ISSN 2277-2685
IJESR/Jan-Mar. 2023/ Vol-13/Issue-1/157-171
Mr. Rohit Kumar *et. al.,* / International Journal of Engineering & Science Research

A Study on the Design and Analytical Evaluation of Liquid PVT Systems for Building-Integrated Renewable Energy

Mr. Rohit Kumar[1], Dr. Dhananjay Yadav[2], Mr. Sachin Baraskar[3]
Research Scholar, Department of Thermal Engineering, SSSUTMS, Sehore, Bhopal[1]
Assistant Professor, Department of Thermal Engineering, SSSUTMS, Sehore, Bhopal[2]
Assistant Professor, Department of Thermal Engineering, SSSUTMS, Sehore, Bhopal[3]

ABSTRACT

The integration of photovoltaic thermal (PVT) systems in building structures represents a significant advancement in sustainable energy generation, enabling simultaneous production of electricity and thermal energy from a single collector area. This study aims to evaluate the design parameters and analytical performance of liquid-based PVT systems for building-integrated renewable energy applications. The research objectives include assessing thermal and electrical efficiency variations across different absorber configurations, examining the influence of operational parameters such as mass flow rate and solar radiation intensity, and evaluating the overall energy performance of building-integrated photovoltaic thermal (BIPVT) systems. The methodology adopted a mixed-method research design incorporating both quantitative analysis of experimental data from existing literature and comparative evaluation of various liquid PVT collector configurations. The hypothesis proposed that liquid-based PVT collectors with optimized absorber designs demonstrate superior combined thermal-electrical efficiency compared to conventional standalone photovoltaic systems. The results indicate that spiral flow absorber configurations achieve the highest PVT efficiency of 68.4%, comprising 13.8% electrical and 54.6% thermal efficiency at optimal operating conditions. The discussion reveals that mass flow rate optimization and absorber design significantly influence system performance. In conclusion, liquid PVT systems present viable solutions for building integration, contributing substantially toward renewable energy targets and sustainable building development.

Keywords: Photovoltaic Thermal Collector, Building-Integrated Renewable Energy, Liquid PVT, Thermal Efficiency, Sustainable Buildings

1. INTRODUCTION

The escalating global energy demand coupled with environmental degradation from fossil fuel consumption has necessitated urgent transition toward renewable energy sources. Buildings account for approximately 40% of global energy consumption and contribute significantly to greenhouse gas emissions, making the building sector a critical target for renewable energy integration (Chow, 2010). Solar energy emerges as the most abundant and accessible renewable resource, offering immense potential for decentralized energy generation. However, conventional photovoltaic systems suffer from efficiency limitations, primarily due to excessive heat accumulation that raises cell temperature and subsequently reduces electrical output (Fudholi et al., 2014). Photovoltaic thermal (PVT) technology addresses this fundamental limitation by combining photovoltaic cells with thermal collectors to simultaneously generate electricity and harvest thermal energy. This hybrid approach maximizes solar energy utilization per unit collector area while maintaining optimal cell operating temperatures (Zondag et al., 2003). The liquid-based PVT systems, particularly water-cooled configurations, demonstrate superior heat transfer characteristics compared to air-based systems, making them highly suitable for building applications requiring both electrical power and domestic hot water supply (Ibrahim et al., 2014).

Building-integrated photovoltaic thermal (BIPVT) systems represent an advanced application where PVT collectors are architecturally integrated into building envelopes, including rooftops, facades, and windows. This integration approach reduces installation costs, conserves valuable roof space in urban environments, and enhances building aesthetics while contributing to energy self-sufficiency (Agrawal & Tiwari, 2010). The European Union directive on nearly zero-energy buildings and similar regulations globally have accelerated research interest in BIPVT technologies as means to achieve stringent energy performance standards (Yang & Athienitis, 2016). The efficiency of PVT systems depends on numerous design parameters including absorber configuration, heat transfer fluid properties, mass flow rate, and thermal insulation. Research by Sopian et al. (2009) established that absorber design significantly influences both thermal and electrical performance, with various configurations including serpentine, spiral, web flow, and oscillatory designs demonstrating different efficiency characteristics. The optimization of these parameters for building integration requires comprehensive understanding of their interrelationships and performance trade-offs.

Despite significant advancements, several challenges persist in liquid PVT implementation for buildings, including system complexity, potential water leakage risks, maintenance requirements, and higher initial investment compared to standalone PV systems (Kalogirou & Tripanagnostopoulos, 2006). Additionally, the performance variability under different climatic conditions and building orientations necessitates location-specific design optimization. This research aims to systematically evaluate liquid PVT system designs for building integration, analyzing performance data to identify optimal configurations and operational parameters. The significance of this study lies in providing comprehensive analytical evaluation that can guide architects, engineers, and policymakers in implementing effective BIPVT solutions. As countries worldwide pursue ambitious renewable energy targets and carbon neutrality goals, building-integrated solar technologies will play increasingly crucial roles in decentralized energy generation infrastructure (Debbarma et al., 2017).

2. LITERATURE REVIEW

The development of PVT technology traces back to the 1970s following the oil crisis, which stimulated research into alternative energy sources. Wolf (1976) first investigated combined solar photovoltaic and heating systems, establishing foundational understanding of hybrid solar collectors. Subsequent decades witnessed progressive refinement of PVT concepts through theoretical modeling and experimental investigations. Zondag et al. (2003) conducted pioneering comparative analysis of nine different PVT collector designs, evaluating their thermal and electrical performance characteristics. Their findings indicated that sheet-and-tube configurations provide reasonable efficiency at lower manufacturing costs, while channel-type absorbers achieve superior heat transfer but with increased complexity. This seminal work established benchmarks for subsequent absorber design optimization studies. The thermal modeling and energy analysis of PVT systems received substantial attention from researchers worldwide. Tiwari and Sodha (2006) developed comprehensive mathematical models for PVT systems, incorporating heat balance equations across collector components. Their analytical framework enabled prediction of thermal and electrical outputs under varying environmental conditions, facilitating system optimization for specific applications.

Regarding liquid-based PVT collectors, Chow (2010) presented an extensive review encompassing system configurations, performance parameters, and application potentials. The review highlighted that water-based systems achieve thermal efficiencies ranging from 40% to 60%, significantly higher than air-based alternatives, making them preferable for applications requiring domestic hot water supply. The author emphasized the importance of thermal contact quality between PV cells and heat exchangers in determining overall system efficiency. Building integration aspects were comprehensively addressed by Ibrahim et al. (2014), who evaluated efficiencies and improvement potential of BIPVT systems. Their investigation revealed that BIPVT systems can achieve overall efficiency approximately 60-70% higher than conventional building-integrated photovoltaics by utilizing waste heat for building heating requirements. The study identified glazing configuration and thermal insulation as critical factors influencing BIPVT performance. Experimental investigations on absorber design variations by Fudholi et al. (2014) demonstrated that spiral flow configurations produce superior performance compared to web flow and direct flow designs. At solar radiation levels of 800 W/m², spiral absorbers achieved thermal efficiency of 54.6% and electrical efficiency of 13.8%, representing primary energy saving efficiency between 79% and 91%. These findings provided practical guidance for collector design optimization.

The influence of nanofluids on PVT performance emerged as significant research direction in recent years. Sardarabadi and Passandideh-Fard (2016) investigated metal-oxide nanofluids' effects on PVT systems from energy and exergy perspectives. Their experimental results demonstrated that nanofluid application enhances thermal conductivity and heat transfer rates, improving overall system efficiency by approximately 5-7% compared to pure water operation. Research on BIPVT systems under various climatic conditions by Agrawal and Tiwari (2010) evaluated energy and exergy performance under cold climatic conditions. Their analysis showed that roof-integrated BIPVT systems in 65 m² effective area could annually produce net electrical and thermal exergies of 16,209 kWh and 1,531 kWh respectively at overall thermal efficiency of 53.7%. These findings demonstrated BIPVT viability across diverse climatic zones. Recent comprehensive reviews by Herrando et al. (2019) assessed alternative absorber-exchanger designs for hybrid PVT-water collectors through detailed thermodynamic analysis. The investigation compared roll-bond, sheet-and-tube, and box-channel configurations, concluding that roll-bond absorbers offer optimal balance between thermal performance, manufacturing cost, and system weight considerations (Abdullah et al., 2018).

Facade-integrated BIPVT systems received attention from Yang and Athienitis (2016), who evaluated designs for electricity generation and thermal performance impacts on building heating and cooling loads. Their modeling indicated that properly designed facade BIPVT systems reduce building heating loads by 25-35% during winter months while generating significant electrical output throughout the year. The performance optimization through operational parameter adjustment was investigated by Fayaz et al. (2018), who analyzed effects of nanofluid flow rate on PVT system energy and exergy. Their numerical and experimental results showed that optimal mass flow rates exist beyond which thermal efficiency improvements diminish due to reduced fluid residence time in collectors. Despite extensive research, Abdullah et al. (2018) identified persistent research gaps in PVT collector optimization, particularly regarding comprehensive design guidelines for building integration applications. The need for standardized testing protocols and performance prediction models applicable across various building configurations and climatic conditions remains unaddressed. This literature review establishes foundation for the present analytical evaluation addressing these identified gaps.

3. OBJECTIVES

1. To evaluate and compare the thermal and electrical efficiency performance of various liquid-based PVT absorber configurations for building integration applications.
2. To analyze the influence of operational parameters including mass flow rate, solar radiation intensity, and inlet fluid temperature on liquid PVT system performance.
3. To assess the overall energy performance and primary energy saving potential of building-integrated photovoltaic thermal systems under different design configurations.
4. To identify optimal design parameters and operational conditions for liquid PVT systems suitable for building integration in Indian climatic conditions.

4. METHODOLOGY

The present research adopted a quantitative analytical approach employing secondary data analysis methodology to evaluate liquid PVT systems for building-integrated renewable energy applications. This research design was selected considering the extensive experimental data available from previous studies, enabling comprehensive comparative evaluation across multiple system configurations and operating conditions. The research design incorporated systematic review methodology combined with quantitative meta-analysis of published experimental and simulation studies on liquid PVT collectors. This approach facilitated extraction of performance data from peer-reviewed sources, ensuring reliability and validity of analytical findings. The study focused specifically on water-based PVT systems with various absorber configurations suitable for building integration applications. The sample selection criteria included published research articles from indexed journals covering experimental and simulation studies on liquid PVT collectors published between 2010 and 2021. Studies were selected based on comprehensive performance data availability including thermal efficiency, electrical efficiency, mass flow rate, solar radiation levels, and absorber specifications. The geographical scope encompassed studies conducted across different climatic conditions to ensure generalizability of findings for Indian building applications.

Data collection tools comprised structured extraction protocols developed for systematic compilation of performance parameters from selected studies. The extraction framework captured collector specifications including absorber type, material, dimensions, PV cell characteristics, heat transfer fluid properties, and operational parameters. Performance metrics extracted included thermal efficiency, electrical efficiency, combined PVT efficiency, primary energy saving efficiency, cell temperature, and outlet fluid temperature under various operating conditions. The analytical techniques employed statistical comparison of performance parameters across different absorber configurations and operating conditions. Descriptive statistical analysis provided performance ranges and central tendencies for various collector types. Comparative analysis evaluated efficiency variations attributable to design parameters and operational conditions. The analysis examined performance data under standardized conditions where available, typically solar radiation levels of 500-1000 W/m^2 and mass flow rates of 0.01-0.05 kg/s.

Data analysis was conducted using Microsoft Excel for statistical calculations and graphical representation of results. Performance correlations were examined to identify relationships between design parameters and system efficiency. The analysis prioritized data from experimental studies conducted under controlled conditions to minimize variability from environmental factors.

Validation of findings involved cross-referencing results across multiple independent studies and comparison with established performance benchmarks from international standards. Limitations arising from variability in testing conditions, measurement techniques, and system specifications across studies were acknowledged and addressed through appropriate data selection criteria.

5. RESULTS

The analytical evaluation yielded comprehensive performance data for liquid-based PVT systems across various absorber configurations and operational parameters. Tables 1 through 6 present quantitative results derived from systematic analysis of published experimental studies.

Table 1: Performance Comparison of Different Absorber Configurations in Liquid PVT Collectors

Absorber Type	Thermal Efficiency (%)	Electrical Efficiency (%)	PVT Efficiency (%)	Mass Flow Rate (kg/s)
Spiral Flow	54.6	13.8	68.4	0.041
Serpentine	50.2	11.5	61.7	0.035
Web Flow	44.0	10.8	54.8	0.033
Direct Flow	42.5	10.5	53.0	0.030
Oscillatory	40.0	10.2	50.2	0.028
Parallel Tube	38.5	9.8	48.3	0.025

Table 1 demonstrates the comparative performance of different absorber configurations evaluated under solar radiation of 800 W/m² (Fudholi et al., 2014). The spiral flow absorber configuration exhibits highest performance with thermal efficiency of 54.6% and electrical efficiency of 13.8%, yielding combined PVT efficiency of 68.4% at mass flow rate of 0.041 kg/s. The serpentine configuration follows with 61.7% PVT efficiency, while web flow and direct flow configurations achieve moderate efficiencies of 54.8% and 53.0% respectively. The oscillatory and parallel tube configurations show lower performance, with PVT efficiencies below 51%, attributed to suboptimal fluid flow patterns and reduced heat transfer contact areas.

Table 2: Effect of Mass Flow Rate on Thermal Efficiency of Water-Based PVT Collectors

Mass Flow Rate (kg/s)	Thermal Efficiency at 500 W/m² (%)	Thermal Efficiency at 800 W/m² (%)	Thermal Efficiency at 1000 W/m² (%)
0.011	32.5	38.2	42.0
0.021	38.8	45.5	49.8
0.031	44.2	51.2	55.4
0.041	48.5	54.6	58.6
0.051	47.8	53.2	56.8
0.061	46.2	51.8	54.5

The data in Table 2 illustrate the relationship between mass flow rate and thermal efficiency across different solar radiation levels (Abdullah et al., 2020). Results indicate that thermal efficiency increases progressively with mass flow rate from 0.011 kg/s to optimal values around 0.041 kg/s across all radiation levels. At 1000 W/m² radiation, maximum thermal efficiency of 58.6% occurs at 0.041 kg/s mass flow rate. Beyond this optimal point, efficiency decreases as observed at 0.051 and 0.061 kg/s, indicating reduced fluid residence time limiting heat absorption. The efficiency improvement from lowest to optimal flow rate ranges between 16-17 percentage points across different radiation intensities.

Table 3: Electrical Efficiency Variation with Cell Temperature in Liquid PVT Systems

Cell Temperature (°C)	Electrical Efficiency (%)	Power Output (W/m²)	Efficiency Drop per °C (%)
25	15.2	152.0	Reference
35	14.0	140.0	0.12
45	12.8	128.0	0.12
55	11.6	116.0	0.12
65	10.4	104.0	0.12
75	9.2	92.0	0.12

Table 3 presents the correlation between PV cell temperature and electrical efficiency for crystalline silicon cells commonly used in liquid PVT applications (Chow, 2010). The data confirm temperature coefficient of approximately 0.12% efficiency reduction per degree Celsius rise in cell temperature above standard test condition of 25°C. At cell temperature of 75°C, electrical efficiency drops to 9.2% compared to 15.2% at reference temperature, representing 39.5% relative efficiency reduction. This temperature sensitivity fundamentally justifies thermal management through liquid cooling in PVT systems, where cell temperature reduction directly translates to improved electrical output.

Table 4: Performance of Building-Integrated PVT Systems under Different Orientations

Building Integration Type	Annual Electrical Output (kWh/m²)	Annual Thermal Output (kWh/m²)	Overall Efficiency (%)	Performance Ratio
Roof (Optimal Tilt)	185.5	425.2	61.5	0.85
South Facade	142.8	328.5	47.4	0.78
East Facade	118.2	272.0	39.2	0.72
West Facade	121.5	280.2	40.4	0.73
Roof (Horizontal)	165.2	380.5	55.0	0.82
Window Integration	95.5	218.8	31.6	0.65

Table 4 compares annual performance metrics for BIPVT systems integrated at different building positions (Ibrahim et al., 2014; Agrawal & Tiwari, 2010). The roof-integrated systems with optimal tilt angle demonstrate superior performance with annual electrical output of 185.5 kWh/m² and thermal output of 425.2 kWh/m², achieving overall efficiency of 61.5% and performance ratio of 0.85. South-facing facade integration provides moderate performance with 47.4% overall efficiency. East and west facades show comparable outputs around 39-40% efficiency due to limited direct solar exposure. Window-integrated systems show lowest performance at 31.6% efficiency, constrained by transparency requirements reducing active collector area.

Table 5: Comparison of PVT Collector Performance with Conventional PV and Thermal Collectors

System Type	Electrical Efficiency (%)	Thermal Efficiency (%)	Total Energy Efficiency (%)	Primary Energy Saving (%)
Liquid PVT (Spiral)	13.8	54.6	68.4	85.2
Liquid PVT (Serpentine)	11.5	50.2	61.7	78.5
Conventional PV Module	15.2	0	15.2	38.0
Solar Thermal Collector	0	65.0	65.0	65.0
Side-by-Side PV+Thermal	15.2	65.0	80.2	91.5

Air-Based PVT	10.2	35.5	45.7	58.2

The comparative analysis in Table 5 contextualizes liquid PVT performance against alternative solar technologies (Debbarma et al., 2017; Kalogirou & Tripanagnostopoulos, 2006). While side-by-side installation of separate PV and thermal collectors achieves highest combined efficiency of 80.2%, liquid PVT systems offer significant advantages in space utilization and installation simplicity. The spiral flow liquid PVT achieves 68.4% total efficiency with 85.2% primary energy saving, substantially outperforming standalone PV modules (15.2% efficiency) and air-based PVT systems (45.7% efficiency). The reduced electrical efficiency in PVT compared to standalone PV is compensated by substantial thermal energy generation.

Table 6: Economic and Energy Performance Indicators of Liquid PVT Systems

Performance Indicator	Spiral Flow PVT	Serpentine PVT	Conventional PV	Unit
Energy Payback Time	2.8	3.2	3.5	Years
Levelized Cost of Energy	0.078	0.085	0.092	€/kWh
CO2 Mitigation	245	218	165	kg/m²/year
Annual Energy Yield	610.7	549.2	152.0	kWh/m²
Exergy Efficiency	14.2	12.8	15.2	%
Thermal Exergy	48.5	42.2	0	kWh/m²/year

Table 6 presents techno-economic indicators demonstrating the viability of liquid PVT systems (Fudholi et al., 2014; Fayaz et al., 2018). Energy payback time for spiral flow PVT is 2.8 years, shorter than conventional PV at 3.5 years due to higher total energy production. Levelized cost of energy at 0.078 €/kWh is competitive with grid electricity costs in many regions. CO2 mitigation of 245 kg/m²/year for spiral PVT significantly exceeds conventional PV at 165 kg/m²/year, attributed to displaced fossil fuel usage for water heating. Annual energy yield of 610.7 kWh/m² represents approximately four times the output of standalone PV systems, justifying the additional system complexity.

6. DISCUSSION

The analytical evaluation reveals significant performance advantages of liquid-based PVT systems for building-integrated renewable energy applications, validating the research hypothesis regarding superior combined thermal-electrical efficiency compared to conventional photovoltaic systems. The results demonstrate that optimized absorber design and operational parameter selection are critical determinants of system performance, with implications for practical implementation in building applications. The superior performance of spiral flow absorber configurations, achieving 68.4% combined efficiency, can be attributed to enhanced heat transfer characteristics arising from extended fluid path length and improved contact area between absorber and PV cells. The spiral geometry promotes turbulent flow conditions at relatively lower flow rates, enhancing convective heat transfer coefficients. These findings align with theoretical predictions from heat transfer analysis and corroborate experimental observations from previous investigators including Fudholi et al. (2014) and Sopian et al. (2009). The approximately 18 percentage point efficiency difference between spiral and parallel tube configurations underscores the importance of absorber design optimization for maximizing energy harvest.

The mass flow rate analysis reveals optimal operating conditions around 0.041 kg/s for the investigated collector dimensions, beyond which efficiency improvements diminish. This optimal point represents balance between enhanced heat removal at higher flow rates and sufficient fluid residence time for heat absorption. The declining efficiency at excessive flow rates indicates that pumping energy requirements and reduced temperature differential between inlet and outlet streams negate potential benefits. For building applications, this finding suggests implementing variable speed pumping systems capable of adjusting flow rates in response to solar radiation intensity and thermal demand variations. The cell temperature sensitivity data emphasize the fundamental rationale for thermal management in photovoltaic systems. The 0.12% efficiency reduction per degree Celsius observed for crystalline silicon cells translates to substantial annual energy losses when PV modules operate at elevated temperatures typical of building-integrated installations. Liquid cooling effectively maintains cell temperatures within acceptable ranges, with spiral flow PVT systems demonstrating cell temperatures approximately 15-20°C lower than non-cooled modules under identical conditions. This temperature reduction corresponds to 1.8-2.4% improvement in electrical efficiency, representing significant additional energy generation over system lifetime.

Building integration orientation analysis reveals that roof-mounted systems with optimal tilt angles provide maximum energy generation, achieving 61.5% overall efficiency compared to 39-47% for facade installations. However, facade integration offers unique advantages including reduced visual impact, utilization of otherwise unproductive building surfaces, and potential for architectural integration enhancing building aesthetics. For high-rise buildings in urban environments where roof area is limited relative to total floor space, facade-integrated BIPVT systems represent viable solutions for distributed energy generation despite lower per-unit-area efficiency. The comparative analysis with alternative technologies demonstrates that liquid PVT systems occupy an advantageous position in the efficiency-complexity trade-off spectrum. While separate installation of standalone PV and thermal collectors achieves marginally higher combined efficiency, this approach requires double the installation area, separate mounting systems, and independent maintenance requirements. Liquid PVT systems achieve approximately 85% of separate system efficiency using roughly half the installation area, presenting compelling value proposition for space-constrained building applications characteristic of urban environments.

Economic performance indicators support the technical viability of liquid PVT systems, with energy payback times of 2.8-3.2 years comparing favorably against conventional PV installations. The levelized cost of energy below 0.10 €/kWh indicates competitiveness with grid electricity prices in most regions, suggesting favorable economics without subsidies. CO2 mitigation potential significantly exceeds conventional PV systems due to displacement of fossil fuel consumption for water heating applications, enhancing environmental benefits beyond electrical generation alone. The exergy analysis reveals an important consideration: while liquid PVT systems achieve higher energy efficiency, exergy efficiency is somewhat lower than standalone PV due to low-grade nature of harvested thermal energy. This thermodynamic quality difference has implications for applications requiring high-temperature heat, where liquid PVT thermal output may require supplementary heating to meet demand temperatures. Nevertheless, for low-temperature applications including domestic hot water preheating and space heating augmentation, liquid PVT systems provide thermodynamically appropriate and economically attractive solutions.

Implementation considerations for Indian climatic conditions suggest favorable performance potential given high solar radiation availability across most regions. However, system design must account for elevated ambient temperatures that may limit thermal energy utilization during summer months, potential for overheating protection requirements, and water quality considerations affecting long-term system reliability. The integration of thermal storage systems enables load shifting and addresses temporal mismatch between generation and demand, enhancing practical utility of BIPVT installations.

7. CONCLUSION

This analytical study evaluated liquid-based photovoltaic thermal systems for building-integrated renewable energy applications through comprehensive analysis of design parameters and performance characteristics. The investigation confirms that liquid PVT collectors represent viable and advantageous solutions for simultaneous electricity and thermal energy generation in building applications. The spiral flow absorber configuration demonstrates optimal performance achieving 68.4% combined efficiency with 13.8% electrical and 54.6% thermal efficiency at mass flow rate of 0.041 kg/s and solar radiation of 800 W/m². Mass flow rate optimization significantly influences system performance with 16-17 percentage point efficiency improvement achievable through appropriate flow control. Building integration at roof positions with optimal tilt angles maximizes energy harvest at 61.5% overall efficiency, while facade integration provides moderate performance suitable for high-rise applications. Economic indicators including 2.8-year energy payback time and 0.078 €/kWh levelized cost support commercial viability. CO2 mitigation potential of 245 kg/m²/year substantially exceeds conventional photovoltaic systems. The findings provide valuable guidance for architects, engineers, and policymakers in implementing effective BIPVT solutions contributing toward sustainable building development and renewable energy targets.

REFERENCES

1. Abdullah, A. L., Misha, S., Tamaldin, N., Rosli, M. A. M., & Sachit, F. A. (2018). Photovoltaic thermal/solar (PVT) collector (PVT) system based on fluid absorber design: A review. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 48*(2), 196-208.
2. Abdullah, A. L., Misha, S., Tamaldin, N., Rosli, M. A. M., & Sachit, F. A. (2020). Theoretical study and indoor experimental validation of performance of the new photovoltaic thermal solar collector (PVT) based water system. *Case Studies in Thermal Engineering, 18*, 100595.

3. Agrawal, B., & Tiwari, G. N. (2010). Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions. *Applied Energy, 87*(2), 417-426.
4. Baraskar, S., Aharwal, K. R., & Lanjewar, A. (2012). *Experimental investigation of heat transfer and friction factor of V-shaped rib roughed duct with and without gap*. International Journal of Engineering Research and Applications, 2(6), 1024–1031. https://www.ijera.com
5. Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. *Applied Energy, 87*(2), 365-379.
6. Debbarma, M., Sudhakar, K., & Baredar, P. (2017). Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. *Renewable and Sustainable Energy Reviews, 73*, 1276-1288.
7. Fayaz, H., Nasrin, R., Rahim, N. A., & Hasanuzzaman, M. (2018). Energy and exergy analysis of the PVT system: Effect of nanofluid flow rate. *Solar Energy, 169*, 217-230.
8. Fudholi, A., Sopian, K., Yazdi, M. H., Ruslan, M. H., Ibrahim, A., & Kazem, H. A. (2014). Performance analysis of photovoltaic thermal (PVT) water collectors. *Energy Conversion and Management, 78*, 641-651.
9. Herrando, M., Ramos, A., Zabalza, I., & Markides, C. N. (2019). A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. *Applied Energy, 235*, 1583-1602.
10. Ibrahim, A., Fudholi, A., Sopian, K., Othman, M. Y., & Ruslan, M. H. (2014). Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Conversion and Management, 77*, 527-534.
11. Ji, J., Lu, J. P., Chow, T. T., He, W., & Pei, G. (2007). A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. *Applied Energy, 84*(2), 222-237.
12. Kalogirou, S. A., & Tripanagnostopoulos, Y. (2006). Hybrid PV/T solar systems for domestic hot water and electricity production. *Energy Conversion and Management, 47*(18-19), 3368-3382.

13. Sardarabadi, M., & Passandideh-Fard, M. (2016). Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT). *Solar Energy Materials and Solar Cells, 157*, 533-542.
14. Singh, R., Baraskar, S., Klaraiya, S., & Verma, A. (2017). Performance of solar cooker with a round fin absorber plate. *International Journal of Innovative Trends in Engineering (IJITE), 34*(1), 40. ISSN 2395-2946.
15. Sopian, K., Alghoul, M. A., Alfegi, E. M., Sulaiman, M. Y., & Musa, E. A. (2009). Evaluation of thermal efficiency of double-pass solar collector with porous–nonporous media. *Renewable Energy, 34*(3), 640-645.
16. Tiwari, A., & Sodha, M. S. (2006). Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study. *Renewable Energy, 31*(15), 2460-2474.
17. Wolf, M. (1976). Performance analyses of combined heating and photovoltaic power systems for residences. *Energy Conversion, 16*(1-2), 79-90.
18. Yang, T., & Athienitis, A. K. (2016). A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. *Renewable and Sustainable Energy Reviews, 66*, 886-912.
19. Zondag, H. A., de Vries, D. W., van Helden, W. G. J., van Zolingen, R. J. C., & van Steenhoven, A. A. (2002). The thermal and electrical yield of a PV-thermal collector. *Solar Energy, 72*(2), 113-128.
20. Zondag, H. A., de Vries, D. W., van Helden, W. G. J., van Zolingen, R. J. C., & van Steenhoven, A. A. (2003). The yield of different combined PV-thermal collector designs. *Solar Energy, 74*(3), 253-269.