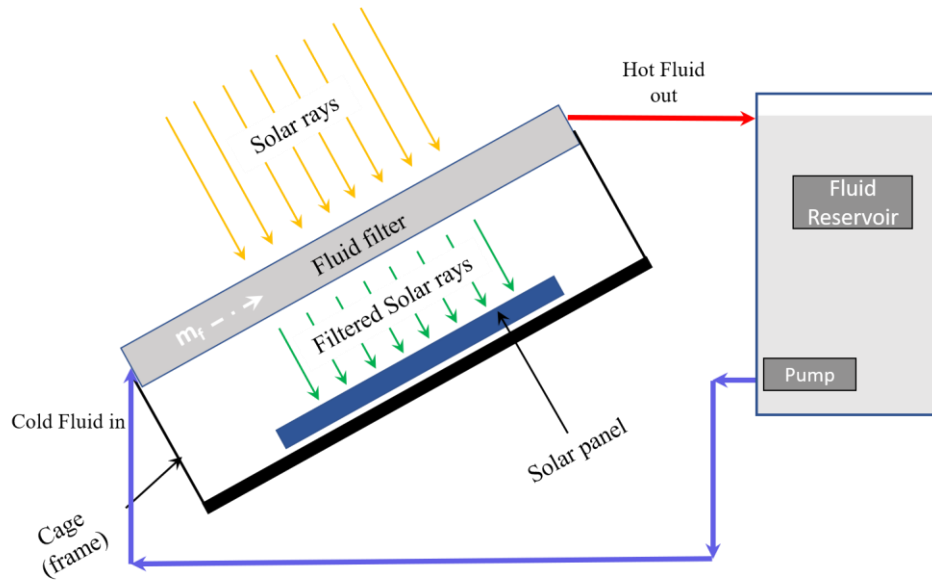


Figure 5.9 Schematic diagram of the closed-loop circulation of the working fluid within the BSPVT system.

The flow of the working fluid in the experimental setup follows a closed-loop circulation, as illustrated in Figure 5.9. A Submersible pump draws the nanofluid from the reservoir and directs it to the inlet of the fluid filter. Inside the filter, the fluid flows as a layer between two transparent PMMA sheets placed above the photovoltaic (PV) module. When solar radiation falls on the filter, the nanofluid absorbs the heating component of the spectrum, which contributes primarily to heating, while the Si responsive range is selectively transmitted through the fluid and reach the PV surface for electrical conversion. As the solar heating rays are absorbed, the fluid temperature increases during its passage through the filter. The fluid exits through the outlet and returns to the reservoir, where the absorbed heat is stored or measured. The pump then recirculates the fluid, maintaining a continuous closed loop and steady flow. Complete fluid mixing is chosen over stratification. Thermal stratification requires steady fluid which may lead to agglomeration or sedimentation of nanoparticles.

The submersible pump, shown in Figure 5.10, is employed to maintain a continuous and uniform flow of the nanofluid through the experimental setup. The pump outlet is connected with a flow control valve, enabling regulation of the fluid flow rate

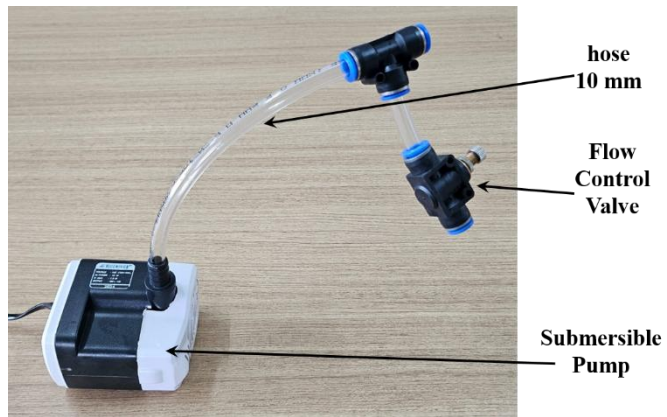


Figure 5.10 Submersible pump for circulation of fluid.

during testing. Polyurethane (PU) hoses of 10 mm internal diameter are used to establish the flow circuit between the pump, fluid filter, and reservoir, ensuring flexibility and leak-proof connections.

5.4 Supporting frame

The frame design plays a critical role in supporting the fluid-based BSPVT system and ensuring accurate, stable, and safe operation under outdoor experimental conditions. The frame must provide structural rigidity, adjustability, and ease of integration with the PV module, fluid filter, and instrumentation. The following requirements were considered during the frame design process:

- The frame should provide a rigid and stable support for the PV module and fluid filter assembly maintaining the closed loop fluid flow explained in section 5.1.
- It should be lightweight yet strong, ensuring easy portability and long-term durability under outdoor conditions.
- The structure must be resistant to corrosion, preferably made from mild steel with anti-rust coating or paint.
- The cage should be mountable on the supporting frame, allowing it to be adjusted to any desired tilt angle for optimal solar incidence.
- It should provide easy access for assembly, maintenance, and alignment of the PV module and filter.
- The design must permit accurate angular adjustment using a tilt adjustment screw or locking mechanism.

- The frame should be compatible with outdoor installation and ensure safety and stability during prolonged testing.

The experimental setup employs a portable frame specifically designed to facilitate ease of outdoor experimentation and performance evaluation. The frame is constructed to house the fluid filter assembly, PV module, pyranometer, and thermocouples. To ensure capture of maximum solar energy, the frame permits adjustable inclination of the PV module and the filter assembly, aligning them with the solar elevation angle so that the incident irradiation remains nearly perpendicular throughout the testing period.

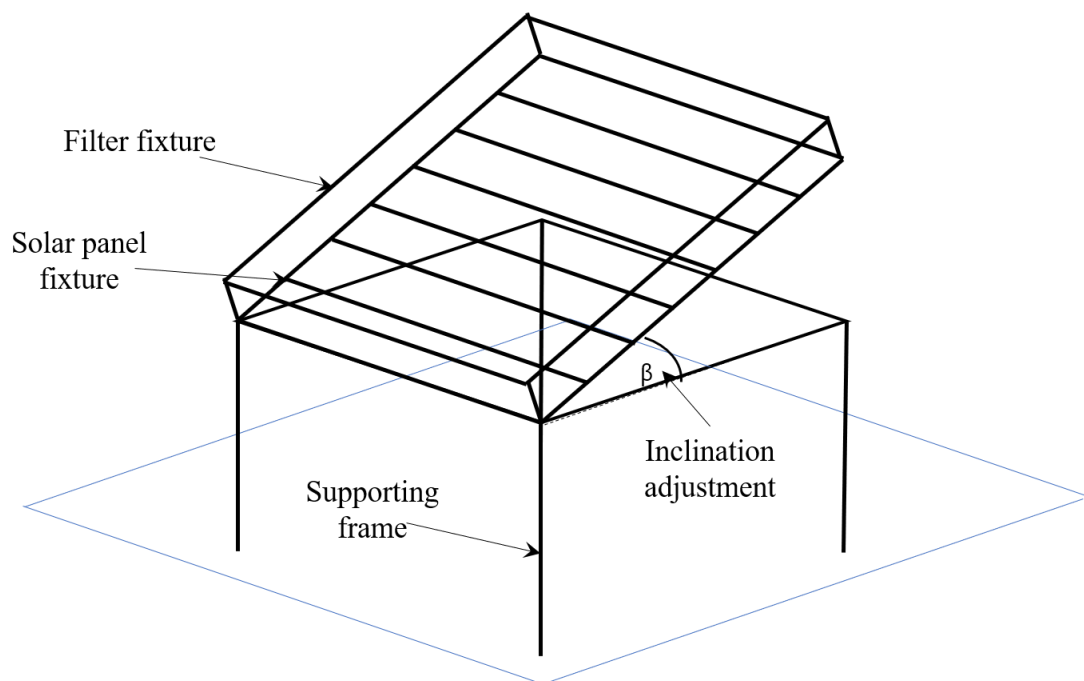


Figure 5.11 Drawing of MS frame.

The supporting structure is fabricated using square-channel & L-channel mild steel (MS), offering a balanced combination of strength, rigidity, and durability. A cage-type assembly securely houses the PV module and filter, which is mounted on the main MS frame through a hinged connection that permits smooth tilting (Figure 5.11). An adjustment screw mechanism enables precise locking at any desired tilt angle, facilitating optimal solar alignment during experiments. The use of mild steel enhances structural integrity and resistance to outdoor stresses, while the modular and portable design ensures convenient relocation, reassembly, and modification for various experimental configurations. Figure 5.12 (a & b) illustrate the fabricated frame structure used in this study.

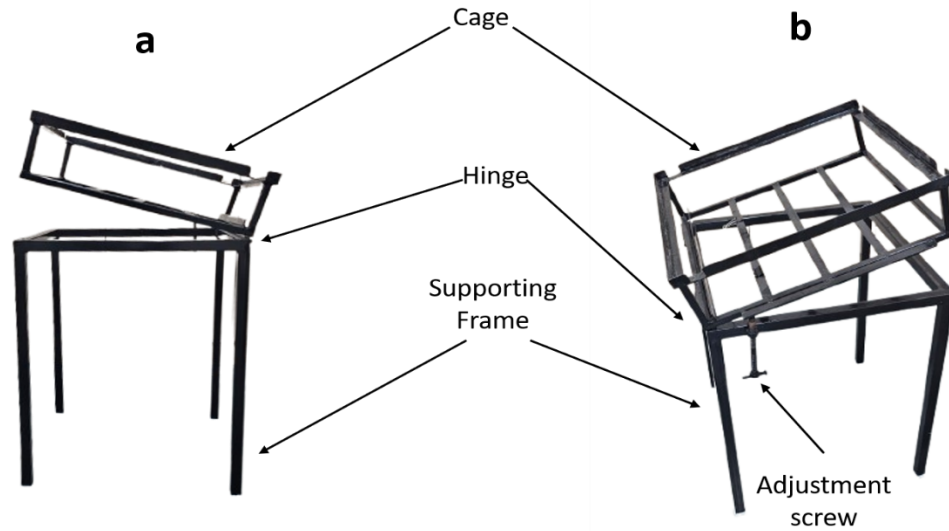


Figure 5.12 Photographic views of the fabricated cage and supporting frame structure featuring a hinge and adjustment screw mechanism for setting the tilt angle.

5.5 Instrumentation

The fluid filter is instrumented with thermocouples at the inlet and outlet to quantify the temperature gain of the nanofluid and thereby determine the thermal energy gained. Solar irradiance is measured using a pyranometer, which is positioned above the filter and below alternately to capture both the incident radiation and transmitted radiation, allowing accurate evaluation of spectral attenuation. A submersible pump is used to regulate the volumetric flow rate of the working fluid, ensuring stable operating conditions for reliable data acquisition. The instrumentation layout is depicted in Figure 5.13, while Figures 5.14 and 5.15 present photographs of the measurement equipment employed in the experimental setup.

A PV analyzer is used to measure electrical output characteristics, including the maximum power ($P_{\max}$), while a rheostat is employed to modulate the electrical load and evaluate performance at different operating conditions.

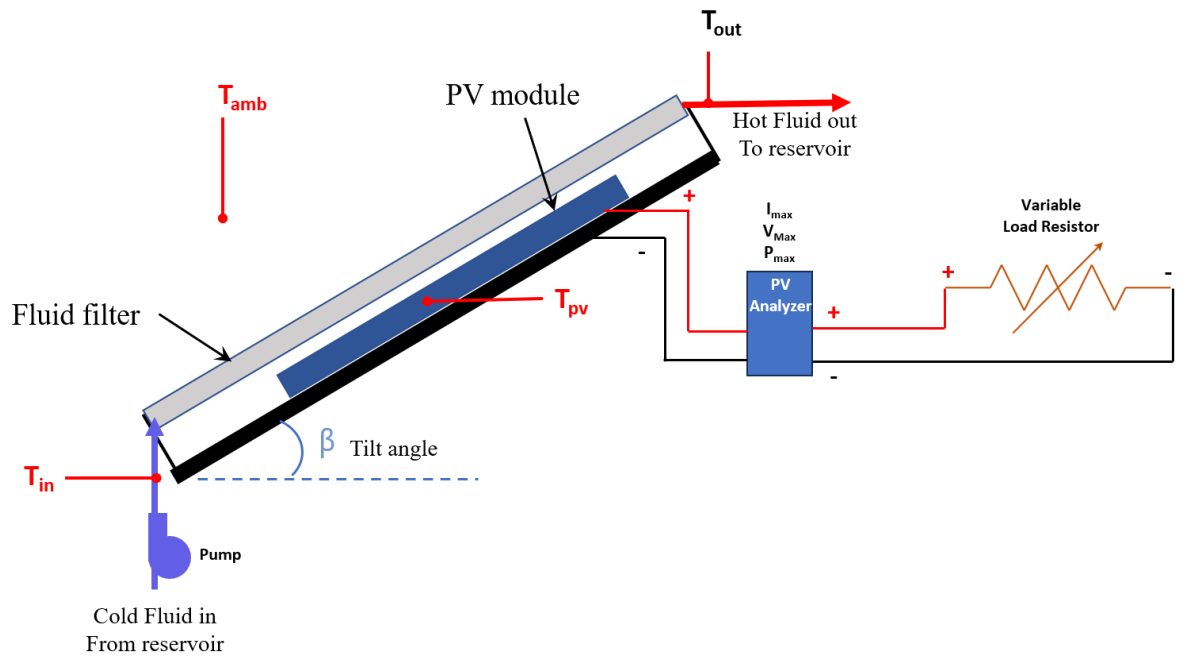


Figure 5.13 Fluid flow, PV analysis and instrumentation circuit.

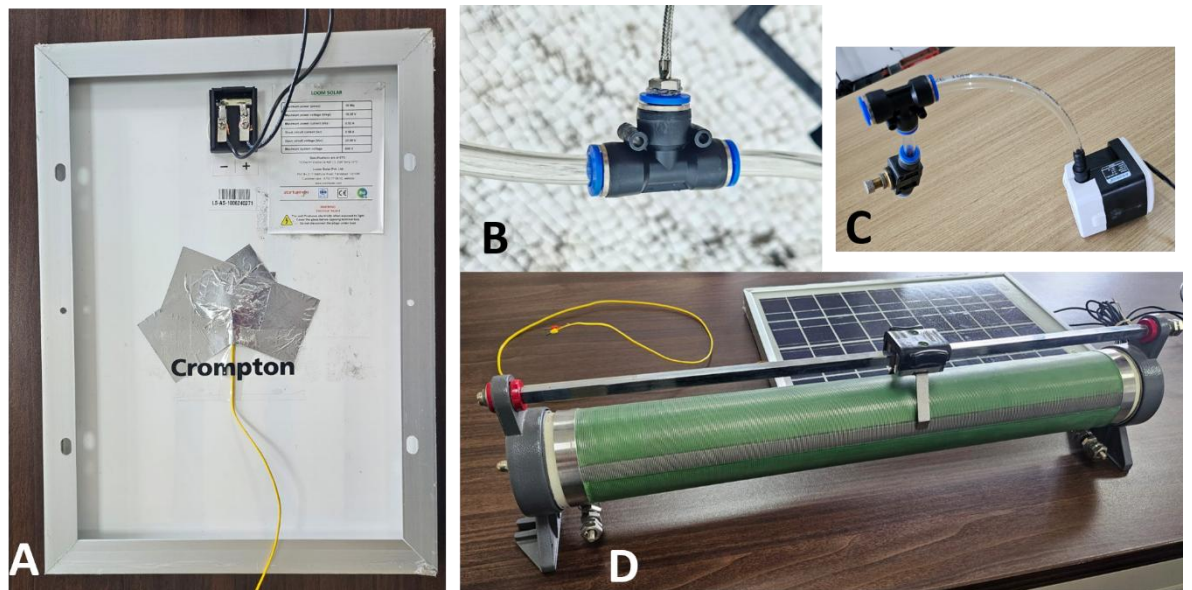


Figure 5.14 a) rear-mounted K-type thermocouple for T_{pv} monitoring, (b) fluid temperature sensors, (c) flow regulation system, and (d) electrical load rheostat

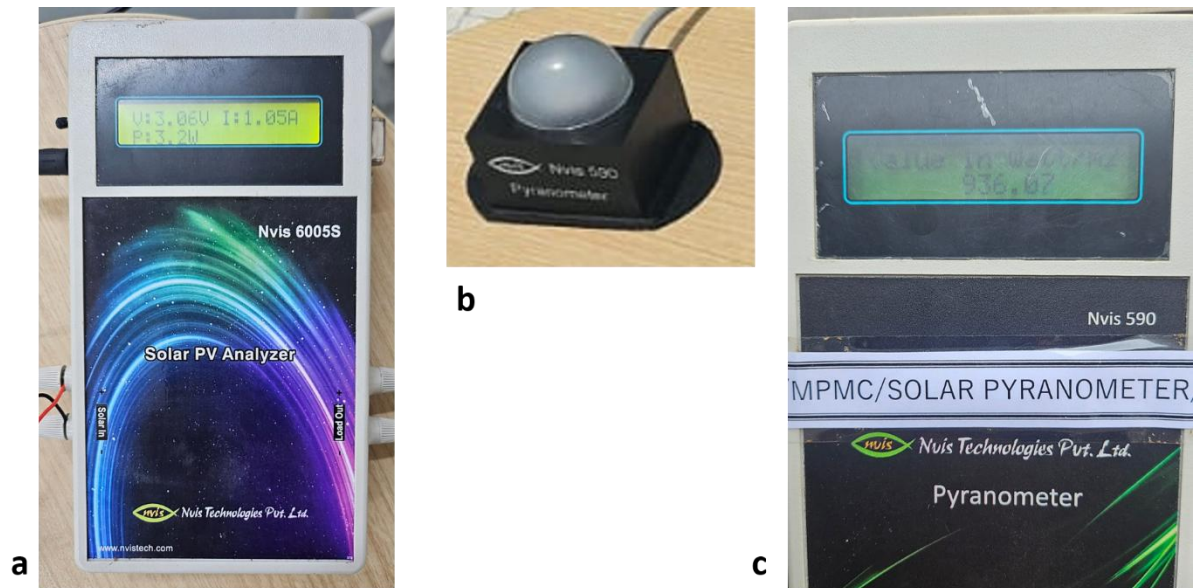


Figure 5.15 a) a Solar PV analyzer b) Pyranometer receiver c) Pyranometer digital display

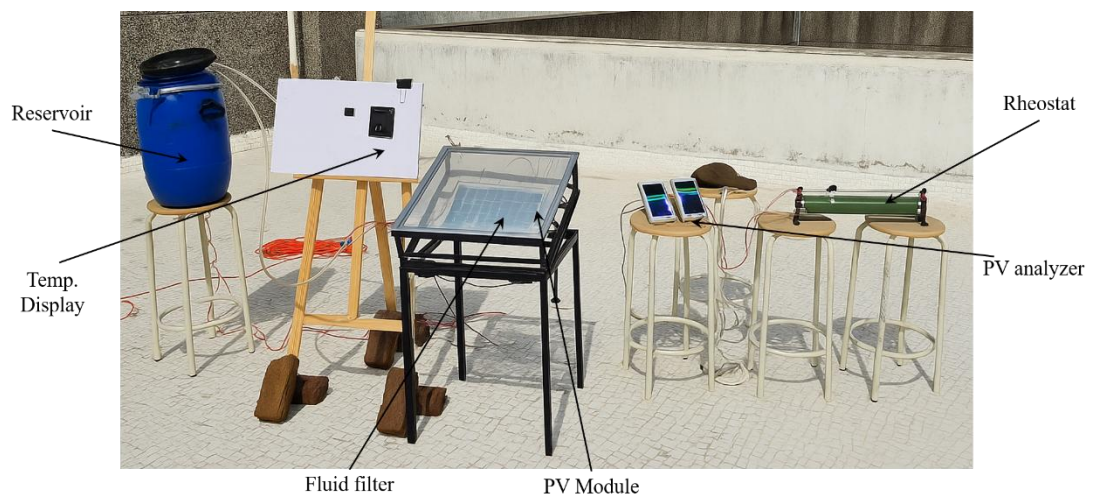


Figure 5.16 Complete Experimental Test Rig for the BSPVT System.

The fabricated experimental setup illustrates the integrated beam-splitting photovoltaic-thermal system, featuring the 10 W C-Si solar module positioned beneath the TiO₂ nanofluid spectral filter shown in Figure 5.16. The assembly is mounted on a hinged mild steel supporting frame adjusted to the optimum tilt angle for Daman, India. The setup includes the closed-loop fluid circulation system with a variable-speed pump and a fluid reservoir, enabling controlled flow rates of the working nanofluid.

5.6 Conclusion

The development of the experimental test rig represents a critical transition from theoretical modelling to empirical validation of the BSPVT system. A modular and adjustable support structure was successfully fabricated, featuring adjustment for precise orientation of tilt angle. The integration of the 10 W crystalline silicon PV module with a 0.04% w/w $\text{TiO}_2/\text{H}_2\text{O}$ nanofluid filter ensures that the system is equipped to perform effective spectral separation under real-world outdoor conditions. Furthermore, the comprehensive instrumentation suite comprising thermocouples for differential temperature measurement, a pyranometer for spectral attenuation analysis, and a submersible pump for flow regulation provides the necessary precision for capturing high-fidelity data. By establishing this reliable and stable experimental platform, the study is well-positioned to evaluate the long-term optical and thermal stability of the nanofluid, ultimately providing the empirical evidence required to validate the theoretical efficiency gains predicted in earlier chapters.

CHAPTER 6

Experimentation Methodology

For establishing a systematic comparison of performance, the photovoltaic (PV) module is evaluated under three configurations:

Case 1: The standalone PV module (without filter),

Case 2: The PV module with an empty filter casing, and

Case 3: The PV module with circulating nanofluid in the filter.

A photographic representation of these three configurations is presented in Figure 6.1

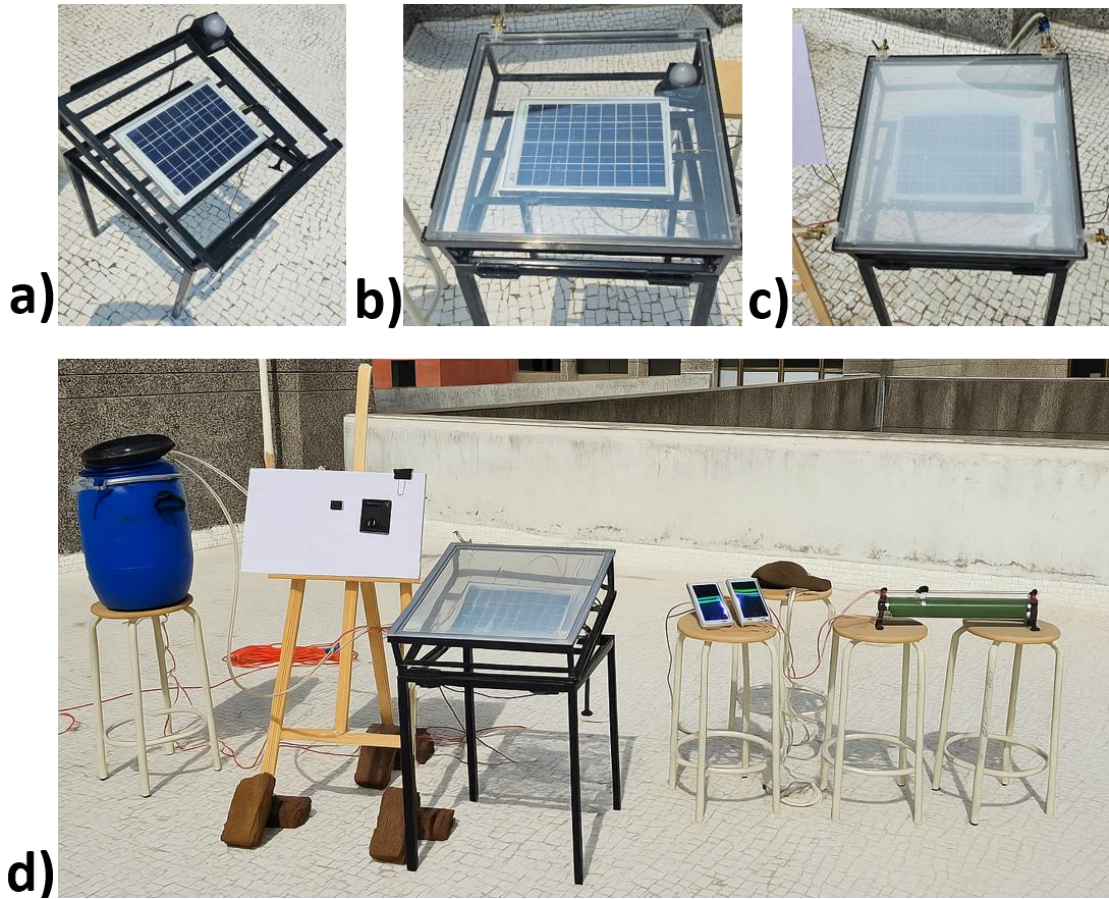


Figure 6.1 Experimental Configurations for Performance Comparison

Photographic representation of the three experimental configurations used to evaluate the BSPVT system: (a) the standalone PV module no filter, (b) the PV module with an empty filter frame, (c) the complete assembly featuring the circulating TiO_2 nanofluid spectral filter for simultaneous electrical and thermal energy harvesting, and (d) complete experimental setup.

The experimental setup is installed at Daman, India (coordinates 20.41° N, 72.86° E) in the month of April 2025 to ensure consistent solar exposure conditions typical of peak summer operation. The performance evaluation is conducted over multiple consecutive days to minimize environmental variability and enable comparative analysis under similar climatic conditions.

On the first day of experimentation, the PV module operates without filter arrangement. Electrical parameters are recorded continuously from 10:00 AM to 17:00 PM to capture the variation in performance parameters across peak solar radiation hours.

On the second day, an empty (no fluid) filter frame is positioned above the PV module. This configuration allows assessment of the optical and thermal influence of the structural frame alone, without the presence of a working fluid. Measurements are recorded over the same time interval to maintain consistency in data acquisition.

On the third, fourth, and fifth days, the complete filter assembly incorporating circulating working fluid is evaluated. The system operates at three different volumetric flow rates: 52 LPH, 58 LPH, and 70 LPH, respectively. This variation enables investigation of the influence of fluid circulation rate on thermal regulation and electrical performance enhancement. The working fluid employed in the system is a prepared TiO₂ nanofluid with a concentration of 0.04%. Prior to data collection, the filter chamber is allowed to fill completely to eliminate air gaps and ensure uniform fluid distribution. Data recording commences only after steady-state circulation conditions are achieved, thereby ensuring reliable and repeatable measurements.

During each experimental run, measurements are recorded in a structured sequence to maintain uniformity across all configurations:

6.1 Instrumentation and Methodology for Real-Time Performance Characterization

6.1.1 Solar Irradiation Measurement:

Incoming solar radiation is measured using a pyranometer. The instrument is positioned alternately above and below the filter assembly to determine incident and transmitted solar irradiance, enabling evaluation of the filter's optical characteristics.

6.1.2 Thermal Parameters:

The fluid inlet temperature (T_{in}), fluid outlet temperature (T_{out}), photovoltaic module temperature (T_{pv}), and ambient temperature (T_{amb}) are recorded using temperature sensors. These measurements facilitate calculation of thermal gain, heat extraction rate, and the cooling effect provided by the circulating nanofluid.

6.1.3 Electrical Performance Parameters:

The electrical parameters of PV module are measured by a PV analyzer. The maximum output power (P_{max}) is recorded. These measurements allow detailed assessment of the effect of thermal regulation on the PV efficiency.

The adoption of identical measurement intervals, consistent time duration, and controlled operating conditions ensures that the comparative analysis among the three configurations remains accurate and scientifically valid. This structured methodology enables comprehensive evaluation of both optical filtering performance and thermo-electrical enhancement achieved through the TiO₂ nanofluid-based filter system.

6.2 Calculations

The performance parameters of the BSPVT system are assessed using standard thermodynamic and photovoltaic relations. The formulas employed for calculating mass flow rate, solar attenuation, heat gain, electrical efficiency and thermal efficiency are adopted from Joshi et al. [23]. The following subsections describe the calculation procedures in detail.

6.2.1 Mass Flow Rate of the Fluid

The mass flow rate, defined as the quantity of nanofluid passing through the filter housing per second. It is determined experimentally using the volume collection method and is calculated using eq 6.1.

$$\dot{m}_{nf} = \frac{\rho_{nf} V_{nf}}{t} \text{ kg/sec} \quad \text{Eq 6.1}$$

The specific heat capacity of the TiO₂ nanofluid is determined via the mass-weighted average rule already discussed in chapter 3 section 3.7.1

$$Cp_{nf} \approx 4178.6 \text{ J/kg}\cdot\text{K}$$

6.2.2 Heat Gained by the Filter (Q_{th})

In the experimental setup, continuous heat removal from the filter is governed by the instantaneous fluid temperature difference across the filter channel rather than the absolute level of the reservoir temperature. The useful heat gained by the filter represents the absorbed thermal energy gained by the circulating nanofluid while flowing through the absorption chamber. It is determined using the standard energy balance relation:

$$Q_{th} = \dot{m}_{nf} C_{p_{nf}} (T_{out} - T_{in}) \text{ Watt} \quad \text{Eq 6.2}$$

6.2.3 Thermal Efficiency (η_{th})

Thermal efficiency represents the part of solar radiation on the filter which is converted into thermal energy by circulating fluid. The area of the filter is considered the solar radiation capture area for thermal efficiency, as the solar radiation, is absorbed by the entire filter surface as discussed in section 4.7.2.

$$\eta_{th} = \left(\frac{Q_{th}}{A_{filter} \times G_a} \right) \times 100 \quad \text{Eq 6.3}$$

6.2.4 Electrical Efficiency (η_{ele})

Electrical efficiency specifies the part of solar radiation transmitted through filter and incident on the PV panel and converted into electrical yield. The area of the PV panel is considered the solar radiation capture area for electrical efficiency, as the solar radiation, after passing through the optical filter, is absorbed exclusively by the PV panel surface as discussed in section 4.7.1.

$$\eta_{ele} = \left(\frac{P_{max}}{A_{pv} \times G_a} \right) \times 100 \quad \text{Eq 6.4}$$

6.2.5 Overall Efficiency ($\eta_{overall}$)

The overall efficiency represents the overall performance (thermo-electrical) of the BSPVT system. It accounts for useful heat recovery and the electrical power generation, thereby providing a comprehensive measure of system effectiveness.

$$\eta_{overall} = \eta_{th} + \eta_{ele} \quad \text{Eq 6.5}$$

6.3 Flow Chart of the experimental methodology

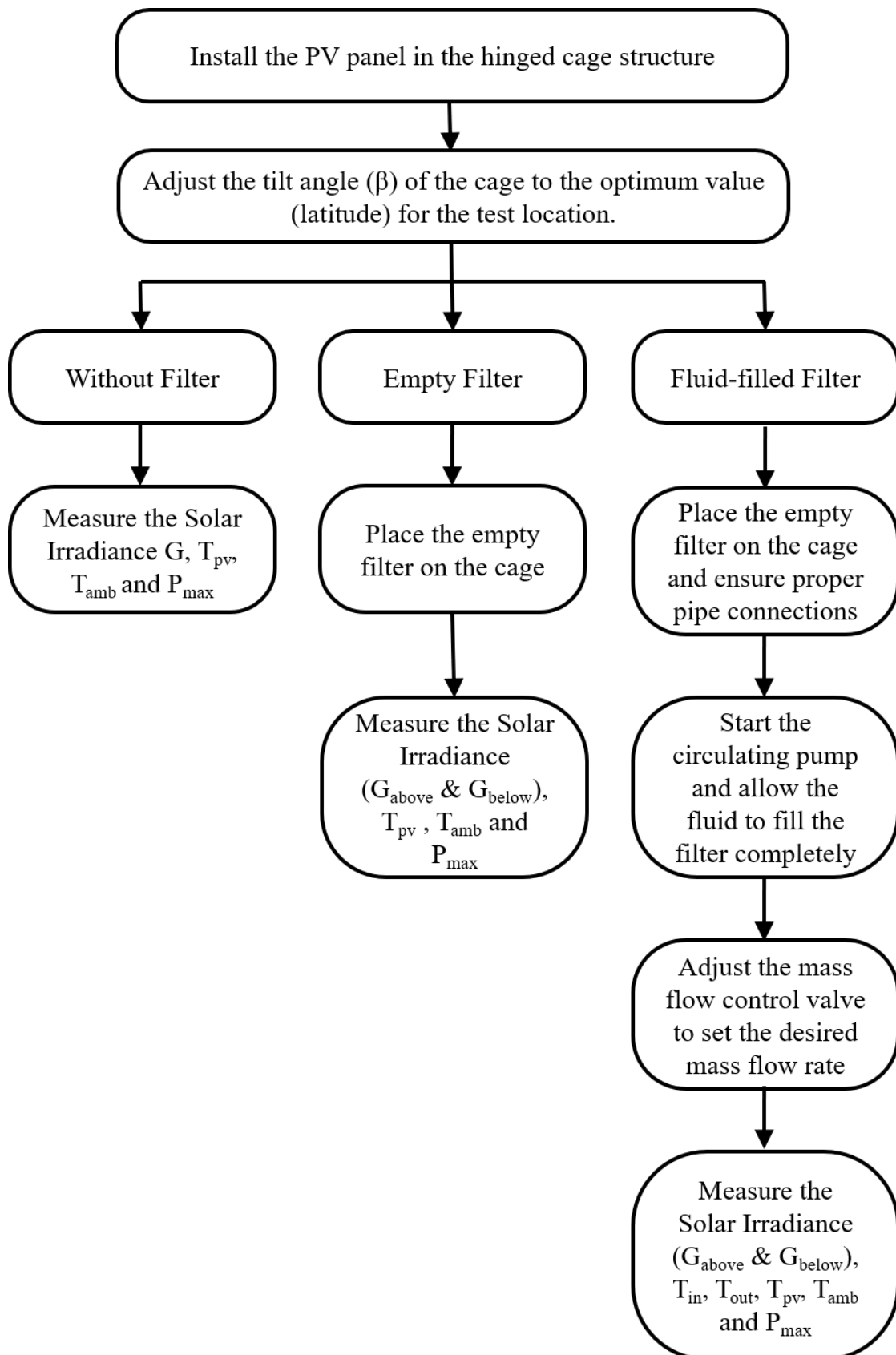


Figure 6.2 Procedural Flowchart for the Experimental Evaluation and Performance Study of the BSPVT System

6.4 Conclusion

The experimental phase of this study successfully established a robust comparative framework to evaluate the performance of the Beam-Splitting Photovoltaic-Thermal (BSPVT) system under real-world outdoor conditions in Daman, India. by systematically testing the PV module across three distinct configurations i.e. unfiltered, with an empty filter, and a circulating TiO₂ nanofluid filter. The study isolated the optical and thermal impacts of each system component. The implementation of variable volumetric flow rates (52, 58, and 70 LPH) provides a critical dataset for understanding the sensitivity of thermal gain and electrical efficiency to fluid dynamics. Furthermore, the application of mass-weighted average properties for the 0.04% w/w TiO₂ nanofluid ensures that the subsequent efficiency calculations are grounded in accurate thermophysical data. This experimental rigor transitions the research from theoretical estimation to empirical validation, laying the necessary groundwork for the detailed results and discussion presented in the following chapter, where the dual-generation benefits of the spectral beam-splitting approach are quantified.

CHAPTER 7

Observation, Results and Discussion

This chapter presents a comprehensive analysis of the experimental data gathered during the outdoor performance evaluation of the BSPVT system in Daman, India. The results are categorized into three primary experimental cases:

- Case 1:** The standalone PV module (without filter),
- Case 2:** The PV module with an empty filter casing, and
- Case 3:** The PV module with circulating nanofluid in the filter.

By correlating environmental parameters such as ambient temperature and incident solar radiation with critical performance indicators like panel temperature T_{pv} , maximum power output P_{max} , and thermal gain, this section quantifies the efficacy of the spectral beam-splitting approach. The following discussion evaluates the trade-offs between optical attenuation and thermal mitigation, ultimately identifying the optimal operating conditions required to maximize the total solar energy utilization of the hybrid collector.

7.1 Case 1: The standalone PV module (without filter)

The Case 1: standalone PV module setup (without filter) evaluates the photovoltaic (PV) module performance under varying environmental conditions such as incident solar radiation between 10:00 AM and 17:00 PM. The parameters recorded during the experiment include ambient temperature (T_{amb}), panel temperature (T_{pv}), incident solar radiation (G), maximum power output (P_{max}), and electrical efficiency was calculated, as presented in Table 7.1.

Table 7.1 The standalone PV module (without filter) recorded parameters with calculated electrical efficiency of the PV

Time	Incident Solar Radiation $G \text{ W/m}^2$	Ambient Temperature $T_{amb} \text{ (}^\circ\text{C)}$	Panel Temperature $T_{pv} \text{ (}^\circ\text{C)}$	P_{max} (W)	Electrical Efficiency %
10:00	796	32.0	61.0	7.0	10.04
11:00	861	33.9	62.2	7.7	10.17
12:00	910	34.9	63.0	7.4	9.35
13:00	950	35.2	65.2	6.9	8.25
14:00	905	35.5	64.0	6.6	8.33
15:00	865	34.5	62.4	6.0	7.88
16:00	710	33.5	57.1	4.9	7.86
17:00	660	32.4	56.1	2.9	5.09

The graphical representation of panel temperature, electrical efficiency, and maximum power output against time is shown in Figure 7.1, 7.2 & 7.3, respectively. These parameters help in understanding the effect of solar radiation and rise in temperature on the electrical performance of the PV module.

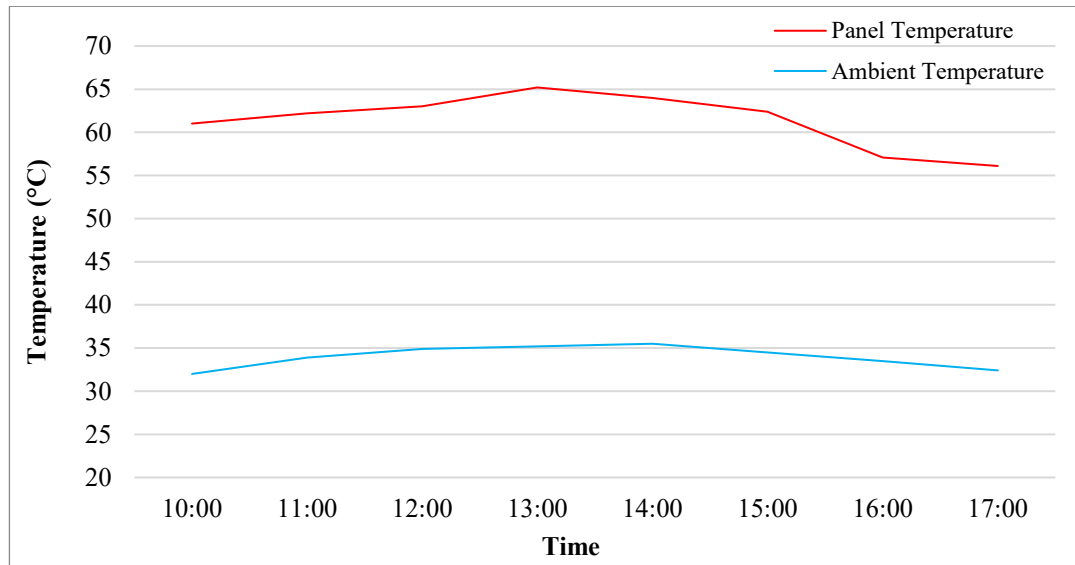


Figure 7.1 Panel temperature variation of PV and ambient temperature against time throughout the day for case 1 (without filter).

The variation of incident solar radiation during the experiment is presented in Table 7.1. The solar radiation increases steadily from 796 W/m² at 10:00 AM to a maximum value of 950 W/m² at 1:00 PM, indicating strong solar intensity during midday. After 13:00 PM, the solar radiation gradually decreases and reaches 660 W/m² at 17:00 PM. This pattern of solar radiation throughout the day significantly influences the temperature and power output of the PV module.

The variation of ambient temperature and panel temperature is presented in Table 7.1, while the trend of panel temperature and ambient temperature with time is illustrated in Figure 7.1. The ambient temperature increases gradually from 32°C at 10:00 AM to a maximum of 35.5°C at 14:00 PM, after which it decreases slightly to 32.4°C at 17:00 PM. Similarly, temperature of the panel increases from 61°C at 10:00 AM to a maximum value of 65.2°C at 13:00 PM. After reaching this peak value, the panel temperature gradually decreases and reaches 56.1°C at 17:00 PM, as shown in Figure 7.1. The higher panel temperature compared to the ambient temperature occurs because the PV module absorbs solar radiation, and a significant portion of this energy is converted into heat.

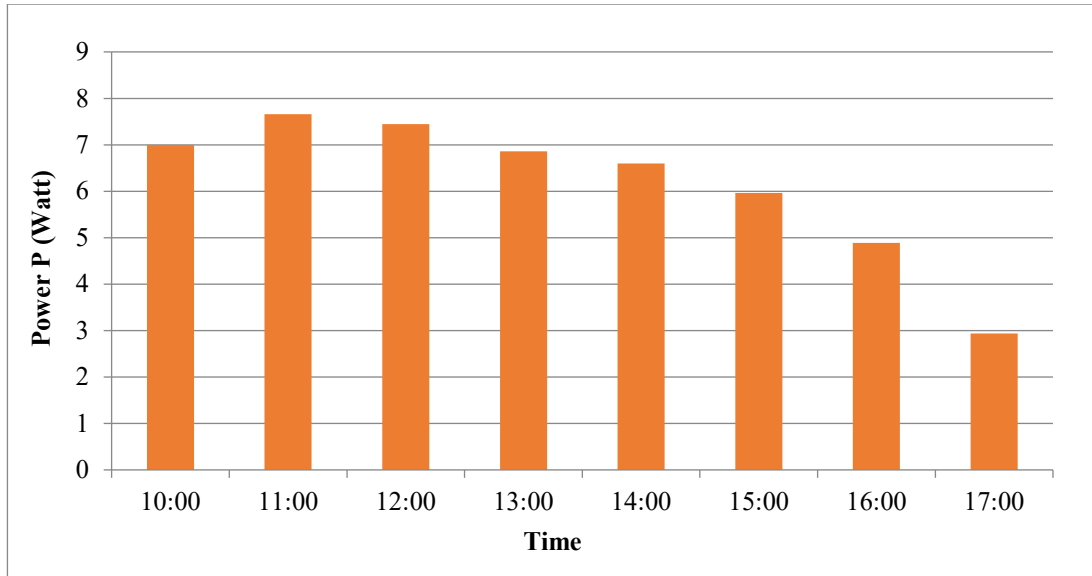


Figure 7.2 Maximum power output (P_{max}) variation with time for case 1 (without filter).

The maximum power output (P_{max}) variation with time is presented in Table 1 and graphically illustrated in Figure 7.2. The power output is 7.0 W at 10:00 AM and increases to the highest value of 7.7 W at 11:00 AM. After this time, although the solar radiation continues to increase, the power output starts decreasing gradually. At 13:00 PM, the power output reduces to 6.9 W, and it further decreases to 2.9 W at 17:00 PM, as shown in Figure 7.2. This decrease in power output despite high solar radiation is attributed to the increase in panel temperature, which negatively affects the electrical characteristics of the PV cells.

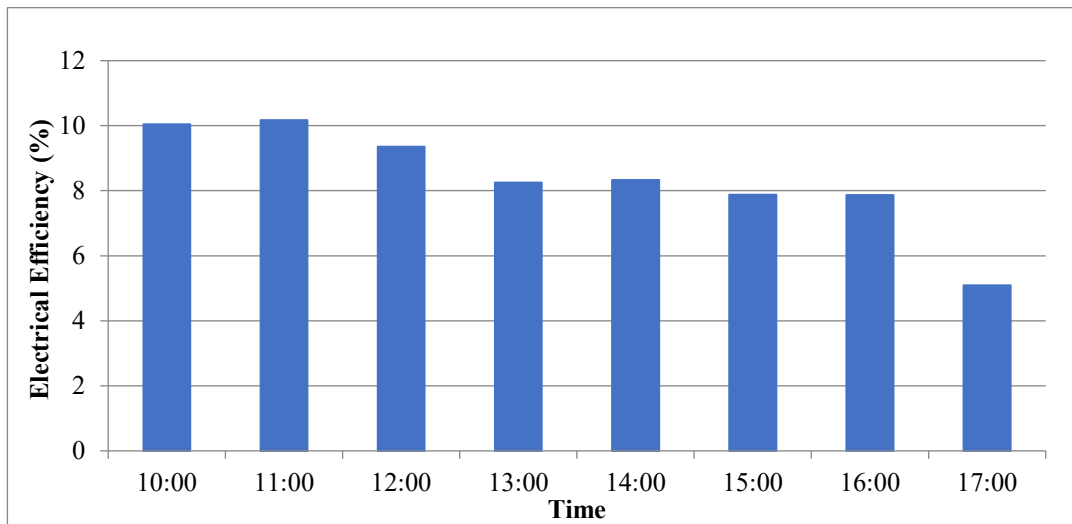


Figure 7.3 Variation of electrical efficiency with time for case 1 (without filter).

The variation of electrical efficiency throughout the day is shown in Table 7.1 and represented in Figure 7.3. The electrical efficiency is 10.04% at 10:00 AM and

reaches the highest value of 10.17% at 11:00 AM. After this point, the efficiency gradually decreases as the panel temperature increases. At 1:00 PM, when the panel temperature reaches its maximum value, the efficiency drops to 8.25%. Later in the afternoon, the efficiency continues to decrease and reaches 5.09% at 5:00 PM, as illustrated in Figure 7.3. This reduction in efficiency occurs mainly due to the rise in PV module operating temperature as well as reduction in solar intensity during the second half of the day.

From the observations presented in Table 7.1 and Figures 7.1-7.3, it is observed that solar radiation and panel temperature significantly influence the performance of the PV module. Although higher solar radiation increases the potential for power generation, excessive heating of the PV module leads to a decrease in electrical efficiency and power output. The results indicate that the PV module performs more efficiently during the early morning hours, while the panel temperature remains high.

7.2 Case 2: The PV module with an empty filter casing (Empty Filter)

The Case 2: PV module with an empty filter casing setup (empty filter) examines the the photovoltaic (PV) module performance integrated with an empty filter under varying environmental conditions between 10:00 AM and 17:00 PM. The recorded parameters include ambient temperature (T_{amb}), panel temperature (T_{pv}), incident solar radiation above the filter (G_a), solar radiation below the filter (G_b), maximum power output (P_{max}), and electrical efficiency, as presented in Table 7.2.

Table 7.2 The PV module with an empty filter casing recorded parameters with calculated electrical efficiency of the PV

Time	Ambient Temperature T_{amb} (°C)	Panel Temperature T_{pv} (°C)	Incident Solar Radiation Above Filter G_a W/m ²	Incident Solar Radiation Below Filter G_b W/m ²	P_{max} (W)	Electric Efficiency %
10:00	32.3	59.0	824	697	6.5	10.66
11:00	34.5	59.9	885	756	7.0	10.58
12:00	36.5	62.8	945	819	6.7	9.35
13:00	36.6	63.7	984	863	6.2	8.21
14:00	37.3	63.8	937	812	6.0	8.44
15:00	36.5	60.9	910	788	5.5	7.98
16:00	35.5	54.9	823	691	4.5	7.44
17:00	32.5	53.3	690	560	2.6	5.31

The variation of panel temperature, electrical efficiency, and maximum power output with time is illustrated in Figure 7.4, 7.5, and 7.6, respectively. These parameters help in evaluating the influence of the filter on solar radiation transmission and PV module performance.

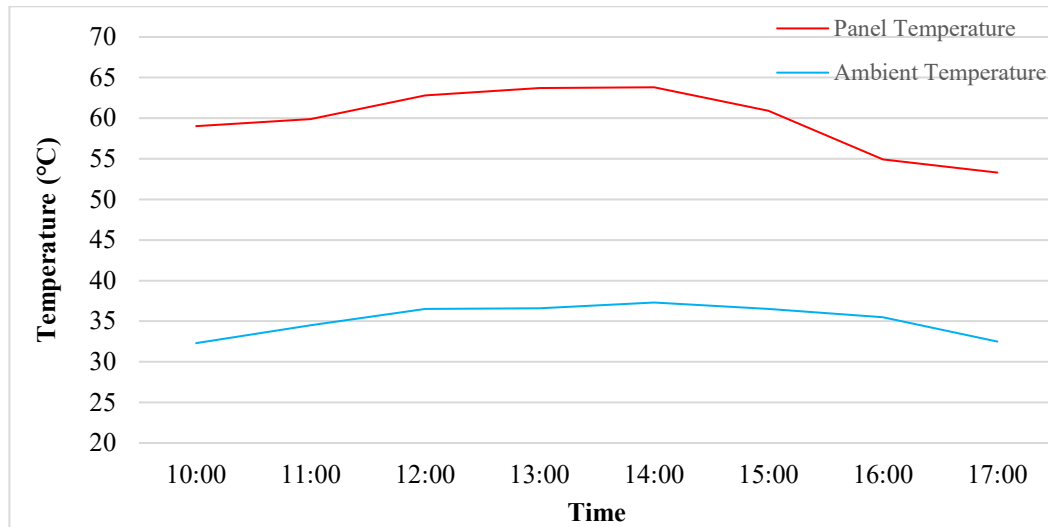


Figure 7.4 Temperature variation of PV panel and ambient temperature against time throughout the day for case 2 (empty filter).

The variation of ambient temperature and panel temperature throughout the experimental period is presented in Table 7.2, while the graphical trend of panel temperature is shown in Figure 7.4. The ambient temperature increases gradually from 32.3°C at 10:00 AM to a maximum of 37.3°C at 14:00 PM, after which it decreases slightly and reaches 32.5°C at 17:00 PM. Similarly, the panel temperature increases from 59.0°C at 10:00 AM to a peak value of 63.8°C at 14:00 PM. After reaching this maximum value, the panel temperature decreases gradually, reaching 53.3°C at 17:00 PM, as illustrated in Figure 7.4.

The variation of incident solar radiation above the filter (G_a) and below the filter (G_b), is shown in Table 7.2. The solar radiation above the filter increases from 824 W/m² at 10:00 AM to a maximum value of 984 W/m² at 1:00 PM, indicating the highest solar intensity during midday. After this time, the radiation gradually decreases to 690 W/m² at 5:00 PM. The solar radiation measured below the filter is consistently lower, varying from 697 W/m² at 10:00 AM to a maximum of 863 W/m² at 1:00 PM, and finally decreasing to 560 W/m² at 5:00 PM. This difference indicates that the filter reduces a portion of the incoming solar radiation.

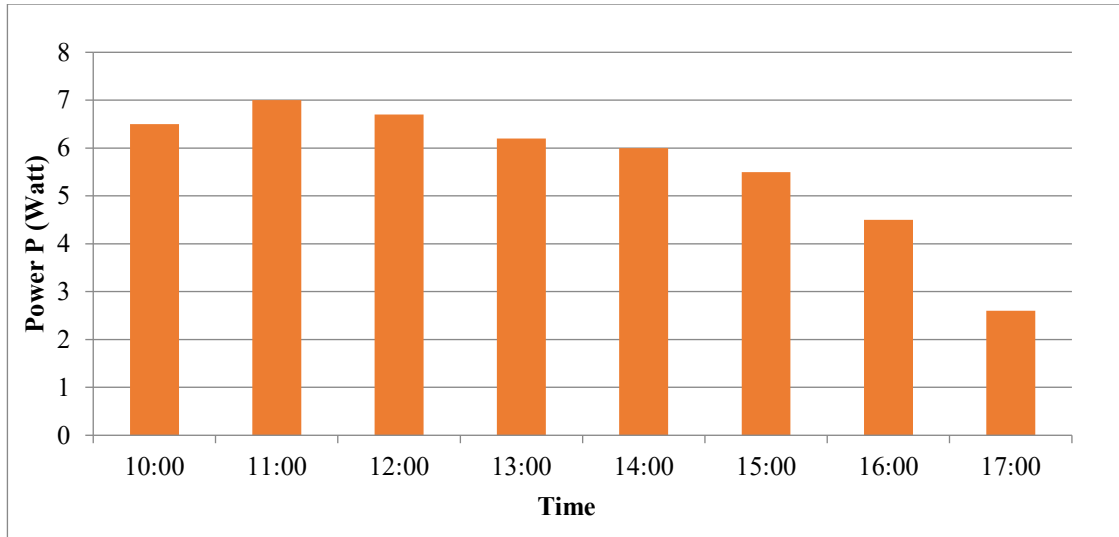


Figure 7.5 Variation of maximum power output (P_{max}) with time for case 2 (empty filter)

The variation of maximum power output (P_{max}) with time is presented in Table 2 and graphically illustrated in Figure 7.5. The power output is 6.5 W at 10:00 AM and increases to a maximum value of 7.0 W at 11:00 AM. After this time, the power output gradually decreases, reaching 6.2 W at 1:00 PM and 6.0 W at 2:00 PM. As the day progresses, the power output continues to decline, reaching 2.6 W at 5:00 PM, as shown in Figure 7.5. This reduction in power output during the afternoon hours occurs due to the combined effect of decreasing solar radiation and changes in panel temperature.

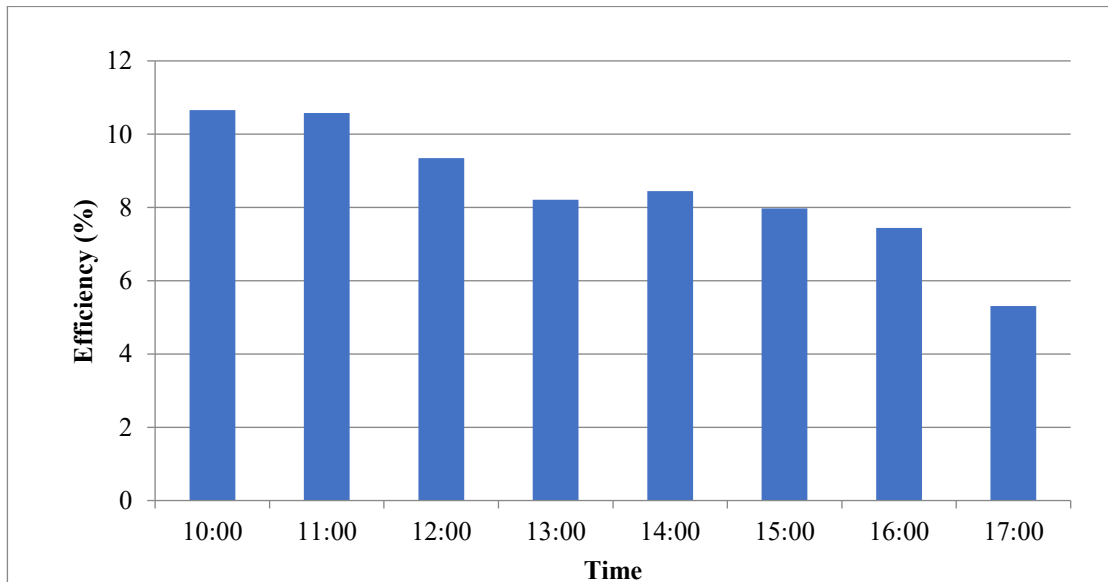


Figure 7.6 Variation of electrical efficiency with time for case 2 (empty filter).

The variation of electrical efficiency during the experiment is shown in Table 7.2 and graphically represented in Figure 7.6. The electrical efficiency is 10.66% at

10:00 AM and remains relatively high at 10.58% at 11:00 AM. After this period, the efficiency gradually decreases with increasing panel temperature and varying solar radiation. At 1:00 PM, the efficiency drops to 8.21%, and it slightly increases to 8.44% at 2:00 PM due to a small variation in temperature and radiation conditions. Later in the afternoon, the efficiency continues to decrease and reaches 5.31% at 5:00 PM, as illustrated in Figure 7.6.

The PV module integrated with the empty filter system operates efficiently during the late morning hours, when solar radiation is sufficiently high and the panel temperature remains moderate. During midday, although solar radiation reaches its maximum value, the increase in panel temperature reduces electrical efficiency and power output.

In terms of electrical efficiency, both cases show similar trends, but Case 2 shows slightly higher efficiency during the early hours due to the reduced panel temperature. The maximum efficiency in Case 1 is 10.17%, whereas in Case 2 it reaches 10.66% at 10:00 AM. However, as the day progresses and solar radiation decreases, the efficiency in both cases gradually declines.

Since the first two cases do not include any thermal component, they primarily assess the PV panel electrical performance under varying temperature conditions. In these cases, the PV module operates without any fluid-based cooling or absorption mechanism. Therefore, the results obtained from these cases serve as a reference or baseline performance of the PV module. These reference results make it possible to quantify the improvement or change in performance when fluid is circulated in the filter.

7.3 Case 3: The PV module with circulating nanofluid in the filter

In Case 3, circulating nanofluid is introduced to the PV system. In this configuration, the nanofluid flows through the filter layer and absorbs a portion of the incident solar radiation before it reaches the PV module. As a result, part of the solar energy is converted into thermal energy within the fluid, while the remaining radiation continues to generate electrical power in the PV panel. Therefore, in this case, both electrical and thermal performances of the system are evaluated simultaneously. To investigate the influence of fluid flow on system performance, three different volumetric flow rates (52 LPH, 58 LPH & 70 LPH) are maintained using a flow control valve.

The experimental performance of the system is observed over three consecutive days to ensure consistency and reliability of the results. Conducting experiments over multiple days helps minimize the effect of random environmental fluctuations and provides a more accurate evaluation of the system performance under real operating conditions.

The data collected for case 3 The PV module with circulating nanofluid in the filter is presented in the following tables 7.3, 7.4 & 7.5 for 52 LPH, 58 LPH & 70 LPH respectively.

Table 7.3 The readings recorded for 52 LPH flow rate of the nanofluid.

Time	Solar Irradiatio n reading G_a (W/m ²)	Solar Irradiatio n reading G_b (W/m ²)	Ambient Temp T_{amb} °C	Fluid Inlet temp T_{in} °C	Fluid outlet temp T_{out} °C	PV Module Temp T_{pv} °C	Electrical Gain Q_e (P _{max}) W
10:00	760	545	30.0	22.0	23.6	45.2	6.0
11:00	820	570	30.8	22.5	24.1	46.8	6.6
12:00	910	642	32.6	23.2	25.2	49.0	5.9
13:00	940	671	32.8	24.7	27.0	50.2	5.8
14:00	905	658	33.0	25.9	27.9	49.6	5.5
15:00	820	590	33.5	26.9	28.3	47.8	6.1
16:00	700	510	33.0	26.9	28.1	43.6	5.5
17:00	650	480	31.0	26.0	26.9	40.0	4.2

Table 7.4 The readings recorded for 58 LPH flow rate of the nanofluid.

Time	Solar Irradiatio n reading G_a (W/m ²)	Solar Irradiatio n reading G_b (W/m ²)	Ambient Temp T_{amb} °C	Fluid Inlet temp T_{in} °C	Fluid outlet temp T_{out} °C	PV Module Temp T_{pv} °C	Electrical Gain Q_e (P _{max}) W
10:00	781	543	31.0	22.3	23.9	46.5	7.5
11:00	852	597	32.9	22.7	24.3	48.0	7.0
12:00	928	637	34.0	23.5	25.5	50.4	6.2
13:00	943	651	34.2	24.4	26.7	51.5	6.1
14:00	901	626	34.5	26.2	28.2	50.9	5.8
15:00	861	590	33.5	27.1	28.5	49.1	6.7
16:00	709	480	32.5	27.0	28.2	45.0	5.8
17:00	682	465	31.4	25.8	26.7	41.6	5.2

Table 7.5 The readings recorded for 70 LPH flow rate of the nanofluid.

Time	Solar Irradiation reading G_a (W/m ²)	Solar Irradiation reading G_b (W/m ²)	Ambient Temp T_{amb} °C	Fluid Inlet temp T_{in} °C	Fluid outlet temp T_{out} °C	PV Module Temp T_{pv} °C	Electrical Gain Q_e (P_{max}) W
10:00	780	540	30.7	23.0	24.5	48.0	6.8
11:00	852	593	32.9	24.0	25.5	49.8	6.6
12:00	950	661	34.9	25.2	27.2	52.2	5.6
13:00	995	701	35.0	27.0	29.4	53.2	5.5
14:00	990	682	35.7	29.1	31.2	52.6	5.5
15:00	927	642	35.0	29.6	31.0	50.8	6.1
16:00	847	591	33.9	29.0	30.3	46.6	5.3
17:00	740	433	30.9	28.0	29.0	43.0	4.2

The empirical data acquired through these experiments facilitates a comparative performance assessment between the baseline PV configurations (Cases 1 and 2) and the integrated BSPVT system employing a nanofluid absorption filter (Case 3). Utilizing the equations in Chapter 6, the thermal gain (Q_t), thermal efficiency (η_{th}), electrical efficiency (η_{ele}), and cumulative overall efficiency ($\eta_{overall}$) for Case 3 have been calculated. These results, which highlight the dual-generation capability of the hybrid system, are systematically presented in the following table 7.6.

Table 7.6 Comparative Performance Metrics for the BSPVT System (Case 3) at Varying Flow Rates.

52 LPH					
Time	Thermal gain Q_t	Thermal Efficiency η_{th}	Electrical Gain Q_e (P_{max}) W	Electrical Efficiency η_{ele}	Overall system Efficiency $\eta_{overall}$
10:00	97.91	51.53	6.0	9.02	60.56
11:00	97.91	47.76	6.6	9.20	56.96
12:00	122.39	53.80	5.9	7.41	61.21
13:00	140.75	59.89	5.8	7.05	66.95
14:00	122.39	54.10	5.5	6.95	61.04
15:00	85.67	41.79	6.1	8.50	50.29
16:00	73.43	41.96	5.5	8.98	50.94
17:00	55.08	33.89	4.2	7.38	41.28

58 LPH					
Time	Thermal gain Q_t	Thermal Efficiency η_{th}	Electrical Gain Q_e (P_{max}) W	Electrical Efficiency η_{ele}	Overall system Efficiency $\eta_{overall}$
10:00	107.86	55.24	7.5	11.00	66.24
11:00	107.86	50.64	7.0	9.39	60.03
12:00	134.82	58.11	6.2	7.64	65.75
13:00	155.04	65.77	6.1	7.39	73.16
14:00	134.82	59.85	5.8	7.31	67.16
15:00	94.37	43.84	6.7	8.89	52.74
16:00	80.89	45.64	5.8	9.35	54.99
17:00	60.67	35.58	5.2	8.71	44.30

70 LPH					
Time	Thermal gain Q_t	Thermal Efficiency η_{th}	Electrical Gain Q_e (P_{max}) W	Electrical Efficiency η_{ele}	Overall system Efficiency $\eta_{overall}$
10:00	123.20	63.18	6.8	9.96	73.14
11:00	123.20	57.84	6.6	8.85	66.69
12:00	164.26	69.16	5.6	6.74	75.90
13:00	197.11	79.24	5.5	6.32	85.56
14:00	172.47	69.69	5.5	6.35	76.04
15:00	114.98	49.61	6.1	7.52	57.14
16:00	106.77	50.42	5.3	7.15	57.57
17:00	82.13	44.39	4.2	6.49	50.88

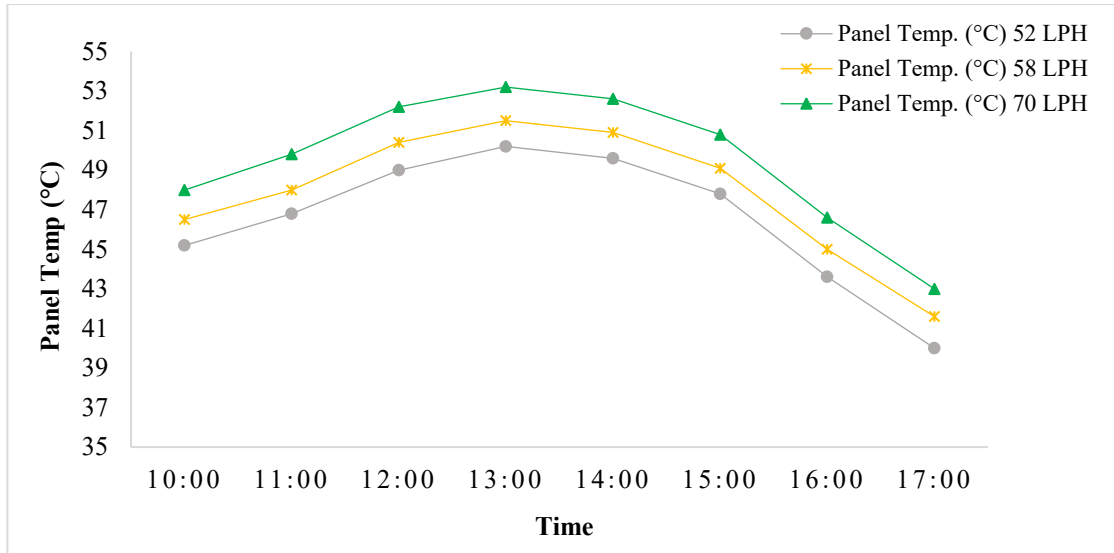


Figure 7.7 Comparative analysis of PV panel temperature (T_{pv}) vs time across volumetric flow rates of case 3.

The variation of panel temperature with time for different flow rates is presented in Figure 7.7. The panel temperature shows a gradual increase during the morning hours and reaches its peak around early afternoon before decreasing in the late afternoon. For the 52 LPH flow rate, the panel temperature increases from 45.2°C at 10:00 AM to a maximum of 50.2°C around 13:00 PM, and then decreases to 40.0°C at 17:00 PM. Similarly, for 58 LPH, the panel temperature increases from 46.5°C to about 51.5°C, while for 70 LPH, it varies between 48.0°C and 53.2°C. It is observed that higher flow rates slightly increase the measured panel temperature due to less absorption of solar radiation by the fluid due to flow, although the circulating nanofluid simultaneously removes heat from the system.

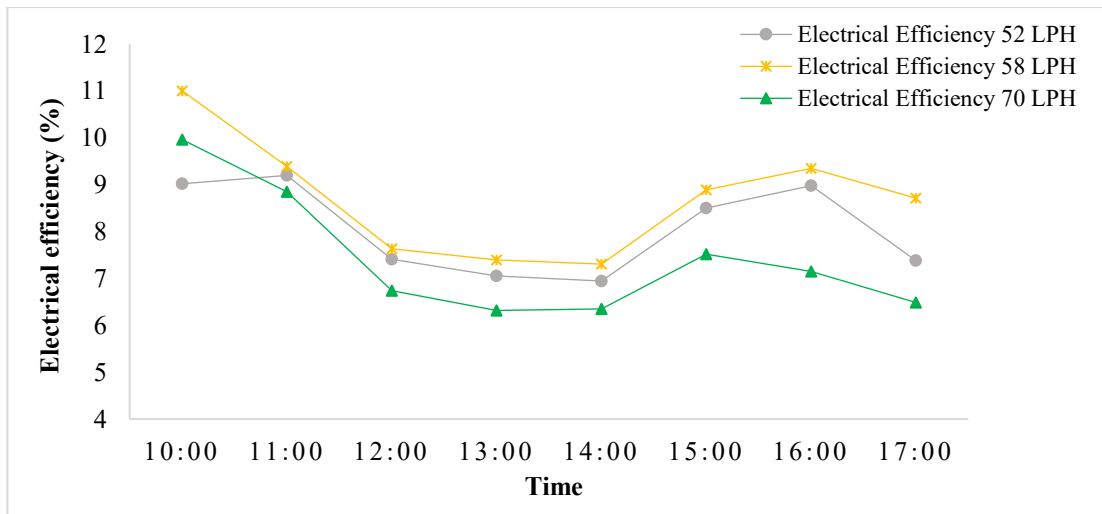


Figure 7.8 Comparative analysis of electrical efficiency (η_{ele}) vs time across all flow rates of case 3

The electrical efficiency variation with time for the three flow rates is shown in Figure 7.8. For 52 LPH, the electrical efficiency ranges from about 9.02% in the morning to around 7.38% in the late afternoon, showing a decreasing trend as solar radiation and panel temperature vary throughout the day. For 58 LPH, the electrical efficiency shows comparatively higher values, reaching a maximum of 11.0% at 10:00 AM and gradually decreasing afterward. For the 70 LPH case, the electrical efficiency varies between 9.96% and 6.49%, which is slightly lower than the 58 LPH case. This indicates that moderate flow rates provide better electrical performance, as excessive flow may reduce the amount of radiation reaching the PV panel due to increased absorption in the fluid.

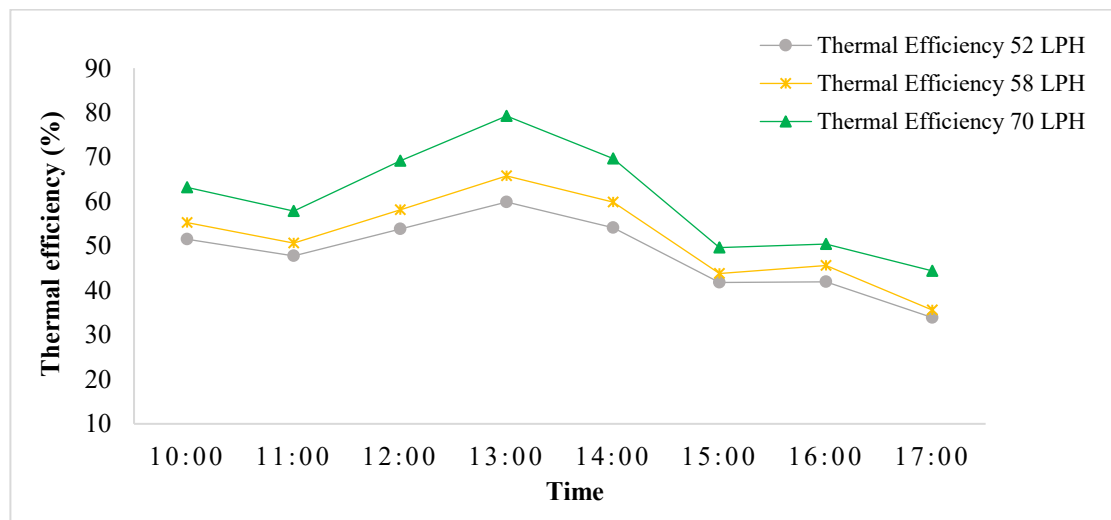


Figure 7.9 Variation of thermal efficiency (η_{th}) vs time across all flow rates of case 3.

The variation of thermal efficiency with time for the three volumetric flow rates is illustrated in Figure 7.9. The thermal efficiency increases significantly with increasing flow rate. For 52 LPH, the thermal efficiency ranges between 33.89% and 59.89%. For 58 LPH, it increases further, reaching values up to 65.77%. The highest thermal efficiency is observed for 70 LPH, where it reaches a maximum of 79.24% around midday. This increase in thermal efficiency occurs because higher flow rates enhance the heat absorption and heat transfer capability of the circulating nanofluid, allowing more solar energy to be captured as thermal energy.

For the 52 LPH flow rate, the maximum thermal gain is about 140.75 W, whereas for 58 LPH it increases to approximately 155.04 W, and for 70 LPH it reaches a maximum of 197.11 W. This clearly indicates that increasing the flow rate

significantly improves the heat extraction from the system, which enhances the thermal performance of the PV–thermal configuration.

The overall efficiency, which is the combination of electrical and thermal efficiency, also shows a clear improvement with increasing flow rate. For 52 LPH, the overall efficiency ranges approximately between 41% and 66%. For 58 LPH, it increases to about 44%-73%. The highest overall efficiency is observed for the 70 LPH case, reaching approximately 85.56% at peak solar radiation conditions. This demonstrates that higher volumetric flow rates improve the total energy utilization of the solar system by increasing the thermal energy recovery while maintaining reasonable electrical output.

From the observations presented in the tables 7.6 and Figures 7.7-7.9, it is clear that the volumetric flow rate of the circulating nanofluid significantly influences the performance of the PVT system. A higher flow rate enhances the thermal efficiency and overall efficiency of the system by increasing the heat absorption capacity of the nanofluid. However, the electrical efficiency is slightly higher at moderate flow rates, indicating that an optimal balance between thermal absorption and radiation transmission to the PV panel is required.

7.4 Combined Performance Comparison of All Experimental Cases

7.4.1 Panel Temperature Variation

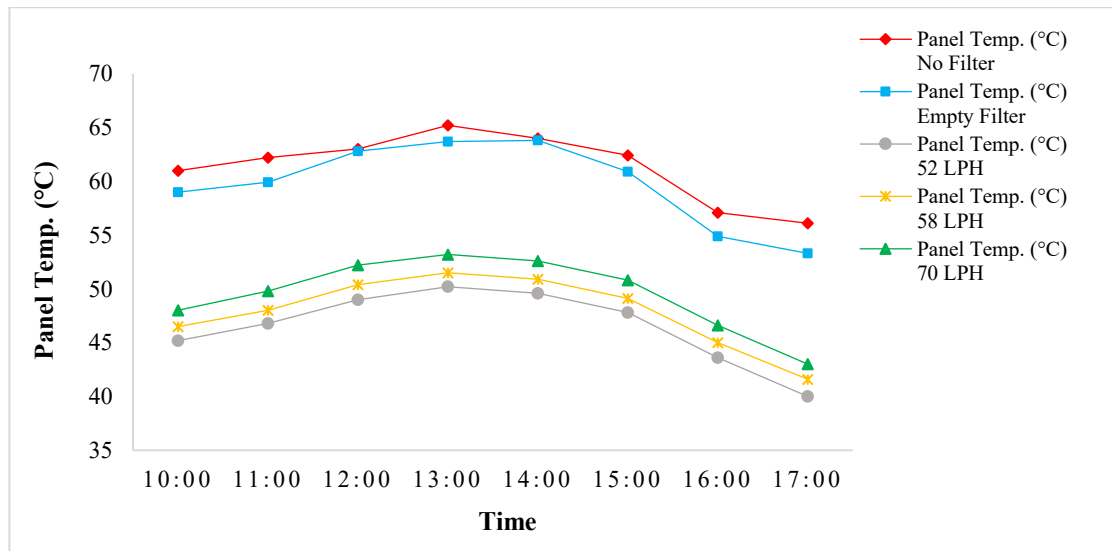


Figure 7.10 Variation of PV panel temperature (T_{pv}) across all cases.

Figure 7.10 presents the hourly variation in PV panel temperature for the five experimental settings: without-filter, empty filter, and TiO_2 nanofluid filter at flow rates

of 52, 58, and 70 LPH. The no-filter condition exhibits the highest temperatures throughout the day, with a peak of approximately 65°C at 13:00. This behaviour is expected since the PV panel receives the entire solar spectrum, including the thermally dominant radiation, resulting in significant heat accumulation on the PV surface.

The empty filter condition shows only a slight reduction in temperature, approximately 1-2°C lower than the no-filter case. This minor reduction occurs due to partial shading and the additional optical interface created by the PMMA enclosure, although no active thermal absorption or cooling mechanism is present.

In contrast, the TiO₂ nanofluid filter cases significantly reduce the PV panel temperature across all flow rates. The cooling effect is particularly evident during peak solar hours, where the panel temperature remains within 50-54°C, representing a temperature reduction of approximately 10-12°C compared to the no-filter condition. These results clearly demonstrate the thermal management capability of TiO₂ nanofluid, which absorbs NIR radiation and continuously transports the absorbed heat away from the filter through fluid circulation.

7.4.2 Electrical Efficiency Variation

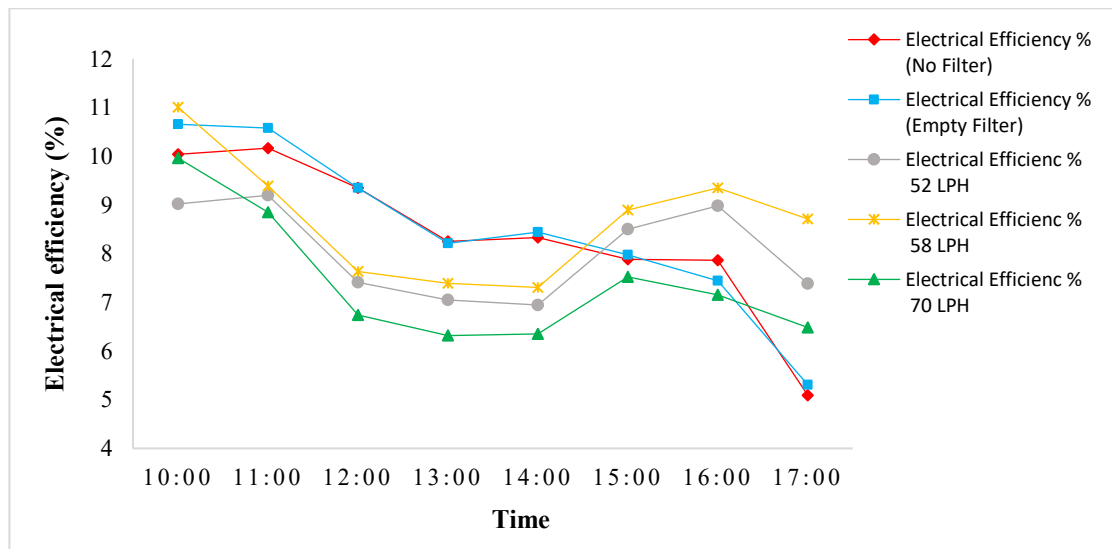


Figure 7.11 Variation of electrical efficiency (η_{ele}) across all cases.

The variation of electrical efficiency with time for all experimental conditions is shown in Figure 7.11. The electrical efficiency trend follows the inverse relationship with panel temperature. In the no-filter and empty-filter cases, where panel

temperatures remain highest, the electrical efficiency gradually decreases from approximately 10-11% in the morning to below 6% by late afternoon. This reduction occurs due to the temperature sensitivity of crystalline silicon photovoltaic modules, where an increase in cell temperature reduces the open-circuit voltage and overall conversion efficiency.

The nanofluid-filter cases initially show slightly lower efficiency during early morning hours due to the attenuation of a small portion of the useful spectral band by the TiO₂ suspension. However, during peak solar irradiance hours (12:00-15:00), the cooling effect provided by the nanofluid becomes dominant, resulting in improved electrical performance compared with the baseline cases. Notably, at 58 LPH and 70 LPH, the system maintains electrical efficiencies of approximately 8-9% during peak solar conditions, while the no-filter and empty-filter cases decline to around 7-8%.

The improved electrical performance during nanofluid operation confirms that spectral beam splitting effectively reduces temperature-induced electrical losses. The results validate the dual functionality of the BSPVT system, where useful wavelengths are transmitted for electricity generation while excess thermal energy is absorbed by the nanofluid.

7.4.3 Thermal Efficiency Performance

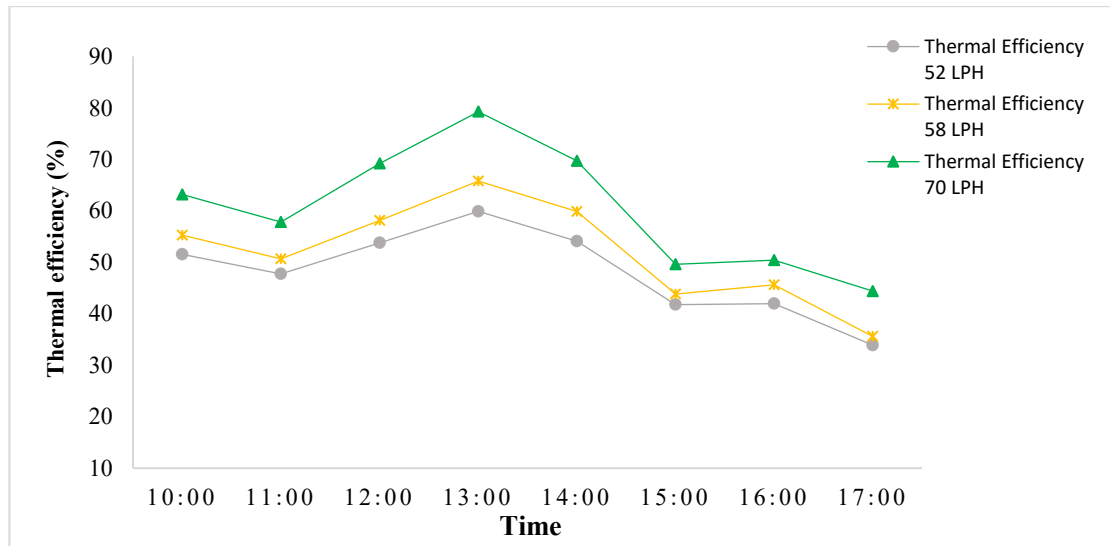


Figure 7.12 Variation of thermal efficiency (η_{th}) across all cases.

Figure 7.12 illustrates the variation of thermal efficiency with time for the TiO₂ nanofluid-based BSPVT system at flow rates of 52 LPH, 58 LPH, and 70 LPH. Thermal

efficiency is reported only for the nanofluid cases because the no-filter and empty-filter configurations do not include a thermal energy absorption mechanism.

At 10:00 AM, the thermal efficiency begins at approximately 52% for 52 LPH, 56% for 58 LPH, and 63% for 70 LPH, indicating that higher flow rates enhance heat extraction even during early morning hours. As solar irradiance increases throughout the day, thermal efficiency increases steadily, reaching peak values at 13:00 of approximately 60% (52 LPH), 66% (58 LPH), and nearly 80% (70 LPH).

This clear performance hierarchy indicates that higher volumetric flow rates improve convective heat transfer in the nanofluid, preventing thermal stagnation and enabling continuous absorption of non-responsive solar radiation. After 15:00, thermal efficiency gradually decreases for all cases due to reduced solar irradiance, reaching approximately 42-45% by 17:00. The observed thermal behaviours strongly correlates with the earlier panel temperature trends shown in Figure 7.10.

Furthermore, the enhanced thermal management also explains the electrical efficiency trends observed earlier. For example, at 13:00, while the no-filter case shows an electrical efficiency of approximately 8.2%, the nanofluid cases maintain efficiencies of approximately 7.2% (52 LPH), 7.4% (58 LPH), and 6.3% (70 LPH). Although electrical efficiency slightly decreases at higher flow rates due to optical attenuation, this reduction is compensated by the significant increase in thermal energy recovery, where thermal efficiency reaches up to 80% at 70 LPH.

7.4.4 Overall Efficiency of the BSPVT System

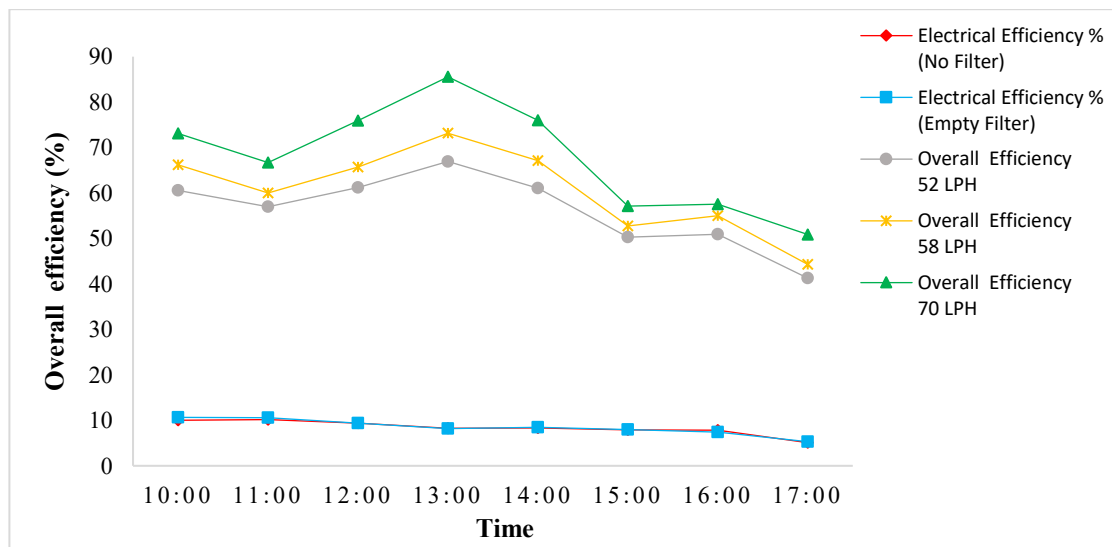


Figure 7.13 Variation of Overall Efficiency ($\eta_{overall}$) across all cases.

The overall efficiency, which represents the combined electrical and thermal outputs of the system, is presented in Figure 7.13. The no-filter and empty-filter cases exhibit very low overall efficiencies, since they generate only electrical energy and lose a significant portion of solar energy as heat. Their efficiencies remain within 10–11% during the morning hours and decrease to around 5–7% by late afternoon.

In contrast, the nanofluid-based BSPVT system demonstrates significantly higher overall efficiency because it simultaneously produces electrical energy and useful thermal energy. At 10:00, the overall efficiency begins at approximately 62% (52 LPH), 67% (58 LPH), and 72% (70 LPH). As solar irradiance increases, overall efficiency also rises and reaches peak values at 13:00 of approximately 68% (52 LPH), 73% (58 LPH), and nearly 85% (70 LPH).

These high efficiencies correspond closely with the thermal efficiency trends, where the 70 LPH flow rate achieves the highest thermal performance due to improved heat absorption and effective convective heat removal. The reduction in PV panel temperature also contributes to improved electrical performance compared to the baseline cases.

After 15:00, the overall efficiency decreases due to reduced solar irradiance, reaching approximately 48–52% for the 52 LPH and 58 LPH cases and about 55% for the 70 LPH case by 17:00. However, these efficiencies remain significantly higher than those of the no-filter and empty-filter cases, which fall below 6% during the same period.

7.5 Overall Observation and Optimum Flow Rate

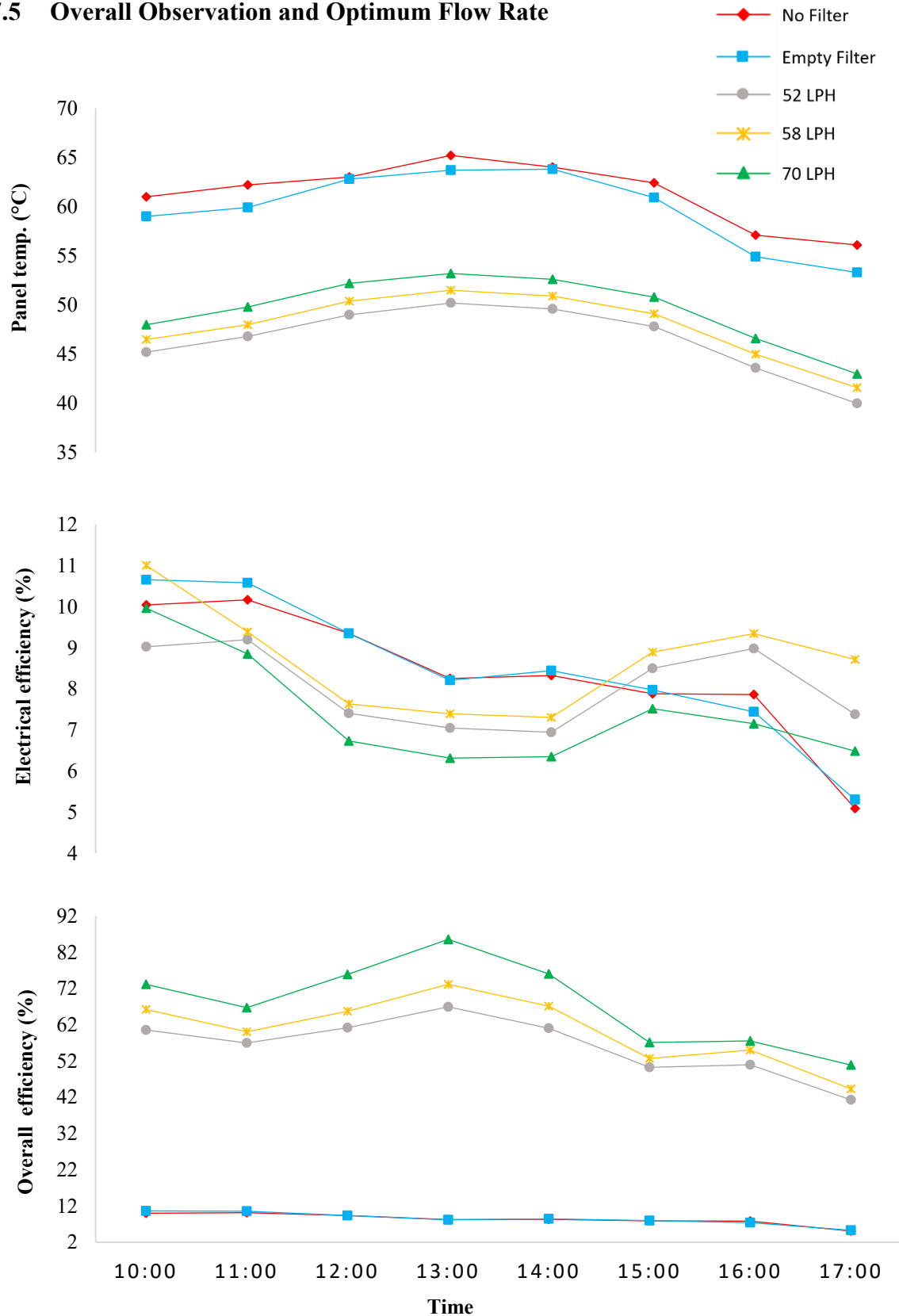


Figure 7.14 A chart showing correlation between panel temperature and its overall and electrical efficiency change throughout the day, clearly highlighting the direct impact of high panel temperatures on reducing efficiency.

The figure 7.14 illustrates a clear inverse relationship between the PV panel temperature (T_{pv}) and the system's efficiency metrics. As solar intensity peaks around 1:00 PM, the panel temperature reaches its maximum, which directly triggers a decline in electrical efficiency. This observation confirms that thermal heating is a primary driver of performance degradation in photovoltaic cells. However, while electrical output dips during these high-temperature periods, the overall efficiency of the system remains significantly higher and more stable. This suggests that the TiO₂ nanofluid filter effectively captures the excess thermal energy that would otherwise be lost, compensating for the electrical drop and providing a more consistent total energy yield. As the afternoon progresses and temperatures begin to subside, a slight recovery in electrical efficiency is noted, further validating the importance of the nanofluid's cooling effect in maintaining module performance under peak irradiance.

The combined analysis of panel temperature, electrical efficiency, thermal efficiency, and overall efficiency clearly indicates that volumetric flow rate plays a critical role in determining the performance of the BSPVT system.

At the highest flow rate (70 LPH), the system achieves the maximum thermal efficiency (~80%) and the lowest PV panel temperatures, but the electrical efficiency slightly decreases due to increased optical attenuation and rapid heat removal.

At the lowest flow rate (52 LPH), optical transmission to the PV panel remains relatively higher, but cooling performance is weaker, leading to higher panel temperatures and lower thermal efficiency.

The 58 LPH flow rate provides the most balanced system performance, maintaining moderate panel temperatures, stable electrical efficiencies (~7.4% at peak hours), and substantial thermal efficiency (~66%). As a result, the overall system efficiency reaches approximately 73%, indicating an optimal balance between electrical and thermal energy outputs. It can be observed in figure 7.14 that the electrical efficiency at 58 LPH flow rate is slightly higher among the other flow rates.

Therefore, the results confirm that 58 LPH represents the optimal flow rate for the TiO₂ nanofluid-based BSPVT system, achieving an effective compromise between spectral transmission, thermal absorption, and heat removal, thereby maximizing the total useful solar energy harvested under real outdoor operating conditions.

Furthermore, more precise volumetric flow rate investigations can be conducted to identify a more optimal and balanced operating condition for the BSPVT system.

7.6 Conclusion

The experimental evaluation of the BSPVT system provides conclusive evidence of the advantages of spectral management using TiO_2 nanofluids. The standalone PV module in Case 1 experienced significant thermal degradation, with temperatures reaching a peak of 65.2°C , which caused a sharp decline in electrical efficiency to 8.25% during peak solar hours. In contrast, the integration of the $\text{TiO}_2/\text{H}_2\text{O}$ nanofluid filter in Case 3 successfully lowered the panel temperature by approximately 17°C . While the filter inherently introduces some optical attenuation, the substantial reduction in thermal stress effectively stabilizes the electrical output, preventing the rapid efficiency drops observed in the unfiltered configurations.

The results from Case 2, which utilized an empty filter frame, further confirm the necessity of active cooling within the system architecture. This underscores the dual role of the nanofluid as a spectral separator and a dynamic heat transfer medium both, that is essential for maintaining module longevity and performance.

A comparative analysis of different volumetric flow rates 52, 58, and 70 LPH identified 58 LPH as the optimal operating condition for this specific setup. While the highest flow rate of 70 LPH achieved a maximum thermal efficiency of approximately 80%, the 58 LPH rate provided a superior overall balance. It maintained a stable electrical efficiency of approximately 7.4% while still delivering a substantial thermal efficiency of 66%, resulting in a total system efficiency of 73%. This balance ensures that neither the electrical nor the thermal output is sacrificed excessively for the benefit of the other.

Ultimately, this study demonstrates that the BSPVT system significantly outperforms standalone PV modules in terms of total energy harvesting per unit area. By capturing high-energy thermal photons that would otherwise contribute to waste heat, the system transforms excess thermal energy into a secondary, useful energy stream. These findings validate the TiO_2 -based spectral beam-splitting approach as a highly viable method for enhancing the utility of solar energy in hybrid applications, offering a more consistent and comprehensive energy solution than traditional photovoltaic systems.

CHAPTER 8

Conclusion And Future Scope

This research addressed the critical challenge of thermal degradation in silicon-based photovoltaic modules by designing and experimentally validating a BSPVT system. By utilizing a $\text{TiO}_2/\text{H}_2\text{O}$ 0.04% w/w nanofluid as a spectral filter, the system successfully decoupled the solar spectrum, directing the effective wavelengths to the PV cell for electricity while absorbing the infrared and ultraviolet portions to generate thermal energy. The outdoor experimental evaluation conducted in Daman, India, provided a rigorous comparative analysis of the system's performance under high-irradiance conditions.

8.1 Key Findings

8.1.1 Thermal Mitigation Performance:

The experimental data confirmed that the standalone PV module (Case 1) reached a highest temperature of 65.2°C at 13:00 PM, leading to a significant drop in electrical efficiency to 8.25%. In contrast, the BSPVT system (Case 3) maintained a peak temperature of approximately 48.2°C under similar conditions. This reduction of 17°C in operating temperature effectively mitigated the power loss associated with the negative temperature coefficient of the silicon cells.

8.1.2 Electrical vs. Thermal Trade-off:

While the standalone module achieved a morning peak efficiency of 10.17%, the integrated BSPVT system at the optimal flow rate delivered a stable electrical efficiency of approximately 7.4%. Although there is a relative electrical drop due to the optical attenuation of the TiO_2 particles, this was compensated for by a massive thermal gain.

The study identified 58 LPH as the optimal volumetric flow rate. While the 70 LPH flow rate achieved the highest thermal efficiency of $\sim 80\%$, it resulted in lower electrical stability. The 58 LPH rate yielded a balanced 66% thermal efficiency and 7.4% electrical efficiency, culminating in a total Overall System Efficiency of 73%. This represents a nearly seven-fold increase in energy harvesting capability per unit area compared to the standalone electrical efficiency.

8.2 Research Contributions to Solar Engineering

The primary contribution of this thesis is the successful empirical validation of metal-oxide nanofluids for spectral beam splitting in a tropical outdoor environment. This research provides a robust framework for overcoming the "thermo-optical conflict" by demonstrating that TiO₂-based filters are a cost-effective and durable alternative to expensive noble metal nanoparticles. Specifically, the study contributes a detailed mapping of the correlation between volumetric flow rates and system efficiencies, proving that a balanced flow (58 LPH) can significantly stabilize electrical output while maximizing thermal recovery.

Furthermore, this work quantifies the specific benefits of the BSPVT configuration, demonstrating that the integration of a nanofluid filter can reduce PV panel operating temperatures by approximately 17°C compared to standalone modules. This temperature mitigation resulted in a stabilized electrical efficiency and a substantial thermal gain, culminating in an overall system efficiency of 73%. By transforming high-energy thermal photons which typically cause efficiency-killing heat into a secondary useful energy stream, this research offers a scalable blueprint for high-efficiency hybrid solar collectors. These findings provide solar engineers with a verified method for significantly increasing the total energy yield per unit of collector area, advancing the development of "net-zero" energy solutions for residential and industrial applications.

8.2.1 Summary of outcomes

- The study demonstrates the feasibility of fluid-based absorbance filters with TiO₂ nanofluids for beam-split PVT applications, providing a pathway for hybrid solar energy utilization.
- Electrical efficiency alone remains low (~10-11%) and declines with rising PV temperature during the day. However, when combined with thermal recovery through the fluid filter, overall efficiency increases 4-8 times higher.
- A low-cost fluid based Spectral Beam Splitter is developed approaching to ideal curve of spectral absorptivity of solar rays and transmittivity of responsive range of PV cell.
- A hybrid system is developed to extract thermal as well as electrical yield simultaneously from a standalone system reaching efficiencies up to 70%.

- Experimental investigation of the fluid and hybrid system is performed in natural sunlight for optimising the feasibility of the system. Moderate flow rate give higher performances (**58 LPH**)
- Integration of TiO₂/H₂O nanofluid filter with PV panel significantly improves overall efficiency surpassing the cases of both without & empty filter.

8.3 Research Limitations

- **Recirculation Temperature Saturation:** In closed-loop batch testing without an external load or secondary heat exchanger, continuous mixing in the reservoir tank gradually elevates fluid inlet temperature, reducing the temperature gradient (ΔT) over extended operation. In a commercial system, continuous heat extraction can be sustained by coupling the batch reservoir with a continuous thermal load (such as a domestic hot water pre-heater, space heating loop, or industrial process heat exchanger).
- **Heat exchanger for heat extraction:** Incorporating a secondary heat exchanger would lower the inlet temperature and increase the temperature gradient and enhance thermal extraction efficiency. But incorporating the heat exchanger for this small-scale prototype would create pressure drop and low velocity of nanofluid, thus causing nano particle sedimentation. Bigger flow channel heat exchangers can be considered for commercial applications.
- **Long-Term Suspension Stability:** Although the 0.04% TiO₂ mixture showed stability during short-to-medium duration testing, prolonged thermal cycling over multi-month operation poses potential risk for nanoparticle agglomeration and settling.
- **Optical Casing Losses:** Reflection and absorption losses attributable to the PMMA/Polycarbonate filter casing reduce total optical transmission to the underlying PV cell by a small fraction.
- **Scalability and Commercial Viability:** While this study evaluated a small-scale 10 W PV module, scaling to commercial multi-kilowatt arrays introduces structural dead-weight, higher fluid pressure drops, and increased pumping demands. Furthermore, current economic metrics and payback periods remain theoretical projections. Full commercial feasibility depends on establishing

pilot-scale manufacturing of leak-proof optical filters and verifying long-term nanofluid stability under practical field conditions

8.4 Future Scope and Recommendations

To build upon the findings of this experimental study and further the commercial viability of Beam-Splitting Photovoltaic-Thermal (BSPVT) systems, the following areas are recommended for future investigation:

- Long-term performance studies of TiO₂ nanofluid under year-round outdoor conditions to assess stability, degradation and aging effects.
- Exploring different fluids for higher thermal conductivity and optical selectivity.
- Optimization of flow rates and filter design for balancing pumping power, heat recovery, and overall efficiency.
- Turbulator and gas diffuser can be integrated with the filter.
- Integration with thermal storage systems (phase change materials, water tanks) for continuous energy utilization even after sunset.
- Economic feasibility and scalability analysis for large-scale solar farms and rooftop applications.
- Hybrid applications: coupling with desalination, or absorption cooling systems.
- AI and IoT-based control for real-time optimization of flow, tilt angle, and energy output.

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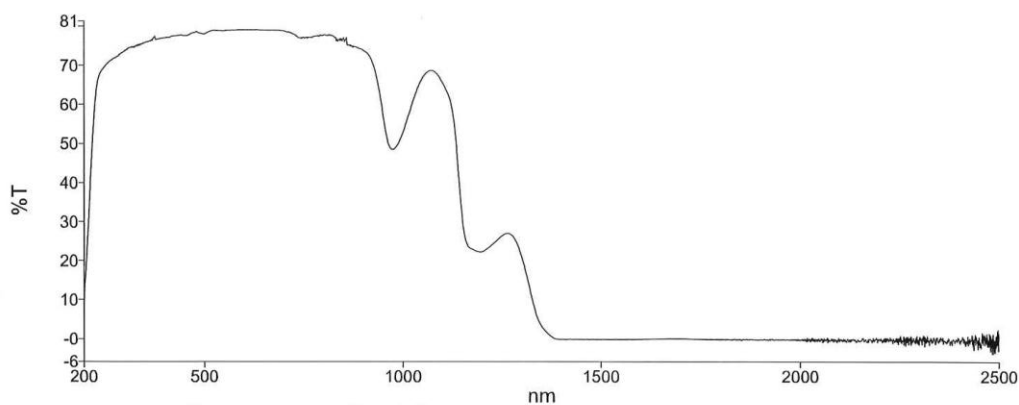
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Appendix A

Test Certificates of Nanofluids Samples

- $\text{H}_2\text{O} + \text{TiO}_2$ 0.01%

SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART, VALLABH VIDYANAGAR



Name: ZnO + TiO2 - 0.02.Sample
Description: 3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By:

Print Date and Time:

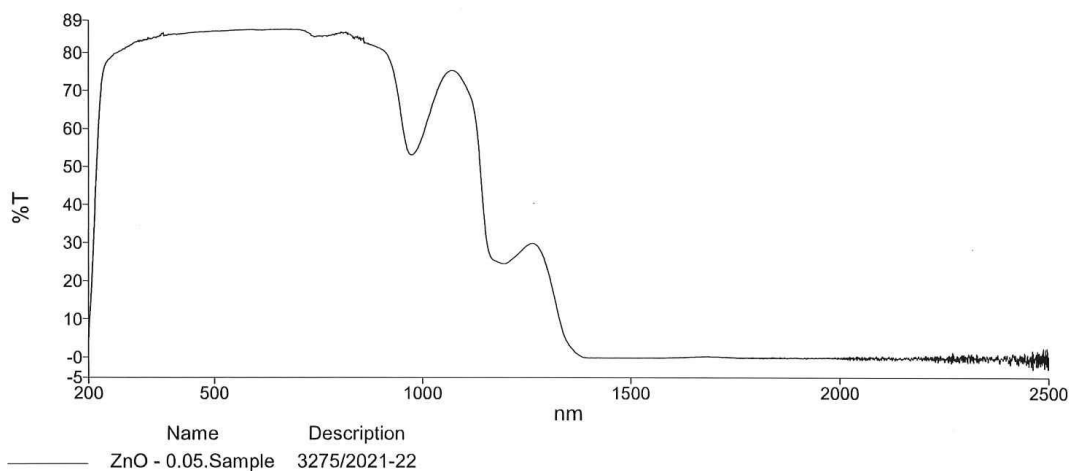
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- $\text{H}_2\text{O} + \text{TiO}_2$ 0.02%

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART, VALLABH VIDYANAGAR**



Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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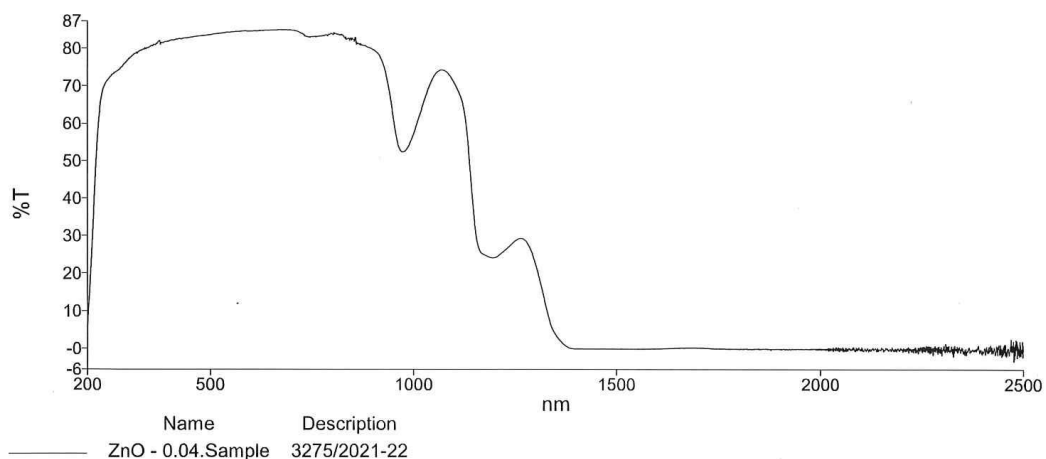
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- **H₂O + TiO₂ 0.03%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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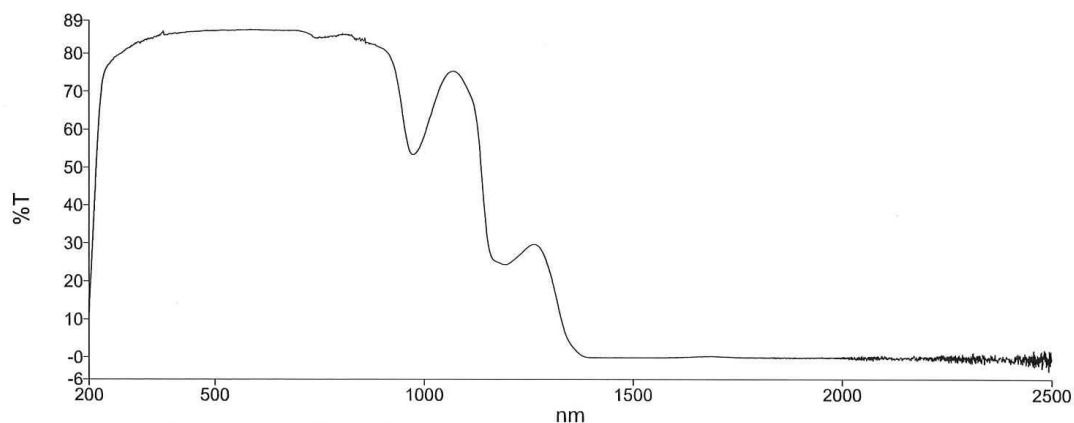
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- **H₂O + TiO₂ 0.04%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Name	Description
ZnO - 0.03.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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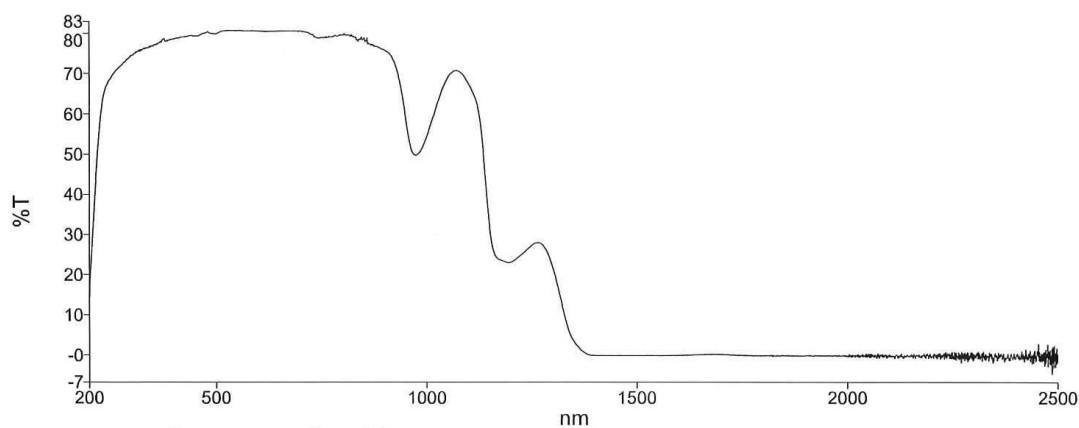
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- **H₂O + TiO₂ 0.05%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Name	Description
ZnO - 0.02.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By: 

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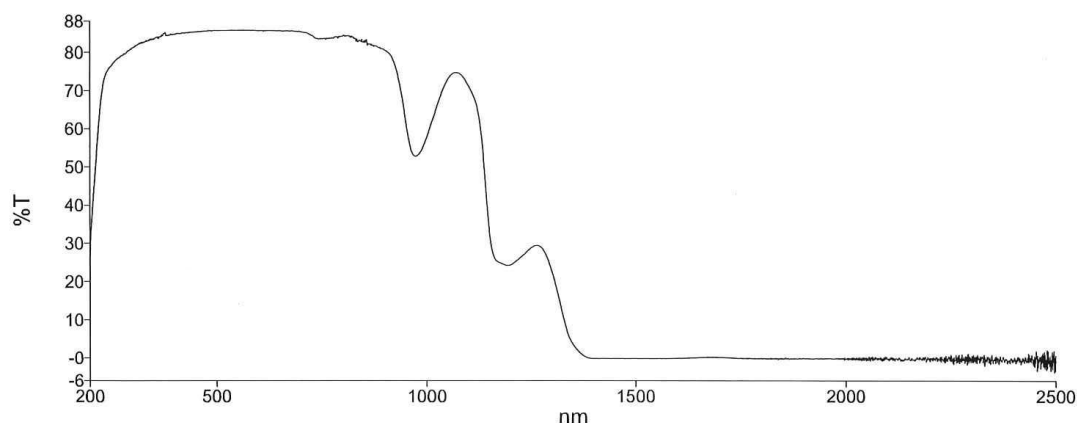
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- **H₂O + ZnO 0.01%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Name	Description
ZnO - 0.01.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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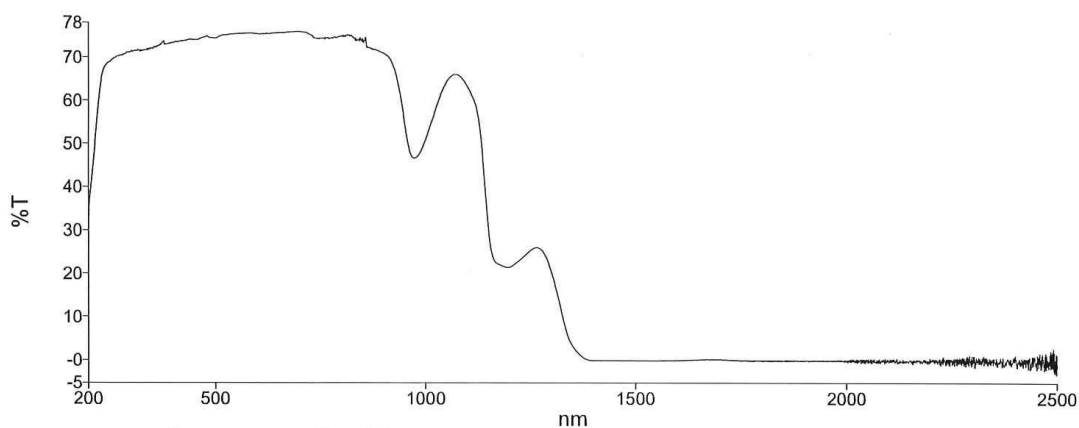
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Print Date and Time: December 21, 2021 17:36:18 India Standard Time



- **H₂O + ZnO 0.02%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Name	Description
————— TiO2 - 0.05.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By: _____

Print Date and Time:

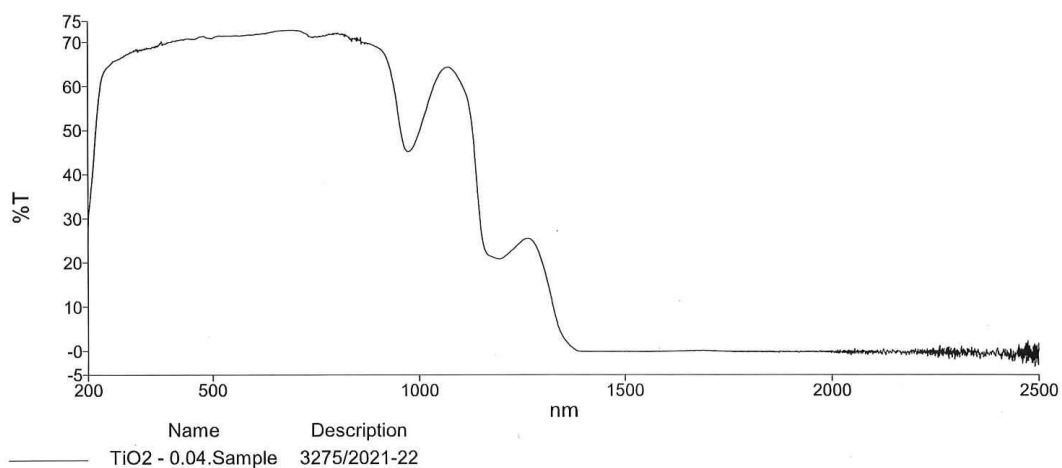
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- **H₂O + ZnO 0.03%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By: 

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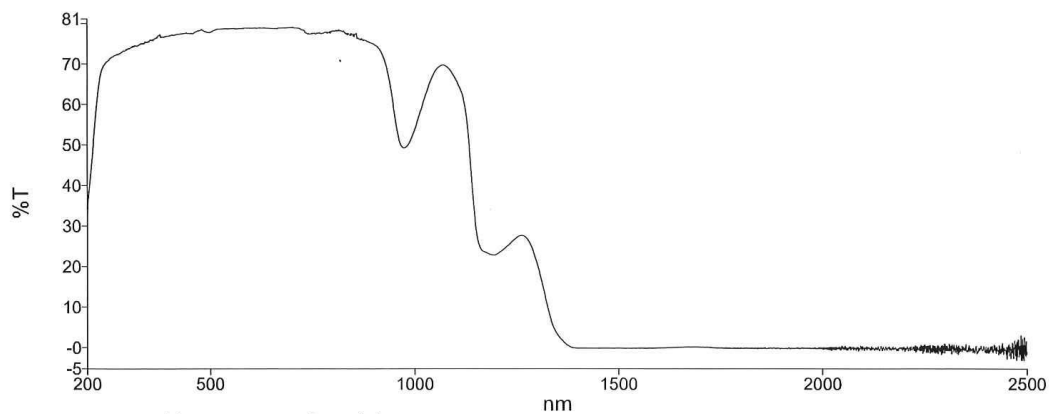
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- **H₂O + ZnO 0.04%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Name	Description
TiO2 - 0.03.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By: 

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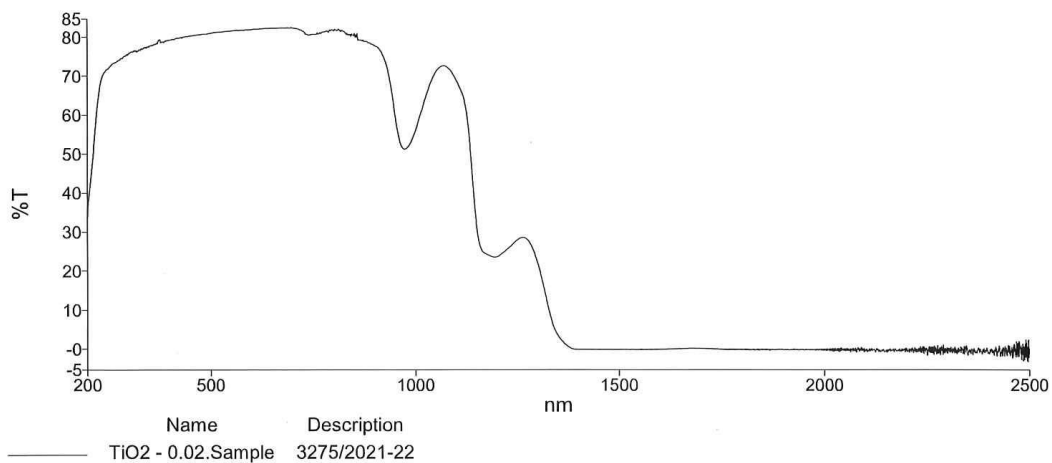
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- **H₂O + ZnO 0.05%**

**SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR**



Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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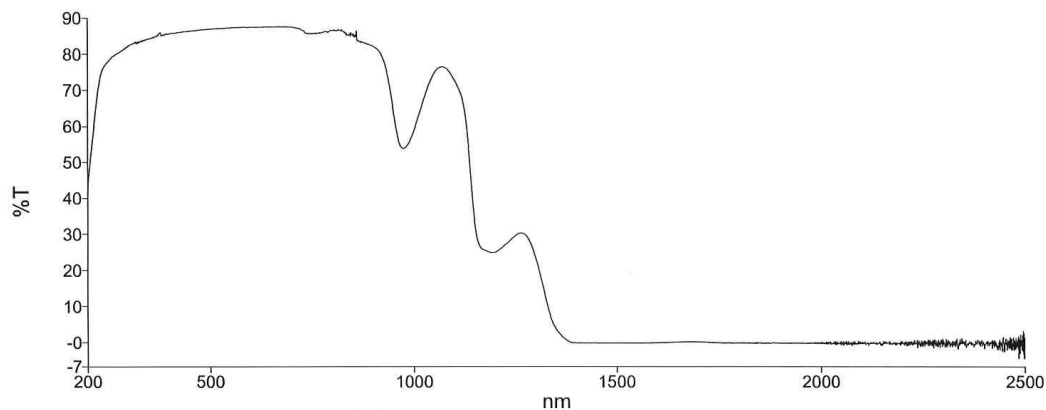
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• **H₂O + ZnO + TiO₂ - 0.02%**

SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART, VALLABH VIDYANAGAR



Name	Description
TiO ₂ - 0.01.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



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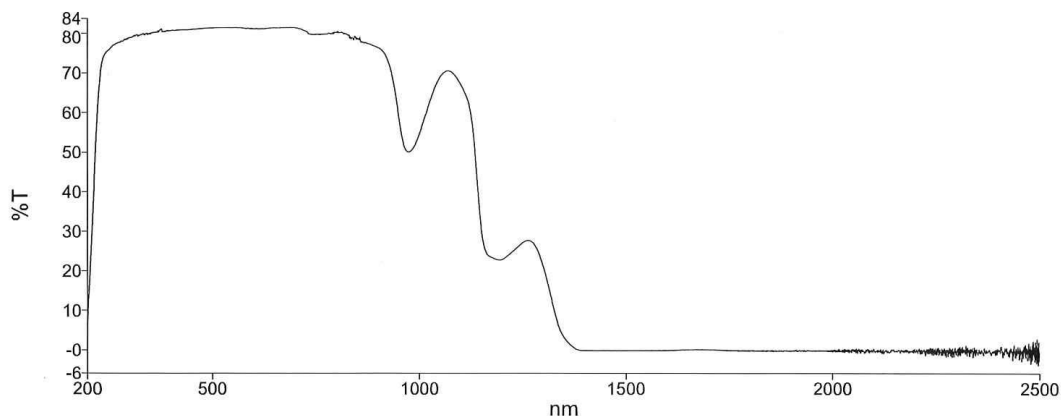
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• $\text{H}_2\text{O} + \text{ZnO} + \text{TiO}_2 - 0.04\%$

SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING
SICART,VALLABH VIDYANAGAR



Name	Description
Zno + TiO2 - 0.04.Sample	3275/2021-22

Instrument Model: LAMBDA 1050+ UV/VIS/NIR & Make By: Perkin Elmer

Scan Speed: 280.80 nm/min

Slit Width: 2.0000 nm

Data Interval: 1.0000 nm

Smooth Bandwidth: 8.00 nm



Analyzed By: 

Print Date and Time: December 21, 2021 17:36:18 India Standard Time



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Appendix B

Sample Calculation for Chapter 7

For demonstration of calculations a typical peak reading of 52 LPH flow rate (case 3) 13:00 hrs values are considered.

- **Mass Flow Rate of the Fluid**

$$\dot{m}_{nf} = \frac{\rho_{nf} V_{nf}}{t} \text{ kg/sec}$$

$$\rho_{nf} = 997.30 \frac{\text{kg}}{\text{m}^3}$$

$$V_{nf} = 0.5 \text{ ltr} = 0.0005 \text{ m}^3$$

Time taken to fill 0.5 ltr beaker $t = 34.6 \text{ sec}$

$$\dot{m}_{nf} = \frac{997.3 \times 0.0005}{34.6} \text{ kg/sec}$$

$$\dot{m}_{nf} = 0.01441 \text{ kg/sec}$$

$$\begin{aligned} \text{Flow in LPH} &= \frac{\dot{m}_{nf} \times 3600}{\frac{\rho_{nf}}{1000}} \\ &= \frac{0.01441 \times 3600}{\frac{997.3}{1000}} = 52 \text{ LPH} \end{aligned}$$

- **Heat Gained by the Filter**

$$T_{out} = 27.0 \text{ }^\circ\text{C}$$

$$T_{in} = 24.7 \text{ }^\circ\text{C}$$

$$Cp_{nf} = 4178.6 \text{ J/kg K}$$

$$Q_{th} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in}) \text{ Watt}$$

$$Q_{th} = 0.0146 \times 4178.6 (27.0 - 24.7)$$

$$Q_{th} = 140.75 \text{ Watt}$$

- **Thermal Efficiency**

$$\eta_{th} = \left(\frac{Q_{th}}{A_{filter} \times G_a} \right) \times 100$$

$$\eta_{th} = \left(\frac{140.75}{0.25 \times 940} \right) \times 100$$

$$\eta_{th} = \mathbf{59.89 \%}$$

- **Electrical Efficiency**

$$\eta_{ele} = \left(\frac{P_{max}}{A_{pv} \times G_a} \right) \times 100$$

$$\eta_{ele} = \left(\frac{5.8}{0.35 \times 0.25 \times 940} \right) \times 100$$

$$\eta_{ele} = \mathbf{7.05 \%}$$

- **Overall Efficiency**

$$\eta_{overall} = \eta_{th} + \eta_{ele}$$

$$\eta_{overall} = 59.89 + 7.05$$

$$\eta_{overall} = \mathbf{66.95 \%}$$

Appendix C

Uncertainty Analysis

The uncertainty analysis is carried out by Root Sum Square (RSS) method

For calculating uncertainty, a typical peak reading of 52 LPH flow rate (case 3) 13:00 hrs values are considered.

- **Uncertainty in Solar Irradiation**

$$G_a = 940 \frac{\text{W}}{\text{m}^2}$$

$$\therefore u_{G_a} = 0.0105 \times 940 = \pm 9.87 \frac{\text{W}}{\text{m}^2}$$

- **Uncertainty in Temperature difference**

$$\Delta T = T_{out} - T_{in}$$

$$\frac{u_{\Delta T}}{\Delta T} = \sqrt{\left(\frac{u_{T_{out}}}{T_{out}}\right)^2 + \left(\frac{u_{T_{in}}}{T_{in}}\right)^2}$$

$$T_{out} = 27.0 \text{ } ^\circ\text{C}$$

$$\therefore u_{T_{out}} = 0.01 \times 27.0 \text{ } ^\circ\text{C} = 0.27^\circ\text{C}$$

$$T_{in} = 24.7 \text{ } ^\circ\text{C}$$

$$\therefore u_{T_{in}} = 0.01 \times 24.7 \text{ } ^\circ\text{C} = 0.247^\circ\text{C}$$

$$\frac{u_{\Delta T}}{\Delta T} = \sqrt{\left(\frac{0.27}{27.0}\right)^2 + \left(\frac{0.247}{24.7}\right)^2}$$

$$\frac{u_{\Delta T}}{\Delta T} = 0.0141$$

$$\frac{u_{\Delta T}}{\Delta T} = 1.41\%$$

$$u_{\Delta T} = 0.0141 \times \Delta T$$

$$u_{\Delta T} = 0.0141 \times 2.3$$

$$u_{\Delta T} = 0.0325^\circ\text{C}$$

$$\Delta T = 2.3 \pm 0.0325^\circ\text{C}$$

$$\Delta T = 2.3 \pm 1.41\%$$

- **Uncertainty of Thermal efficiency**

$$\eta_{th} = \left(\frac{Q_{th}}{A_{filter} \times G_a} \right) \times 100$$

$$\eta_{th} = \left(\frac{\dot{m}_{nf} C_{p_{nf}} (\Delta T)}{A_{filter} \times G_a} \right) \times 100$$

$$\eta_{th} = 59.89 \%$$

Uncertainty

$$\frac{u_{\eta_{th}}}{\eta_{th}} = \sqrt{\left(\frac{u_{\Delta T}}{\Delta T} \right)^2 + \left(\frac{u_{G_a}}{G_a} \right)^2}$$

$$\frac{u_{\eta_{th}}}{\eta_{th}} = \sqrt{\left(\frac{0.0325}{2.3} \right)^2 + \left(\frac{9.87}{940} \right)^2}$$

$$\frac{u_{\eta_{th}}}{\eta_{th}} = \sqrt{(0.0141)^2 + (0.0105)^2}$$

$$\frac{u_{\eta_{th}}}{\eta_{th}} = 0.0423$$

$$\frac{u_{\eta_{th}}}{\eta_{th}} = 4.23\%$$

$$u_{\eta_{th}} = 0.0423 \times \eta_{th}$$

$$u_{\eta_{th}} = 2.534 \%$$

$$\eta_{th} = 59.89 \pm 4.23\% \text{ (% uncertainty)}$$

$$\eta_{th} = 59.89 \pm 2.53\% \text{ (actual value uncertainty)}$$

- **Uncertainty in Electrical Efficiency**

$$\eta_{ele} = \left(\frac{P_{max}}{A_{pv} \times I_{above}} \right) \times 100$$

$$\eta_{ele} = 7.05 \%$$

Uncertainty

$$\frac{u_{\eta_{ele}}}{\eta_{ele}} = \sqrt{\left(\frac{u_{P_{max}}}{P_{max}} \right)^2 + \left(\frac{u_{G_a}}{G_a} \right)^2}$$

$$\frac{u_{\eta_{ele}}}{\eta_{ele}} = \sqrt{(0.005)^2 + (0.0105)^2}$$

$$\frac{u_{\eta_{ele}}}{\eta_{ele}} = 0.0116$$

$$\frac{u_{\eta_{ele}}}{\eta_{ele}} = 1.16 \%$$

$$u_{\eta_{ele}} = 0.0116 \times \eta_{ele}$$

$$u_{\eta_{ele}} = 0.081\%$$

$$\eta_{ele} = 7.05 \pm 1.16\% \text{ (% uncertainty)}$$

$$\eta_{ele} = 7.05 \pm 0.082\% \text{ (actual value uncertainty)}$$

- **Uncertainty in Overall Efficiency**

$$\eta_{overall} = \eta_{th} + \eta_{ele}$$

$$\eta_{overall} = 66.95 \%$$

Uncertainty

$$\frac{u_{\eta_{overall}}}{\eta_{overall}} = \sqrt{\left(\frac{u_{\eta_{th}}}{\eta_{th}}\right)^2 + \left(\frac{u_{\eta_{ele}}}{\eta_{ele}}\right)^2}$$

$$\frac{u_{\eta_{overall}}}{\eta_{overall}} = \sqrt{(0.0423)^2 + (0.0116)^2}$$

$$\frac{u_{\eta_{overall}}}{\eta_{overall}} = 0.0438$$

$$\frac{u_{\eta_{overall}}}{\eta_{overall}} = 4.38\%$$

$$u_{\eta_{overall}} = 0.0438 \times \eta_{overall}$$

$$u_{\eta_{overall}} = 2.937 \%$$

$$u_{\eta_{overall}} = 66.95 \pm 4.38\% \text{ (% uncertainty)}$$

$$u_{\eta_{overall}} = 66.95 \pm 2.93\% \text{ (actual value uncertainty)}$$

Uncertainty of parameters is shown in Table C1

Table C1 Uncertainty of Parameters

Parameters	Total Uncertainty (%)
Solar Irradiation (G_a)	1.05
Temperature Difference (ΔT)	1.41
Thermal Efficiency (η_{th})	4.23
Electrical Efficiency (η_{ele})	1.16
Overall Efficiency ($\eta_{overall}$)	4.38

Appendix D
List of Publications

Sr. No.	Title of the Paper	Name of the Authors	Name of Journal	ISSN Number	Publisher	Month & Year of Publication
1	Fluid based solar spectral beam splitters for hybrid photovoltaic thermal systems: a review	Pushparaj R. Jiwanapurkar, Hitesh A. Bhargav Bharat Ramani	International Journal of Renewable Energy Technology	1757-3971	Inderscience Online	August-2023
2	Spectroscopic Analysis of Water-Based TiO ₂ and ZnO Nanofluid for Fluid-Based Beam Split Photovoltaic-thermal System	Pushparaj Jiwanapurkar, Hitesh Bhargav	Journal of Solar Energy Research (JSER)	2588-3100	University of Tehran	June-2025
3	Experimental investigation of a TiO ₂ nanofluid spectral beam-splitting photovoltaic-thermal system under outdoor conditions	Pushparaj Jiwanapurkar, Hitesh Bhargav et.al.	Discover Nano	2731-9229	Springer	April-2026
4	Performance Evaluation of a Fluid-Based Beam Splitting Photovoltaic-Thermal System Using TiO ₂ Nanofluid Spectral Filter	Pushparaj Jiwanapurkar, Hitesh Bhargav	International Journal of Engineering Research & Technology	2278-0181	IJERT	September-2026
5	Experimental Characterization of Aqueous Zinc Oxide Nanofluid for Liquid Spectral Beam Splitting Photovoltaic-Thermal (BSPVT) Systems	Pushparaj Jiwanapurkar, Hitesh Bhargav	International Journal for Scientific Research & Development	2321-0613	IJSRD	September-2026

