Experimental Characterization of Aqueous Zinc Oxide Nanofluid for Liquid Spectral Beam Splitting Photovoltaic-Thermal (BSPVT) Systems

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Abstract — Photovoltaic-Thermal (PVT) systems suffer from a thermal-electrical efficiency trade-off due to module overheating under high solar irradiance. Spectral Beam Splitting (SBS) resolves this by selectively transmitting the PV-responsive solar spectrum while capturing non-useful wavelengths for thermal conversion. In this study, aqueous zinc oxide nanofluids at concentrations ranging from 0.01 wt% to 0.05 wt% were synthesized using probe ultrasonication with Sodium Dodecyl Sulfate (SDS) surfactant stabilization. Spectrophotometric characterization (200-2500 nm) was conducted to evaluate spectral transmissivity across the active bandwidth of crystalline silicon (c-Si) solar cells (751-1126 nm). Spectrophotometric characterization revealed that the 0.03 wt% formulation achieved maximum spectral selectivity, yielding a peak transmissivity of 85.48 % (average 74.45 % across the c-Si active region, while providing near-complete optical extinction (<5% transmission) in the UV (<350 nm) and deep NIR (>1400 nm) thermal bands. Thermophysical modeling of the optimal 0.03 wt% nanofluid yielded a density of 997.25 kg/m^3, a specific heat capacity of 4178.9 J/kg · K, and a thermal conductivity of 0.6001 W/m · K. These results validate 0.03 wt% aqueous zinc oxide as an efficient optical filter and thermal absorber for hybrid BSPVT applications.

Keywords: Photovoltaic-Thermal (PVT) Systems; Spectral Beam Splitting; Zinc Oxide Nanofluids; Spectral Selectivity; Solar Energy Conversion; Thermal Energy Absorption;

I. INTRODUCTION

The fast depletion of conventional fossil fuels and rising global energy demand have driven a major transition toward sustainable alternatives, among which solar photovoltaic (PV) technology has emerged as one of the fastest-growing worldwide due to its simplicity, modularity, low maintenance, and declining costs [1], [2]. Silicon (Si) solar cells currently dominate the market with over a 95% share owing to their stability and maturity [3]. While typical Si modules achieve 15-20% efficiency under Standard Test Conditions (STC), real-world outdoor operation especially in tropical climates often pushes operating temperatures above 60°C, causing a thermal efficiency loss of roughly 0.45-0.5% per °C rise due to a decrease in the semiconductor band-gap energy and open-circuit voltage (V_{oc}) [4], [5], [6], [7] . To counter this thermal degradation, Photovoltaic-Thermal (PVT) systems circulate a working fluid (such as air, water, or nanofluids) around the module to extract excess heat, simultaneously producing electrical and thermal energy for applications like space or water heating and maximizing overall energy yield compared to standalone systems [8] . Figure 1 shows a traditional PVT system.

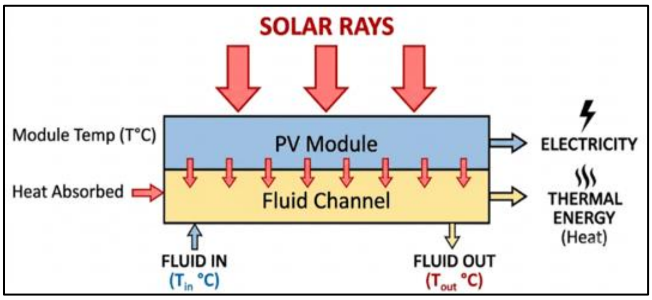

Fig. 1: Traditional PVT system concept

However, traditional Photovoltaic-Thermal (PVT) systems face an inherent thermo-optical conflict that creates a trade-off between electrical and thermal performance [9]. To maintain higher electrical efficiency and prevent thermal degradation, the working fluid must be kept at a low temperature, which inherently reduces the quality and yield of the recovered thermal energy; conversely, operating at higher fluid temperatures improves thermal utility but leads to module overheating and lower electrical output. Because conventional direct-contact configurations restrict thermal output to lower temperatures to protect the solar cells, they cannot maximize both electrical and thermal efficiencies simultaneously, thereby preventing these systems from achieving their full potential energy yield.

To overcome the efficiency trade-off of conventional systems, Spectral Beam Splitting (SBS) technology can be used which separates the solar spectrum (300–2500 nm [10], [11]) into useful and thermal bands [12], [13] . First proposed by Jackson in 1955 [14] and comprehensively reviewed by Imenes and Mills [15], SBS directs only a solar cell's responsive wavelength range such as 751-1126 nm [16] for crystalline silicon to the photovoltaic module for electricity generation, while routing non-responsive, heat-generating wavelengths to a secondary thermal absorber [16], [17] .

Compared to solid optical splitters, liquid-based SBS systems offer cost-effective, tuneable optical and thermal properties. Building on the fluid-based SBS framework introduced by Powell [18] , positioning a fluid absorption filter directly before the PV module allows it to selectively absorb thermal wavelengths before they strike the solar cells while transmitting the electricity-generating spectrum. This arrangement keeps the PV cells cooler to preserve electrical efficiency, while the circulating fluid recovers high-temperature thermal energy simultaneously [17].

II. CHARACTERISTIC REQUIREMENTS OF SPECTRAL BEAM SPLITTING FLUID

The performance of a fluid-based SBS system 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 1 outlines the fundamental requirements and optimal properties required for a fluid to function effectively as a spectral beam splitter for hybrid PVT system.

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

Table 1: Requirements and Characteristics of a Fluid for Spectral Beam Splitting (SBS) Applications

III. SELECTION OF BASE FLUID AND NANOPARTICLES FOR SYNTHESIZING NANOFLUID

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.[19]. 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 2, indicates negligible absorbance in the wavelength range of approximately 751-1126 nm, which aligns with the responsive region of silicon (Si) solar cells [20]. 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.

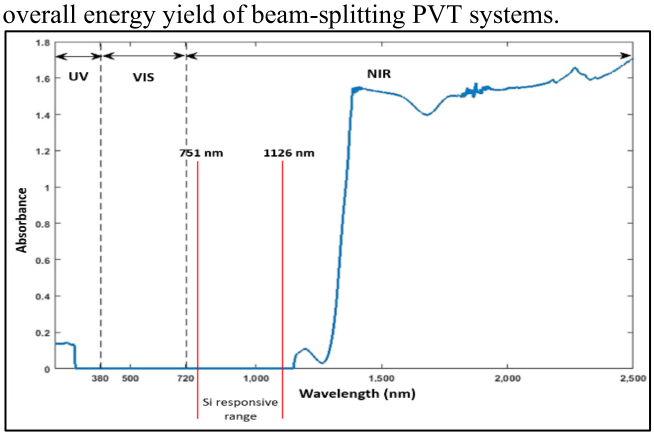

Fig. 2: Spectroscopic analysis of water plotted absorbance against wavelength [20]

While other fluids such as glycerol, Ethylene glycol, propylene glycol [21] , Valvoline oil [22], $CuSO_4$[23], silicone oil [24] , synthetic oil [25] , alcohol [26] etc 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. Zinc oxide (ZnO) have been identified as suitable nanoparticle materials for the fluid based SBS. ZnO is semiconducting metal oxide 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. ZnO is non-toxic, chemically stable, and exhibit excellent dispersion stability in aqueous media. Other nano particles have been researched for their optical characterization such as MgO [27], Cu_9S_5 [28] etc. The ZnO nanoparticles are widely available at a relatively low cost compared to precious metal nanoparticles such as gold (Au) and silver (Ag) [29] [30] [31] , which, although effective, are prohibitively expensive for large-scale implementation.

ZnO is extensively used in cosmetic and coating industries for UV protection due to their superior radiation absorption characteristics [32], [33]. 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.

IV. PREPARATION OF NANOFLUID

Five nanofluid samples were prepared using water as the base fluid with 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 [34]. Furthermore, Sodium Dodecyl Sulfate (SDS) was added at a ratio 1:1 of ZnO particles as recommended by Nahid Hassan et.al. [35] as an anionic surfactant to provide electrostatic stabilization, effectively preventing agglomeration and ensuring long-term suspension stability [36]

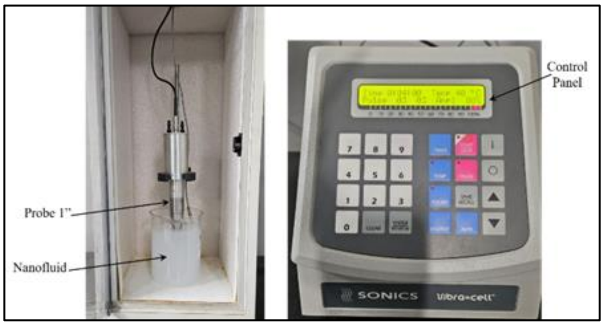

Fig. 3: Nanofluid preparation setup featuring a Sonics Vibra-Cell™ probe sonicator.

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 shows a Sonics Vibra-Cell probe sonicator during the process of preparation of nanofluids. No visual sedimentation was observed for 14 days post-sonication due to SDS steric-electrostatic repulsion

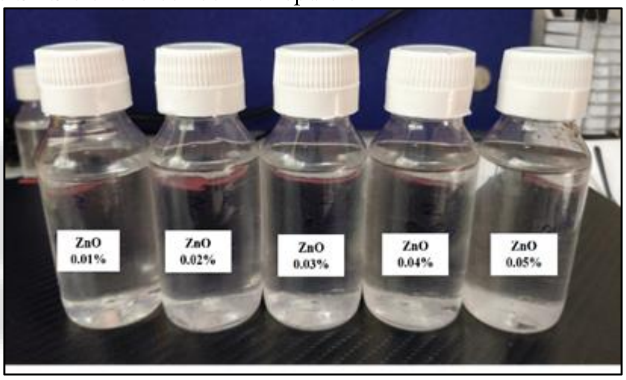

Fig. 4: Photograph of fluids sample showing ZnO (0.01 to 0.05 wt%)

In total, five nanofluid compositions were developed shown in Figure 4, and listed in Table 2. 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.

Sr. No.	Composition wt%
1	H_2O + ZnO (0.01%)
2	H_2O + ZnO (0.02%)
3	H_2O + ZnO (0.03%)
4	H_2O + ZnO (0.04%)
5	H_2O + ZnO (0.05%)

Table 1: Composition and concentration levels of the prepared nanofluid samples

Thus, 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.

V. 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 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) [10][11]. Figure 5 presents the working principle of the spectrophotometer employed in this study.

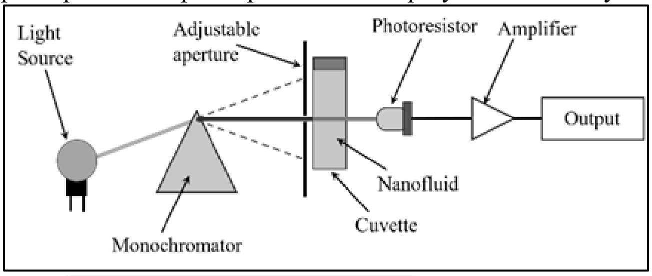

Fig. 5: Operational layout of the spectrophotometer, illustrating the light path from the source through the monochromator and the nanofluid-filled cuvette to the output.

Prior to optical characterization, the UV-Vis-NIR spectrophotometer (PerkinElmer LAMBDA 1050+) was allowed to warm up for 30 minutes to ensure baseline lamp stability in accordance with manufacturer guidelines. Standard quartz cuvettes with a fixed optical path length of 10 mm were thoroughly cleaned using deionized water and high-purity ethanol to eliminate surface contaminants and residual particulates. Each sample was carefully loaded into the cuvette to avoid air bubble entrapment. Transmissivity and absorbance spectra were recorded across a wavelength range of 200-2500 nm at ambient temperature 25°C, utilizing a scanning speed of 600 nm/min with a sampling interval of 1.0 nm. During each trial, the filled cuvette was positioned in the primary sample holder, and full-spectrum optical scans were performed to determine the spectral attenuation characteristics of the prepared nanofluids.

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 aqueous ZnO nanofluids, which are essential for evaluating their potential as fluid-based SBS filters in hybrid PVT systems.

VI. 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.

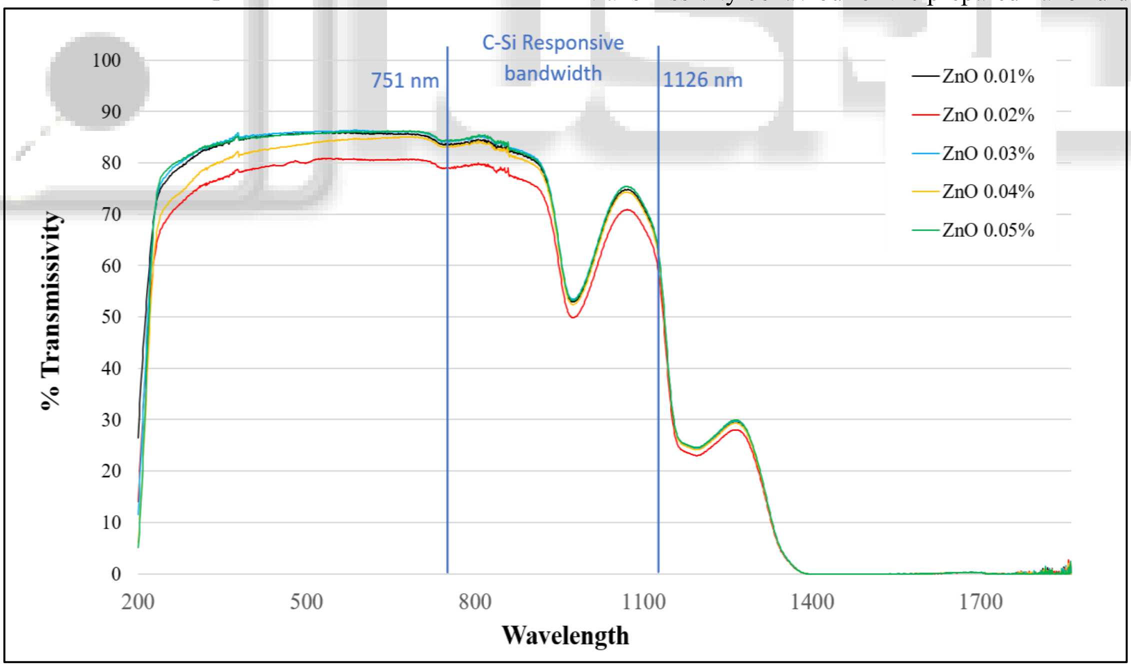

Fig. 6: Spectral transmissivity of aqueous ZnO nanofluids (0.01 wt%-0.05 wt% concentration) highlighting the c-Si responsive bandwidth.

Figure 6 illustrates the spectral transmissivity of aqueous ZnO nanofluids across mass concentrations ranging from 0.01 to 0.05 wt% over the terrestrial solar spectrum 200-1800 nm, with two vertical reference indicators delineating the responsive bandwidth of crystalline Silicon (c-Si) photovoltaics 751-1126 nm. In the short-wavelength ultraviolet (UV) region (200-350 nm), all nanofluid samples exhibit sharp optical extinction, with transmissivity dropping rapidly to near 0% at 200 nm. Beyond 350 nm, the optical transmission undergoes a steep rise, reaching a high-transmission plateau in the visible spectrum near 400 nm. Within the c-Si responsive window (751 -1126 nm), the 0.03 wt% ZnO nanofluid achieves a maximum peak transmissivity of approximately 86%, representing the highest overall photon delivery among all tested concentrations. Conversely, the 0.02 wt% concentration demonstrates an anomalous reduction in transmissivity, averaging lowest across the target band. The localized drop in transmissivity at 0.02 wt% can be attributed to transitional aggregate formation. At 0.01 wt%, particles are dilute and dispersed.

Across the visible and short-wavelength near-infrared (NIR) spectrum (400-900 nm), the nanofluids demonstrate favorable optical clarity, maintaining transmissivity values between 80 % & 86 %. A localized absorption dip is observed between 930 nm and 1020 nm, where the transmissivity reaches a minimum of approximately 52-53 % centered near 980 nm. Subsequent to this dip, a second high-transmission band emerges between 1020 nm and 1126 nm, attaining a peak transmissivity of ~75% at approximately 1070 nm. For wavelengths exceeding 1150 nm, transmissivity experiences a rapid exponential decline, falling below 30% past 1200 nm and approaching complete opacity (0%) beyond 1400 nm due to strong NIR infrared absorption by the base fluid.

Table 3 presents a comparative summary of nanofluid samples across varying concentrations, highlighting their average, minimum, and maximum transmissivity (τ) 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 ZnO nanofluid at 0.03% concentration exhibits the highest average transmissivity within the 751-1126 nm range, confirming its superior filtering performance in transmitting the c-Si responsive wavelengths. This makes it the most promising candidate for efficient spectral beam-splitting photovoltaic-thermal (BSPVT) applications.

Nanofluid Sample	Average τ (%)	Minimum τ (%)	Maximum τ (%)
ZnO 0.02%	69.71	49.85	80.05
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

Table 2 Comparative analysis of the average, minimum, and maximum spectral transmissivity for aqueous ZnO nanofluid samples.

A detailed evaluation within the target c-Si spectral range 751-1126 nm reveals non-linear optical behavior with respect to nanoparticle mass fraction. The average transmissivity within the initial segment 751-900 nm peaks at approximately 85.5 % for the 0.03 wt% concentration, closely matched by the 0.01wt% (85.0 %) and 0.05 wt% (85.2%) formulations. Conversely, the 0.02 wt% nanofluid exhibits a noticeable reduction in transmissivity, averaging around 79.5% in the same band. This non-monotonic trend suggests that at 0.02 wt%, subtle particle agglomeration leads to the formation of secondary clusters whose characteristic diameters approach the wavelength of incident solar radiation, thereby enhancing Rayleigh and Mie scattering losses [37], [38], [39] . Increasing the concentration to 0.02 wt% elevates the Sodium Dodecyl Sulfate (SDS)-mediated surface charge density and zeta potential, effectively disrupting these transient aggregates into smaller, uniformly dispersed primary particles [40]. This superior spatial dispersion and electrostatic stabilization minimize backscattering and optimize forward photon transmission across the active photovoltaic spectrum.

A. Validation of Results

The findings of the current study are consistent with those reported by Mohit Barthwal [41], who developed an optical theoretical model based on Rayleigh scattering to predict the transmittance and absorbance characteristics of ZnO, Fe_3O_4, and SiO_2 nanofluids across the solar spectrum (300-2500 nm). The transmittance-wavelength relationship for aqueous ZnO nanofluid obtained from his theoretical model exhibits a trend comparable to the experimental observations presented in this work. Figure 7 illustrates the transmittance behaviour of ZnO-based nanofluid as predicted by the Rayleigh scattering model.

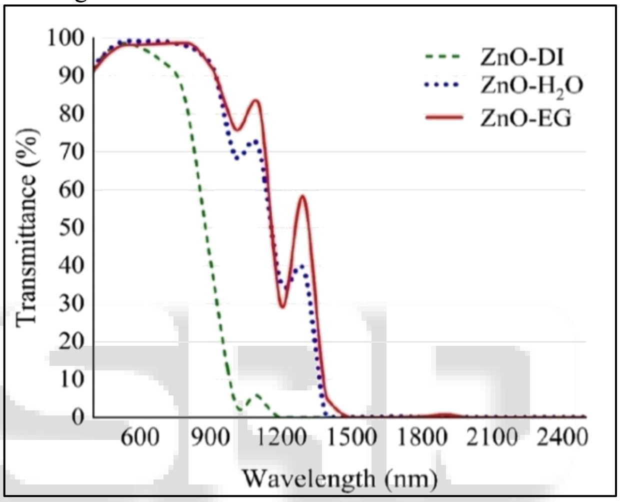

Fig. 7: Transmittance behaviour of ZnO-based nanofluid as predicted by the Rayleigh scattering model [41]

B. Thermophysical Properties of Aqueous ZnO 0.03 wt% Nanofluid:

The thermophysical properties of Aqueous ZnO 0.03 wt% nanofluid are calculated by the process modelled in by T. Feng et.al and B.C. Pak et.al [41], [42]

Specific heat per unit mass (mass-weighted) [42]

Values

- Mass fraction of ZnO nanoparticles: ω_p= 0.03% = 0.00003 g/kg(nf)
- Specific heat of water (Cp_w): 4180 J/kg·K
- Specific heat of ZnO (Cp_p): 523 J/kg·K
- Density of water (ρ_w): 997 kg/m³
- Density of ZnO (ρ_p): 5606 kg/m³

The specific heat of the nanofluid (Cp_{nf}) using mass-weighted average method [42]

$$Cp_{nf} = \omega_p Cp_p + (1 - \omega_p) Cp_w \quad (4.1)$$

$Cp_{nf} = 4178.9\, J/kg\, K$

Convert mass fraction to volume fraction

mass fraction ω_p =0.0003 (0.03 wt%)

ρ_p (ZnO) = 5606 kg/m³

ρ_w (water, 25°C) = 997 kg/m³

Volume fraction φ

$$\varphi = \frac{\frac{\omega_p}{\rho_p}}{\frac{\omega_p}{\rho_p} + \frac{1-\omega_p}{\rho_w}} \quad (4.2)$$

$$\varphi \approx 5.34 \times 10^{-5} \quad (\approx 0.00534\%)$$

Density of Nanofluid (rule of mixtures)[42]

$$\rho_{nf} = \frac{1}{\frac{\omega_p}{\rho_p} + \frac{1-\omega_p}{\rho_w}} \quad (4.3)$$

$$\rho_{nf} \approx 997.25\ kg/m^3$$

Thermal conductivity - Maxwell's Model [42]

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

$$k_{nf} = k_f \frac{k_p + 2k_w - 2\emptyset(k_w - k_p)}{k_p + 2k_w + \emptyset(k_w - k_p)} \quad (4.4)$$

k_w (water, 25°C) ≈ 0.60 W/m K

k_p (ZnO, typical bulk) ≈ 23 W/m K

$$\varphi \approx 5.34 \times 10^{-5}$$

$$k_{nf} \approx 0.6001\ \text{W/m K}$$

C. Summary of properties of aqueous ZnO 0.03 wt%.

The following table 4 shows the calculated values of thermophysical properties of the aqueous ZnO 0.03 wt% nanofluid.

Sr. No.	Property	Value
1.	Volume fraction φ	5.33×10^{-5}
2.	Density ρ_{nf}	$997.25\ kg/m^3$
3.	Specific heat Cp_{nf}	$4178.9\ J/kg\ K$
4.	Thermal conductivity k_{nf}	0.6001 W/m K

Table 1: Summary of properties of aqueous ZnO 0.03% nanofluid.

VII. CONCLUSION

In this study, aqueous zinc oxide (ZnO) nanofluids were successfully synthesized across mass concentrations ranging from 0.01 wt% to 0.05 wt% using probe ultrasonication stabilized with Sodium Dodecyl Sulfate (SDS) surfactant. Comprehensive spectrophotometric characterization 200-2500 nm was conducted to evaluate their viability as liquid-based Spectral Beam Splitting (SBS) optical filters for hybrid Photovoltaic-Thermal (PVT) systems. Among all tested formulations, the aqueous ZnO 0.03 wt% nanofluid demonstrated optimal optical performance, achieving a peak transmissivity of 85.48 % and an average transmissivity of 74.45 % within the 751-1126 nm active response bandwidth of crystalline silicon (c-Si) solar cells. Simultaneously, all nanofluid samples exhibited total optical extinction (<5% transmissivity) in the ultraviolet region due to the wide direct bandgap excitation of suspended ZnO nanoparticles, alongside strong near-infrared attenuation beyond 1150 nm driven by the base water medium. This dual action can effectively shield the photovoltaic module from thermal overheating while converting non-useful solar radiation into valuable thermal energy.

Evaluating optical performance across concentrations revealed non-monotonic behaviour, where a localized reduction in average transmissivity at 0.02 wt% was attributed to transient nanoparticle cluster formation that enhanced Rayleigh and Mie scattering losses. Increasing the concentration to 0.03 wt% elevated SDS-mediated surface charge density and zeta potential, effectively breaking up transient aggregates into primary particles, minimizing backscattering, and restoring high forward photon transmission. Furthermore, theoretical thermophysical modelling of the optimal aqueous ZnO 0.03 wt% nanofluid yielded a density of 997.25 kg/m^3, a specific heat capacity of 4178.90 J/kgK, and a thermal conductivity of 0.6001 W/mK, confirming its balanced thermo-hydraulic and heat recovery characteristics. Overall, the synthesized aqueous ZnO 0.03 wt% nanofluid proves to be a cost-effective, non-toxic, and highly efficient optical filter capable of resolving the thermal-electrical efficiency trade-off in hybrid BSPVT systems, laying the groundwork for future indoor and outdoor prototype testing under concentrated solar irradiance.

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