Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Spectroscopic Analysis of Water-Based TiO_2 and ZnO Nanofluid for Fluid-Based Beam Split Photovoltaic-thermal System

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ARTICLE INFO

Article Type:

Research Article

Received:22.07.2024
Accepted:02.06.2025

Keywords:
Solar Energy;
Solar Spectrum;
Photovoltaic Thermal;
Hybrid PV/T;
Spectral Beam Splitting;
Nanofluids

A B S T R A C T

Traditional photovoltaic thermal (PVT) systems struggle to simultaneously maximize electrical and thermal efficiencies due to inherent heating issues and incomplete utilization of the solar spectrum. Although nanofluid-based direct absorption methods have been explored, they remain limited by insufficient spectral control and rising cell temperatures. To overcome these challenges, this research investigates the development of a fluid-based spectral beam splitting (SBS) system using water-based titanium dioxide (TiO_2) and zinc oxide (ZnO) nanofluids as low-cost, tuneable optical filters for beam-split PVT (BSPVT) applications. Twelve nanofluid samples with concentrations ranging from 0.01% to 0.05% were prepared and analysed using UV–Vis–NIR spectrophotometry across 200–2500 nm. The objective is to assess the optical properties of TiO_2 and ZnO nanofluids and identify a suitable nanofluid composition capable of effectively separating the solar spectrum to enhance both electrical and thermal outputs. The results show that the TiO_2 nanofluid at 0.04% concentration provides optimal spectral filtering performance, achieving up to a 74 % transmissivity. Additionally, water's inherent transparency between 751–1126 nm makes it an ideal base fluid silicon PV cell's responsive range. This study establishes a foundation for developing high-efficiency, low-cost SBS-PVT systems with tuneable energy output profiles.

1. Introduction

Solar energy can be harnessed in three primary ways: solar thermal systems, solar photovoltaic (PV) systems, and hybrid photovoltaic/thermal (PVT) systems. Among these, hybrid PVT systems have attracted significant research interest due to their ability to simultaneously convert the full solar spectrum into both electricity and heat within a single integrated unit. Notably, the combined efficiency of a

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Cite this article: 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. doi: 10.22059/jser.2025.379717.1445

DOI: 10.22059/jser.2025.379717.1445

PVT system surpasses the individual efficiencies of standalone photovoltaic and thermal collectors[1].

However, the performance of photovoltaic modules is adversely affected by increases in cell temperature. It is well-established that the open-circuit voltage of a silicon solar cell decreases as temperature rises, leading to a corresponding reduction in overall power output [2, 3]. Another fundamental challenge lies in the material limitations of single-junction solar cells, which are unable to efficiently utilize the complete terrestrial solar spectrum. A solar cell primarily responds to photons whose energy matches the band gap of its material [4]. Photons with energies either lower or higher than the band gap are not efficiently converted into electricity, resulting in significant rise in temperature of the solar cell [1].

Traditional PVT systems attempt to address this heating problem by directly extracting heat from the solar panel to maintain a lower operating temperature. M. R. Mohaghegh [5], in his review, demonstrated the use of nanofluids such as Al_2O_3 /water and other blends of fluids in solar energy technologies to enhance the efficiency and performance of solar thermal systems through the direct absorption method. Also, Mohammad Hassan S et.al. [6] conducted a long-term simulation study using TRNSYS 16 software, showing that integrating a PVT/0.4% Al_2O_3 nanofluid system with a traditional house significantly reduced annual energy consumption and improved thermal and electrical performance compared to conventional PVT/water systems. In conventional PV/T systems, maximizing both electrical and thermal efficiencies simultaneously is challenging because maintaining a lower temperature to preserve PV module efficiency and prevent overheating inherently limits the thermal output.

To overcome both spectral and thermal inefficiencies, the concept of spectral beam splitting was proposed by Jackson [7]. In Beam-Split Photovoltaic Thermal (BSPVT) systems, the incoming solar beam is divided into two components: one containing photons beneficial for photovoltaic conversion and another containing photons that would otherwise be wasted. The non-beneficial portion of the solar spectrum can be absorbed separately and utilized for thermal energy generation [2].

When compared to glasses or solid beam splitters, the liquids are less expensive, easier to pump in and out, and adjustable. An advanced realization of this concept involves the use of a fluid-based spectral beam splitting (SBS) system. In this method, a fluid filter is placed above the PV module to selectively absorb the thermal wavelengths of the solar spectrum, allowing only the responsive wavelengths to pass through and reach the PV cell. Figure 1 shows visualization of the concept.

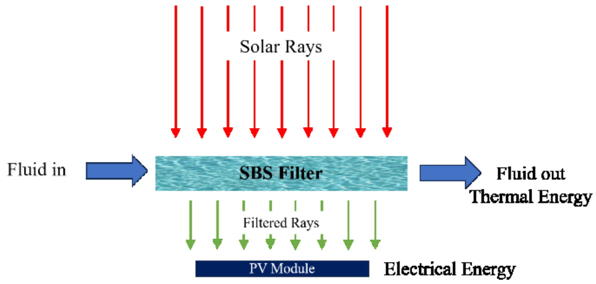

Figure 1. Visualization of the concept of fluid-based spectrum beam splitter placed above PV module to filter out the heating waves

In a fluid-based SBS system, heat can be extracted from the fluid, and electricity can be generated from the PV cell without significantly increasing the cell's temperature [8]. An important advantage of using fluids is that their optical and thermal properties can be tuned, and effective heat extraction can be achieved through fluid circulation.

Given these benefits, identifying a low-cost and efficient nanofluid as an absorption filter for BSPVT systems is an important research focus. This study aims to explore the potential of titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles through spectroscopic analysis, to assess their suitability as effective absorption filters for fluid-based BSPVT systems.

Previous experimental studies have largely focused on pure fluids like water[1-4, 9, 10], Therminol VP-1 [1-4, 10], Brayco 888 F [1-4, 10], ethylene glycol [2-4, 10, 11], propylene glycol, silicone oil [4, 11, 12], nanofluids [13], Valvoline [10], and coconut oil [4, 12].

Studies have been performed on various organic and synthetic fluids and blending them with nanoparticles to evaluate the feasibility of fluids to be used as a beam splitter. The studies collectively emphasize the critical role of fluid selection in optimizing the efficiency and performance of solar energy systems. The performance and suitability of various fluids as spectral beam splitters (SBS) and optical filters for photovoltaic thermal (PVT) systems have been extensively investigated through experimental and numerical simulations.

Maiti et al. [9] examined ionic liquids and glycols, finding issues with oxidation stability and viscosity, making them unsuitable for solar applications. In contrast, Vijayaraghavan et al. [14] found that concentration variations in copper sulphate ($CuSO_4$) solutions had minimal impact on solar system performance. $CuSO_4$ at 40 g/L absorbed 67% of the solar spectrum, while at 60 g/L, it absorbed 69%. Joshi et al. [12] explored 13 fluids and identifying tap water, transformer oil, and coconut oil as effective for enhancing solar cell performance in PVT systems out of which coconut oil was best among tested fluids. Al Shohani et al. [15] [16] determined that a water thickness of 3 cm served as an optimal SBS filter, improving system performance.

Ramdani et al. [17] demonstrated through numerical simulations that using water as both a direct absorber and SBS filter significantly enhanced the performance of novel PVT systems. Chemisana et al. [18] evaluated the direct immersion of solar cells in fluids such as deionized water and alcohols, finding deionized water mixed with isopropyl alcohol and dimethyl sulfoxide effective despite potential oxidation and freezing concerns.

Challenges also arose with specific fluids. Joshi S [4, 8] noted significant heat gain potential using silicone oil as a spectrum filter and heat absorber, yielding up to 27 watts of average heat gain for a 10-watt module when tested with silicone oil. Silicone oil's optical properties showed that it attenuated an average of 239 W/m², but observed degradation over time, which affected electrical performance. Looser [19] identified propylene glycol and Duratherm G as optimal fluids for durability in PVT systems, emphasizing the need for comprehensive modelling. Han et al. [20] highlighted the Valvoline oil filter in concentrated photovoltaic-thermal (CPVT) systems, which showed the highest merit function value, indicating superior thermal energy production.

Nanofluids, composed of nanoparticles dispersed in a base fluid, have been extensively studied for their potential to enhance the efficiency of Photovoltaic Thermal (PVT) systems. The application of nanofluids in PVT systems for Spectrum Beam Splitter (SBS) filters and enhanced performance has been extensively researched, yielding promising results. MgO/Water nanofluids, as studied by Cui et al. [21], demonstrated that increasing nanoparticle concentration improves overall efficiency despite a decrease in electrical efficiency. Siddharth Saroha et al. [22] highlighted the feasibility of using gold and silver nanofluids as Spectrum Beam Splitter (SBS) filters, recommending optimization of nanofluid-PV combinations for enhanced performance. Jing et al. [23] found that Silicon Dioxide/Water nanofluids performed optimally at 40 suns solar concentration and 0.015 m/s filter fluid velocity. Wei An et al. [24] showed that the heat-to-electricity ratio in an oleylamine solution of Cu_9S_5 nanoparticles could be tailored by adjusting nanoparticle concentration. DeJarnette et al. [25] achieved efficiencies of 56% for C-Si cells and 62% for GaAs cells using gold nanoparticles and ITO nanocrystals based on individual nanoparticle properties. Felipe et al. [26] demonstrated that core-shell Ag-SiO_2 nanoparticles in water produced 12% higher weighted energy output compared to standalone PV systems, making them suitable for industrial combined heat and power generation. Jin et al. [27] proposed Magnetic Electrolyte Nanofluid (ENF) as an effective low-cost optical liquid filter for SBS PVT Systems. Todd Otanicar et al. [28] achieved an electrical efficiency of 4% and a thermal efficiency of 61% under 14X concentration using gold and indium tin oxide in Duratherm S, highlighting the potential for low-cost alternatives to gold nanoparticles. Han et al. [29] found that Ag/$CoSO_4$-water nanofluid outperformed Ag/water nanofluid, with a 9% greater total efficiency using Ag in fused base fluid. Natasha E. Hjerrild et al. [30] increased total efficiency by 30% compared to a water filter alone using core-shell Ag@SiO_2 nanodiscs and carbon nanotubes in water. Later, Hjerrild et al. [31] developed and tested nanofluids composed of Ag-SiO_2 nanoplates and silica-coated Au and AuCu nanorods for filtering light for various PV cells, achieving the highest overall efficiency of 40%. Li et al. [32] demonstrated strong absorptivity in visible light wavelengths and good transmittance in the silicon PV cell's spectral response range using Ag@TiO_2 nanoparticles in water. Liang H. [33] found ZnO in glycol base fluid to be a cost-effective alternative to Ag and Au nanofluids. Huang Ju et al. [34] matched the spectrum with a silicon concentrator solar cell at a 25.4 mg/L concentration using Ag@SiO_2/$CoSO_4$-PG nanofluid. Abdelrazik et al. [35] showed that a hybrid PV/OF system using Ag-water as base fluid performed excellently compared to single PV systems, achieving overall efficiency up to 75% at 45°C.

Meibo Xing et.al.[36] introduced a Fe_3O_4 magnetic nanofluid-based spectral beam filter for PV/T systems, where an external magnetic field was used to dynamically control nanoparticle distribution and optical properties. The system achieved a total solar energy conversion efficiency of 73.75% at a 0.0025 wt% concentration under a 100 mT magnetic field, with a 109% improvement in the function of merit compared to conventional setups. This highlights the promising role of tuneable magnetic nanofluids for enhancing both thermal and electrical outputs in advanced BSPVT applications.

Research gap: Despite extensive studies on nanofluids for solar thermal applications, limited research has focused on optimizing low-cost water-based TiO_2 and ZnO nanofluids specifically for fluid-based spectral beam-splitting photovoltaic thermal (BSPVT) systems.

This study is the first to seek the lowest cost suitable nanofluids by conducting a spectroscopic analysis to evaluate their transmittance and absorbance properties. This helps in determining the optimal materials for BSPVT systems. A key novelty of this work lies in comparative spectroscopic characterization of titanium dioxide (TiO_2) and zinc oxide (ZnO) nanofluids specifically as low-cost, tuneable absorption filters for fluid-based spectral beam-splitting PVT systems.

2. Selection of base fluid and nanoparticles for making nanofluid

Coconut oil, transformer oil, and water have emerged as promising candidates for spectrum splitting due to their effective spectral properties and compatibility with the wavelength ranges of solar cells shown by Joshi et.al [12]. Among these, water stands out due to its unique properties, such as being a universal solvent, having a high specific heat capacity, and its ability to mix with a wide range of substances. Water's widespread use is attributed to these characteristics, making it a common fluid in many applications. Water can serve as a spectrum filter both individually and when mixed with other substances, although other potential fluids like propylene glycol, Valvoline oil, and silicone oil may offer superior performance, they are not as economically feasible as water. Figure 2 shows spectroscopic analysis of water plotted absorbance against wavelength [8]. The absorption spectrum of water, as depicted in the figure, reveals that water exhibits zero absorbance, corresponding to approximately 100% transparency, in the wavelength range between 751 nm and 1126 nm, which coincides with the responsive range of silicon solar cells [37]. This characteristic makes water an ideal and highly tailorable base fluid for developing low-cost nanofluids aimed at spectral beam splitting applications. Furthermore, the figure 2 shows a significant rise in absorbance beyond 1126 nm in the infrared (IR) region, indicating water's strong ability to absorb heating infrared rays. This property is particularly advantageous for enhancing the thermal yield of fluid-based BSPVT systems by efficiently harvesting thermal energy from the non-responsive part of the solar spectrum.

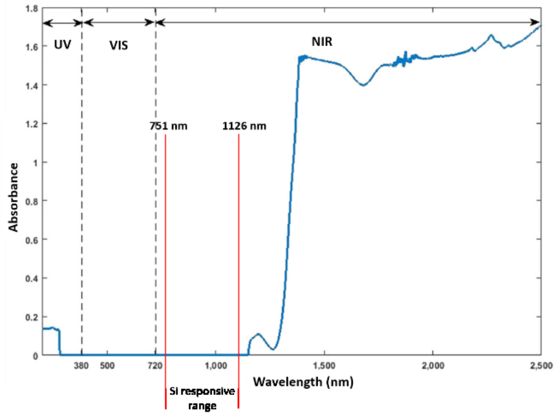

Figure 2. Spectroscopic analysis of water plotted absorbance against wavelength Joshi et.al.[8]

Based on the literature reviewed, water is selected as a potential base fluid for SBS filters in nanofluid-based PVT systems. This recommendation is supported by several factors: water's cost-effectiveness and availability make it practical for large-scale applications; its suitability as a base fluid for nanofluids, allowing for enhanced thermal and optical properties through nanoparticle addition; the cost-prohibitive nature of using precious metal nanoparticles like silver and gold; and the identification of low-cost alternatives, which further underscores water's favourable attributes in terms of availability and affordability.

Titanium Dioxide (TiO_2) and Zinc Oxide (ZnO) are highlighted as cost-effective alternatives due to their widespread availability and effective solar radiation absorption properties. Both TiO_2 and ZnO are widely used in cosmetics, such as sunscreen lotions, for their UV protection capabilities [38, 39]. These nanoparticles, when used with water as a base fluid may offer a more affordable solution while maintaining effective performance in photovoltaic thermal (PVT) systems. Specifically, TiO_2 and ZnO are significantly cheaper than other options like gold (Au), silver (Ag), and silicon dioxide (SiO_2), and their blends, making them economically viable for large-scale applications. Their ability to absorb solar radiation effectively enhances the overall efficiency of PVT systems, contributing to improved energy conversion and system performance. Furthermore, the ready availability of TiO_2 and ZnO in the market ensures easy access for widespread use, making them ideal candidates for enhancing the efficiency and affordability of PVT systems.

3. Spectrophotometric analyses of prepared nanofluids & Methodology

Total 12 fluids were prepared with blends of ZnO/H_2O, TiO_2/H_2O and $ZnO+TiO_2/H_2O$ with weight ratio of 0.01% to 0.05%. Figure 3 shows the photograph of the fluids prepared.

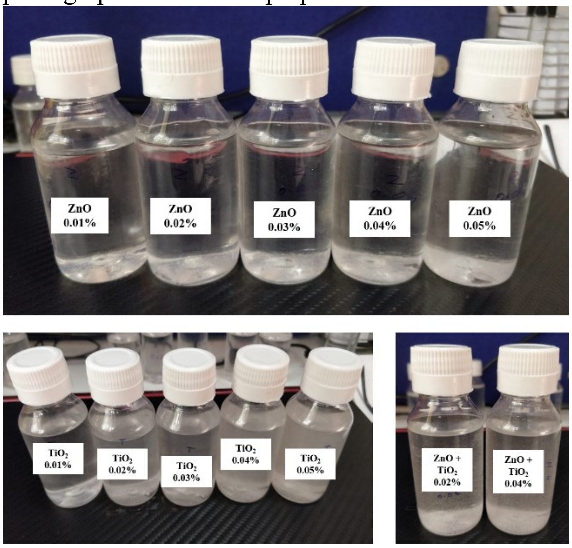

Figure 3. Photograph of fluids sample showing ZnO (0.01 to 0.05%), bottom left TiO2 (0.01 to 0.05%) and bottom right ZnO+TiO2 (0.02 & 0.04%)

To evaluate the optical properties of nanofluids, a detailed methodology was employed using a UV-VIS-NIR spectrophotometer (Model LAMBDA 19, Perkin Elmer, USA). The primary focus was on determining the transmissivity of the nanofluids across a wavelength range of 200-2500 nm at ambient temperature because most of solar irradiation reaching the earth's ground has a wavelength within 300–2500 nm[40]. Figure 4 illustrates the working principle of the spectrophotometer used in this study. The process began with the preparation of nanofluids, where nanoparticles were uniformly dispersed in the base fluid using an ultrasonic bath for 30 minutes to achieve stable and agglomeration-free dispersion. The required volume of nanofluid for each test was then prepared, ensuring consistent nanoparticle concentration. Before measurements, the spectrophotometer was calibrated by allowing it to warm up for 30 minutes, as recommended by the manufacturer. Thorough cleaning of cuvettes with distilled water and ethanol was performed to eliminate any contaminants. Each cuvette was filled with the nanofluid, ensuring no air bubbles were present, and the path length was maintained at 10 mm. The spectrophotometer was set to scan from 200 nm to 2500 nm, with a scanning rate of 600 nm/min and an interval of 1.0 nm. All measurements were conducted at ambient temperature. During the experiment, the cuvette was loaded into the sample holder, as shown in Figure 5, and the scanning process was initiated to measure the transmissivity and absorbance.

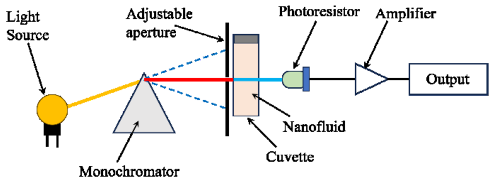

Figure 4. Block Diagram of working of spectrophotometer

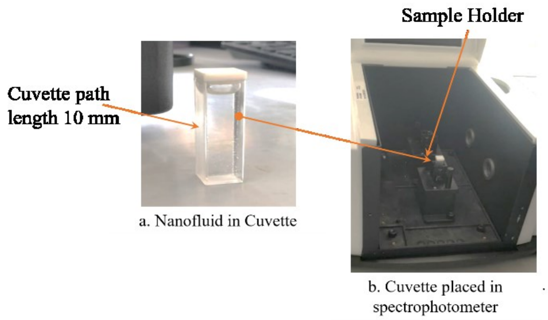

Figure 5. Images of the test procedure. a) a cuvette filled with nanofluid, b) cuvette placed in spectrophotometer

Numerical values of transmissivity against the wavelengths were obtained from the spectrophotometer.

4. Results and Discussion

A graph of transmissivity in % vs. wavelength was plotted to observe the wavelength-specific transmissivity of the prepared fluid samples. Following are the results.

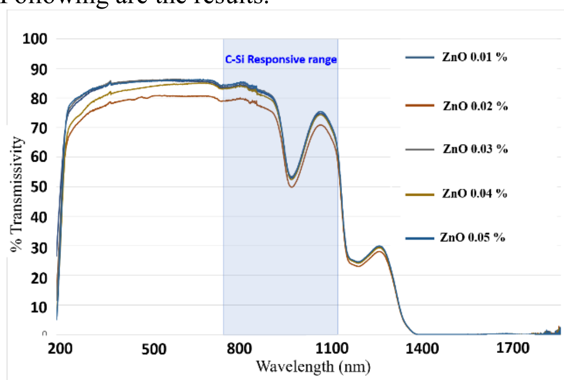

Figure 6. Transmissivity vs wavelength of H2O/ZnO nanofluid with 0.01 to 0.05 % concentration, shaded portion showing C-Si responsive range

Figure 6 illustrates the transmissivity versus wavelength for H_2O/ZnO nanofluids at concentrations ranging from 0.01% to 0.05%. The transmissivity curve for 0.03% concentration reaches a peak of approximately 86%, the highest among all ZnO samples, while 0.02% concentration shows the lowest transmissivity, particularly within the c-Si responsive range (751–1126 nm). Transmissivity significantly reduces with an increase in concentration in the UV region. It may be assumed that due to the scattering effect of particles occurring after 0.02% concentration of the H_2O/ZnO nanofluid, the transmissivity is increased.

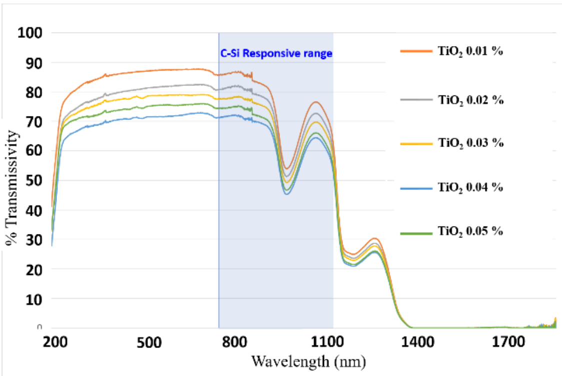

Figure 7. Transmissivity vs wavelength of H2O/TiO_2 nanofluids with 0.01 to 0.05 % concentration, shaded portion showing C-Si responsive range

Figure 7 illustrates the transmissivity versus wavelength for H_2O/TiO_2 nanofluids at five concentrations ranging from 0.01% to 0.05%. The graph shows that transmissivity is highest (~87%) at 0.01% concentration and decreases steadily with increasing concentration, reaching a minimum of ~72% at 0.04% within the c-Si responsive range (751–1126 nm). This trend indicates enhanced light absorption as nanoparticle concentration increases.

The increase in transmissivity at 0.05% concentration is likely due to particle agglomeration and scattering effects, which reduce the effective absorption by disrupting the uniformity of light interaction with dispersed nanoparticles. This suggests that 0.04% is the optimal concentration for maximizing spectral filtering without compromising fluid stability.

In comparison to ZnO nanofluids, TiO_2 nanofluids show consistently lower transmissivity across the spectrum at equivalent concentrations. While ZnO exhibits a sharper decrease in transmissivity in the UV region due to its strong UV-blocking properties, TiO_2 offers more balanced and sustained absorption across both the UV and near-infrared spectrum.

Furthermore, transmissivity differences between 0.02% and 0.03% TiO_2 concentrations are marginal, indicating a point of diminishing optical returns beyond 0.02%. However, the 0.04% sample remains the most effective in filtering the non-useful part of the solar spectrum, crucial for improving thermal output in BSPVT applications.

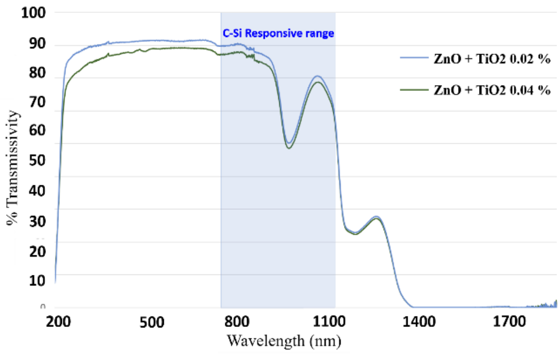

Figure 8. Transmissivity vs wavelength of H2O/ZnO+TiO_2 nanofluids with 0.02 & 0.04 % concentration, shaded portion showing C-Si responsive range

Figure 8 shows the spectral transmissivity of H_2O-based TiO_2 + ZnO nanofluid blends at 0.02% and 0.04% concentrations. As observed, the 0.02% mixture exhibits lower transmissivity than the 0.04% mixture, particularly within the c-Si responsive range (751–1126 nm). However, across the visible and NIR regions, the 0.04% blend shows higher transmissivity, likely due to reduced uniformity or scattering caused by increased particle loading.

While both blends demonstrate a similar spectral trend, the 0.04% sample provides better spectral filtering performance overall. However, neither blend matches the sharper filtering characteristics observed in pure TiO_2 at 0.04% concentration, indicating that although combining nanoparticles offers tunability, it may come at the cost of reduced peak performance.

These results suggest that binary blends offer a compromise between spectral selectivity and material balance, but further optimization would be needed to outperform the best-performing single-component nanofluid.

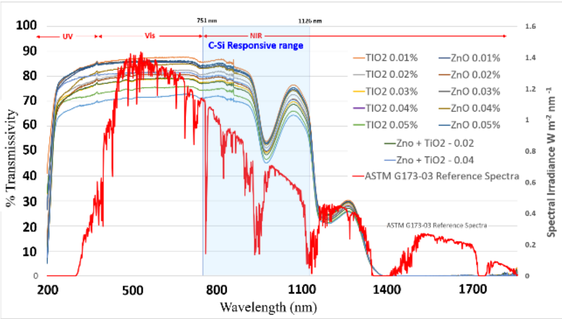

Figure 9. Transmissivity vs. wavelength curves for H_2O/ZnO, H_2O/TiO_2, and ZnO+TiO_2/H_2O nanofluids (0.01%–0.05%) overlaid on ASTM G173-03 solar spectra

Figure 9 illustrates the transmissivity versus wavelength for H_2O/ZnO, H_2O/TiO_2, and their combinations at nanoparticle concentrations ranging from 0.01% to 0.05%, superimposed on the ASTM G173-03 Reference Spectra (W m^{-2} nm^{-1}). The ASTM G173-03 spectra provide standardized solar irradiance data critical for assessing the performance of photovoltaic and thermal systems.

It is observed that a significant drop in transmissivity, up to 45.5%, occurs across all fluid combinations within the wavelength range of 900 nm to 1070 nm, after which the transmissivity trend recovers beyond 1070 nm. Although all fluid combinations exhibit a similar trend, they differ in absolute transmissivity levels.

The Table-1 provides a comparative analysis of twelve nanofluid samples comprising various concentrations of TiO_2, ZnO, and and their combinations based on their average, minimum, and maximum transmissivity values in the 751–1126 nm wavelength range, relevant to the silicon solar cell response. The nanofluids in the table are sorted in increasing order of average transmissivity, providing a clear ranking of their spectral filtering performance, where lower transmissivity corresponds to better absorption and thermal energy capture. TiO_2 at 0.04% concentration demonstrates the lowest average and minimum transmissivity, indicating its superior capacity to filter unwanted infrared radiation, making it highly suitable for BSPVT applications. In contrast, TiO_2 at 0.01% and all ZnO-based nanofluids show higher transmissivity values, suggesting lower spectral filtering effectiveness.

Table 1. Comparison of average, minimum, and maximum transmissivity in 751 – 1126 nm range of TiO_2, ZnO, and TiO_2–ZnO nanofluids

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 behaviour of nanofluids reveals that H_2O/TiO_2 at 0.01% concentration achieves the highest transmissivity, while the same fluid at 0.04% shows the lowest transmissivity in the visible and near-infrared (NIR) regions. In contrast, H_2O/ZnO nanofluid reaches its lowest transmissivity at 0.02% and increases progressively with higher concentrations up to 0.05% in the visible and NIR regions, although transmissivity in the ultraviolet (UV) region decreases with increasing ZnO concentration. For TiO_2-based nanofluids, transmissivity consistently declines with increasing concentration, reaching a minimum at 0.04%. The comparative analysis of twelve different nanofluid blends showed that TiO_2 at 0.04% concentration provided the lowest average transmissivity (63.19%), while still maintaining a moderate maximum transmissivity (72.22%). In contrast, fluids with higher transmissivity, such as TiO_2 at 0.01% and ZnO-based blends, allowed more unwanted infrared radiation to pass through, reducing their spectral filtering effectiveness for BSPVT applications.

These findings highlight TiO_2 0.04% as the most suitable nanofluid because of several critical factors. First, its higher absorption (resulting from lower transmissivity) ensures more non-useful solar radiation is captured and converted into heat, maximizing thermal output and enhancing the overall efficiency of BSPVT systems; although the reduction in transmissivity within the responsive range may slightly decrease PV output, this loss is compensated by the corresponding increase in thermal energy gain. Second, better heat transfer performance is achieved with 0.04% TiO_2 concentration, as it offers an optimal balance between enhancing thermal conductivity and maintaining fluid stability, minimizing risks of nanoparticle agglomeration or sedimentation that could otherwise occur at higher concentrations.

Thus, TiO_2 0.04% nanofluid emerges as the optimal choice for maximizing the combined electrical and thermal performance of the fluid-based spectral beam splitting photovoltaic thermal system.

5. Validation

The findings of this study are supported by the work of Mohit Barthwal [41], who developed an optical theoretical model based on Rayleigh scattering to predict the transmittance and absorbance of ZnO, Fe_3O_4, and SiO_2 nanofluids across the solar spectrum (300–2500 nm). The transmittance versus wavelength graph for ZnO/H_2O nanofluid obtained from his model shows a trend similar to the experimental results reported in this study. Figure 10 shows the graph of transmittance of ZnO based nanofluid obtained by Rayleigh scattering model.

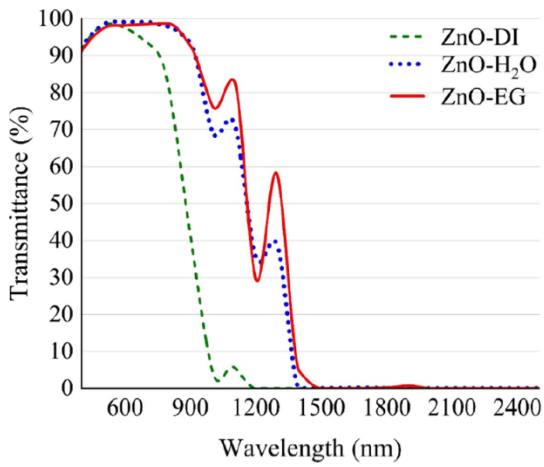

Figure 10. graph of transmittance of ZnO based nanofluid obtained by Rayleigh scattering model

The study by Rashid et al [42]. investigated the optical properties of ZnO, TiO_2 , and ZnO:TiO_2 composite thin films using UV-Vis spectroscopy over the wavelength range of 250–700 nm. Their findings show that the transmittance trend up to 700 nm is consistent with the results obtained in the present study. The figure 11 presents the transmittance versus wavelength behaviour of ZnO, TiO_2 , and ZnO:TiO_2 composite thin films in the range of 250 nm to 700 nm.

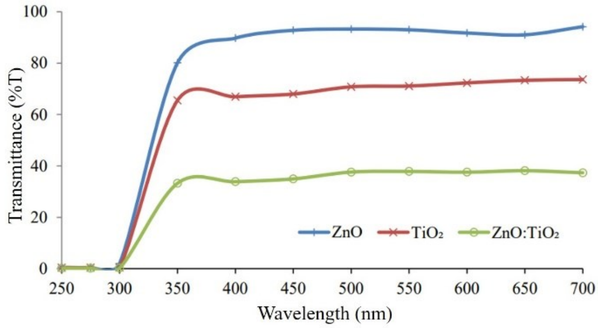

Figure 11. Transmittance versus wavelength behaviour of ZnO, TiO_2 , and ZnO:TiO_2 composite thin films in the range of 250 nm to 700 nm

6. Conclusion

The research paper explores the application of a beam-split photovoltaic thermal system (BSPVT) using titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles in a nanofluid. The goal is to optimize the fluid composition for efficient energy conversion in a solar photovoltaic thermal system.

According to the findings, TiO_2 with a concentration of 0.04% is identified as the best fluid for the fluid-based BSPVT system. The transmissivity results indicate that, in general, transmissivity decreases with increasing nanoparticle concentration, particularly in the UV region. However, interestingly, there are optimal concentrations for both TiO_2 and ZnO where transmissivity is at its highest.

Specifically, for TiO_2, a concentration of 0.03% exhibits the highest transmissivity in the visible region, while for ZnO, the highest transmissivity occurs at 0.01%. The results suggest that beyond certain concentrations, the scattering effect of particles becomes pronounced, leading to a decrease in transmissivity.

Comparisons between H_2O/TiO_2 and H_2O/ZnO show that, at 0.01% concentration, H_2O/TiO_2 has higher transmissivity, and as concentration increases, ZnO becomes more effective in the UV region. Furthermore, the combination of TiO_2 and ZnO in the nanofluid exhibits concentration-dependent transmissivity behaviour.

In conclusion, the research provides insights into the complex relationship between nanoparticle concentration and transmissivity in the context of a solar photovoltaic thermal system. The optimal fluid composition for the BSPVT system is identified as TiO_2 with a 0.04% concentration. The observed trends in transmissivity underscore the importance of carefully selecting nanoparticle concentrations to achieve the desired performance in solar energy applications.

Building on the findings of this research, a natural next step involves experimental validation of the optimized TiO_2 nanofluid (0.04% concentration) under real-world operating conditions. Future studies should focus on integrating the selected nanofluid into a working BSPVT system and conducting outdoor performance tests to assess its effectiveness under varying solar irradiance, ambient temperatures, and weather conditions. This would enable a comprehensive evaluation of the thermal yield, electrical efficiency, and overall system stability over time. Additionally, long-term studies examining the durability, stability, and potential agglomeration of the nanofluid in natural conditions would provide valuable insights for the practical deployment of fluid-based spectral beam-splitting systems in commercial solar applications.

Acknowledgements

Funding: The present work has received no funds in any manner from any organization.

Conflicts of Interest: The authors declare that they are not involved in any organization or entity with any financial interest.

Experiments were conducted at the Sophisticated Instrumentation Centre for Applied Research and Testing (SICART), Department of Science & Technology, Government of India.

Nomenclature

ASTM	American Society for Testing and Materials
BSPVT	Beam Split Photovoltaic-Thermal
CPVT	Concentrated Photovoltaic-Thermal
C-Si	Crystalline Silicon
ENF	Electrolyte Nanofluid
nm	nanometer
NIR	Near Infrared
PV	Photovoltaic
PVT	Photovoltaic-Thermal
SBS	Spectral Beam Splitting
UV	Ultraviolet
Vis	Visible

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