

HEAT PIPE INTEGRATION IN SOLAR PHOTOVOLTAIC/THERMAL (PV/T) SYSTEMS: A REVIEW OF DESIGN SYSTEM AND FUTURE OUTLOOK

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Abstract

The integration of heat pipe technology into Solar Photovoltaic/Thermal (PV/T) systems presents a significant advancement for enhancing overall energy conversion efficiency by simultaneously generating electricity and recovering thermal energy. This review paper systematically examines the design, operational principles, performance, and future outlook of heat pipe-integrated PV/T systems. Heat pipes, as highly efficient passive two-phase heat transfer devices, effectively mitigate the critical issue of efficiency loss in PV modules caused by elevated operating temperatures. By utilizing internal evaporation-condensation cycles, they rapidly extract waste heat from PV cells, thereby lowering cell temperature, increasing electrical output, and enabling the recovery of useful thermal energy for applications such as water and space heating. The review categorizes and analyzes various heat pipe configurations, including conventional designs, Loop Heat Pipes (LHPs), and Pulsating Heat Pipes (PHPs), highlighting their respective advantages in terms of integration ease, long-distance heat transport, and high heat flux management. Despite their promising potential, key technological challenges such as thermal contact resistance, material compatibility, structural integrity, and economic viability are identified as barriers to widespread adoption. Future research directions emphasize the need for innovations in advanced materials (e.g., nanofluids), hybrid systems with Phase Change Materials (PCMs), optimized design through computational modeling, and the development of standardized testing protocols. Ultimately, heat pipe-integrated PV/T systems are poised to play a crucial role in the renewable energy transition, offering a compact, efficient, and sustainable solution for co-generation of electrical and thermal power.

Keywords: Heat Pipe, PV/T System (Photovoltaic/Thermal), Passive Cooling

INTRODUCTION

Global energy transition and increasing concerns about climate change have made solar photovoltaic (PV) technology a principal candidate for sustainable electricity generation worldwide. The advantages of PV systems include scalability, low emissions, and suitability for both urban and remote installations. However, one of the critical limitations affecting the efficiency and reliability of PV modules is temperature rise on the cell surface, driven by continuous exposure to solar irradiation. Elevated operating temperatures—frequently encountered in tropical or arid regions—result in marked reductions in conversion efficiency, accelerate aging, and degrade materials, making thermal management an urgent issue for PV deployment. Solar photovoltaic (PV) systems are increasingly used as a renewable energy source due to their scalability and environmental benefits. However, PV module performance declines when the cell temperature rises, a phenomenon that diminishes electrical output and accelerates module aging, especially in tropical or high-radiation regions. Excessive heat accumulation is recognized as one of the main challenges in maximizing PV system efficiency. It is also the most mature solar power-generating technology employed in the commercial sector, with the largest market share of approximately 107 GW in 2020. This technology is based on the photoelectric effect of a semiconductor material, which uses solar cells as energy-conversion equipment. However, solar cells can only convert a fraction of incoming solar light into electrical energy owing to the limitations of semiconductor materials. Active cooling technology is the most common project that has received substantial research attention. It uses air and liquid as the cooling medium to extract a portion of the electric energy from the system output (or input from external sources) in order to provide power for dynamic components. Specific implementations take a variety of forms, such as water spray,

mini channel, jet impingement, forced air cooling, nanofluid, and two-phase flow. Passive cooling requires no extra energy input, and the temperature of solar cells is controlled by the natural convection of the cooling medium, phase change material (PCM), liquid immersion, radiative cooling, evaporative cooling, heat pipe, etc. To address the issue of thermal management, the integration of passive heat transfer devices such as heat pipes has attracted considerable research interest. The heat pipe is a highly efficient, passive two-phase thermal system, capable of rapidly removing heat from PV panel surfaces due to its internal evaporation and condensation cycle. Implementation of heat pipes in PV and hybrid photovoltaic-thermal (PV/T) systems has been shown to simultaneously lower cell temperature, increase electrical conversion efficiency, and enable the recovery of residual heat for secondary applications such as domestic hot water or industrial preheating. Solar PV/T systems can be categorised into three major groups based on the type of working fluid: air-based PV/T systems, liquid-based PV/T systems, and refrigerant-based PV/T systems. Since liquids (i.e., water) have a significantly higher heat capacity and heat transfer coefficient than air, liquid-based systems frequently outperform air-based systems in terms of thermal performance.

In addition, owing to refrigerant evaporation in the evaporator, refrigerant-based PV/T systems can also achieve better thermal and electrical efficiencies with an extremely low PV panel temperature. Despite enormous efforts and successes, certain issues still need to be addressed further throughout practical implementations. For instance, active cooling invariably results in a larger temperature difference across the panel and imposes parasitic energy use. Passive cooling has a limited cooling effect, and may be uneconomical. Because of freezing concerns, liquid-based PV/T systems are unsuitable for alpine areas. The high initial cost of the compressor, risk of leakage, and sophisticated design of refrigerant based PV/T systems need careful evaluation. Recent experimental and modeling studies report significant thermal and electrical performance improvements when PV panels are equipped with heat pipe systems, including average temperature reductions up to 10°C and efficiency gains in the range of 1–2% over conventional, non-cooled modules. This paper aims to review the latest developments, experimental findings, technological advances, and challenges in applying heat pipe technology to solar PV systems, providing insights for ongoing research and practical implementation.

Principle and Operation of Heat Pipe

The principle and operation of heat pipes are fundamental to understanding their widespread application in thermal management systems. At its core, a heat pipe is a highly efficient heat transfer device that utilizes the phase transition of a working fluid to move thermal energy from a hot source to a cooler sink with minimal temperature difference (Faghri, 2012). This closed-loop system consists of a sealed container, a wick structure, and a small amount of working fluid. The process initiates when heat is supplied to the evaporator section, causing the working fluid within the wick structure to vaporize. This vaporization occurs at a constant temperature, absorbing latent heat and creating a pressure difference within the pipe.

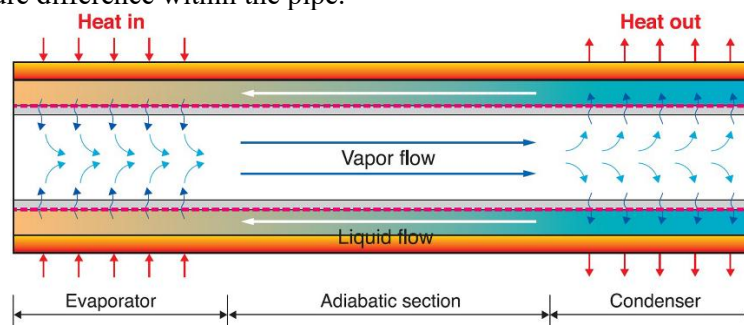


Fig 1. Working Principle of Heat Pipe (Byon, 2016)

This pressure differential drives the vapor from the evaporator, where pressure is higher, to the condenser section, which is at a lower pressure and temperature (Reay et al., 2013). As the vapor reaches the cooler condenser, it releases its latent heat and condenses back into liquid. The condensed liquid then returns to the evaporator section through the capillary action of the wick structure, completing the thermodynamic cycle. This continuous cycle of evaporation, vapor transport, condensation, and liquid return allows for exceptionally high thermal conductivity, often orders of magnitude greater than that of solid copper (Zohuri, 2016). The selection of the working fluid and wick structure is paramount to the heat pipe's performance and operating temperature range. Working fluids such as water, ammonia, and various refrigerants are chosen based on their thermodynamic properties, including latent heat of vaporization, vapor pressure, and compatibility with the pipe material (Peterson, 1994). For instance, water is ideal for moderate temperature applications due to its high latent heat, while ammonia

is preferred for cryogenic or low-temperature systems. Similarly, the wick structure, which can be grooved, meshed, or sintered, must provide sufficient capillary pressure to return the condensed liquid against gravity or other resistive forces, ensuring continuous operation (Faghri, 2012). Moreover, the design of the heat pipe must account for various operational limits, including the capillary limit, entrainment limit, boiling limit, and sonic limit, each of which can impede its heat transfer capability if exceeded (Zohuri, 2016). Understanding these limitations is critical for engineering robust and reliable thermal management solutions. For example, the capillary limit dictates the maximum heat flux that the wick can sustain before dry-out occurs, highlighting the importance of proper wick design and working fluid selection. The theoretical framework underpinning these principles, largely established through extensive research over several decades, remains crucial for predicting and optimizing heat pipe performance in diverse engineering applications, from electronics cooling to spacecraft thermal control (Reay et al., 2013).

Heat Pipe Integration in PV and PV/T Systems

The integration of heat pipe technology within photovoltaic (PV) and photovoltaic/thermal (PV/T) systems represents a critical advancement in enhancing energy conversion efficiency and overall system performance. Heat pipes, renowned for their exceptional thermal conductivity, leverage a phase-change cycle of a working fluid to transfer heat with minimal temperature differences, making them ideal for managing the thermal characteristics of solar energy conversion devices (Faghri, 2012). This application is particularly pertinent in PV systems, where elevated operating temperatures significantly degrade electrical efficiency; a 1°C increase in cell temperature can reduce efficiency by approximately 0.4-0.5% (Skoplaki & Palyvos, 2009). Consequently, heat pipe integration offers a passive yet highly effective thermal management solution, drawing excess heat away from the PV cells to maintain them at optimal operating temperatures.

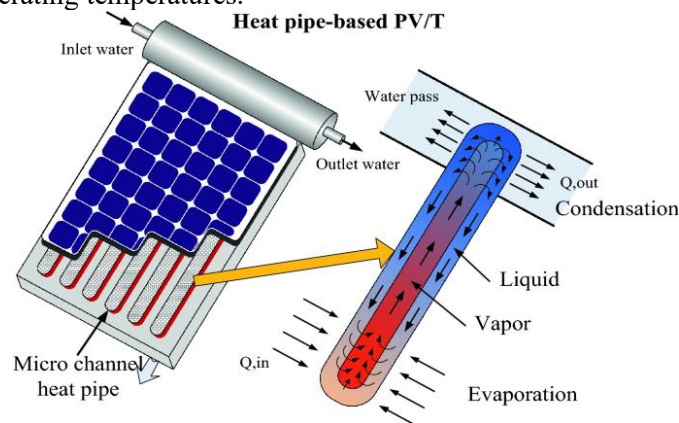


Fig 2. Heat Pipe on PV/T System (Ghazy et al, 2022)

Furthermore, in PV/T systems, the role of heat pipes extends beyond mere thermal regulation to facilitate the useful recovery of thermal energy, thereby achieving a symbiotic dual output of electricity and heat (Chow, 2010). By effectively removing heat from the PV module, heat pipes not only preserve electrical output but also transfer this recovered heat to a fluid for various applications, such as domestic hot water, space heating, or industrial processes. This synergistic approach maximizes the energy yield from a given solar aperture area, rendering PV/T systems with heat pipes inherently more efficient and economically attractive than standalone PV or solar thermal systems (Dubey et al., 2013). The design intricacies often involve integrating the evaporator section of the heat pipe directly with the PV absorber plate, while the condenser section extends into a fluid channel or storage tank.

Several theoretical frameworks underpin the efficiency of heat pipe integration in solar energy systems. The fundamental principles of heat transfer, particularly conduction, convection, and phase change, govern the operation of heat pipes (Incropera et al., 2007). Moreover, thermodynamic efficiency considerations, such as the Carnot efficiency and exergy analysis, provide a basis for evaluating the overall energy quality and conversion potential of PV/T systems utilizing heat pipes (Rosen & Dincer, 2001). Early research by researchers like Akbarzadeh (2009) extensively explored various configurations and working fluids for heat pipes in solar applications, demonstrating their potential to enhance system performance across diverse climatic conditions. However, limitations often arise concerning the specific working fluid selection, optimal tilt angles, and the transient thermal response of such systems under fluctuating solar irradiance. Previous studies have explored various configurations for heat pipe integration, including flat-plate, evacuated tube, and finned designs, each with

distinct advantages and disadvantages depending on the application context (Tyagi et al., 2012). For instance, flat-plate heat pipe collectors are often preferred for their ease of integration with standard PV panels, offering a compact and aesthetically pleasing solution. Conversely, evacuated tube heat pipe collectors, while more complex and costly, provide superior thermal insulation, leading to higher thermal efficiencies, especially in colder climates or for higher temperature applications (Zhao et al., 2015). Despite these advancements, a persistent challenge in the literature involves optimizing the heat pipe design parameters, such as the number and diameter of heat pipes, wick structure, and fill ratio, to achieve peak performance across varied environmental conditions and system scales. The synthesis of literature also reveals a continuous effort to model and simulate the thermal and electrical performance of heat pipe-integrated PV/T systems. Numerical methods, including finite element analysis and computational fluid dynamics (CFD), are extensively employed to predict temperature distributions, heat transfer rates, and fluid flow characteristics within these complex systems (Zondag et al., 2002). These models are crucial for understanding the interplay between different system components and for guiding design improvements before physical prototyping. However, a notable limitation in existing research is the scarcity of comprehensive long-term experimental data validating these models under real-world, fluctuating operational conditions, particularly concerning degradation effects and sustained performance over several years. This gap highlights the need for more robust experimental verification to bridge the divide between theoretical predictions and actual field performance.

RESULTS AND DISCUSSION

System Design Heat Pipes

1. Loop Heat Pipes (LHPs)

Loop Heat Pipes (LHPs) represent a sophisticated passive heat transfer technology that holds significant promise for solar thermal systems, primarily due to their ability to efficiently transport heat over long distances with minimal temperature gradients. Unlike conventional heat pipes, LHPs incorporate a wicked evaporator and a smooth-walled vapor line, which allows for increased flexibility in system design and superior anti-gravity operation (Maydanik, 2014). This characteristic is particularly advantageous in solar applications where collectors might be located at a different elevation or distance from the heat utilization unit, such as a storage tank or a power generation system. The robust operational stability and the capability to handle high heat fluxes make LHPs an ideal candidate for concentrating solar power (CSP) systems, where concentrated solar radiation generates high temperatures requiring efficient and reliable heat removal.

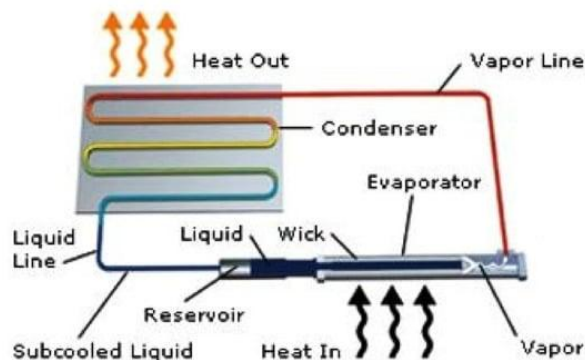


Fig 1. Loop Heat Pipes (Symanski et al, 2021)

Furthermore, the integration of LHPs into solar thermal systems addresses critical challenges related to energy efficiency and system scalability. The inherent phase-change mechanism within LHPs allows for extremely high effective thermal conductivities, far surpassing those of solid conductors, thus minimizing energy losses during heat transport (Zohuri, 2018). This translates directly into improved overall system efficiency, particularly for applications requiring consistent heat delivery over extended periods, like solar water heating or space heating. Previous research has explored various working fluids and wick structures to optimize LHP performance under specific solar irradiation conditions, demonstrating their adaptability across a range of operational parameters (Gungor et al., 2017). However, challenges remain in achieving optimal LHP design for transient solar conditions and ensuring long-term material compatibility under extreme thermal cycling. The integration of Loop Heat Pipes (LHPs) into photovoltaic/thermal (PV/T) systems offers significant advancements in solar energy utilization through an efficient, passive two-phase cooling mechanism. This simultaneously cools photovoltaic cells to boost electrical output and recovers thermal energy (Yu et al., 2020; Diallo et al., 2019). Micro-channel designs

(MCLHPs) have proven particularly effective in enhancing heat transfer capacity and thermal regulation. Research demonstrates that such systems can achieve high thermal efficiency, for instance 45.1% as reported by Zhao et al. (2020), while electrical efficiency also improves with lower operating cell temperatures. Further innovations through the integration of phase change materials (PCMs) for heat storage (Wang et al., 2018) and the use of nanofluids for improved thermal conductivity (Kazem et al., 2022) continue to optimize system performance and stability. To enhance performance, various innovative configurations have been developed, such as dual-inlet air-cooled PV/T systems designed for optimal heat extraction and airflow (Kang et al., 2022). Despite their promise, LHP-integrated systems face several challenges. Key issues include the impact of environmental conditions on rising cell temperatures and performance degradation, as well as the complexity of optimally balancing thermal and electrical efficiencies (Dölek & Arslan, 2024). Consequently, future research is focused on developing accurate modeling and simulation approaches, such as the bond graph modeling explored by Abdin and Rachid (2021), to understand operational parameters and optimize system performance across various climatic conditions. This ongoing work is crucial for advancing LHP-based solutions as a viable and integrated technology in the renewable energy landscape.

2. Pulsating Heat Pipes (PHPs)

Pulsating Heat Pipes (PHPs) represent an innovative and highly efficient two-phase heat transfer device, distinguishing themselves through their unique passive operation and complex thermofluidic dynamics (Akachi, Poláček, & Šulc, 1996). Unlike conventional heat pipes, PHPs consist of a serpentine tube, partially filled with a working fluid, where the liquid and vapor phases are distributed as alternating slugs and plugs, driven by pressure oscillations induced by thermal gradients (Maezawa et al., 2020). This self-sustained pulsation and oscillation mechanism facilitates rapid heat transport, making them attractive for various applications demanding high heat flux removal, such as electronics cooling and thermal management in spacecraft (Shafiey Deh Abad & Jouyban, 2022).

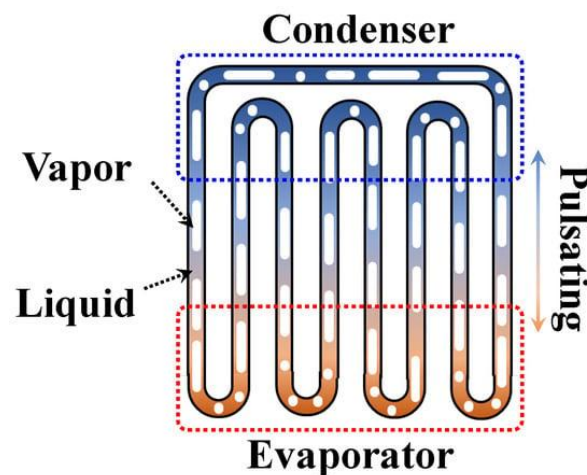


Fig 3. Pulsating Heat Pipe (Lee et al, 2024)

The operational principle of PHPs relies on a complex interplay of various phenomena, including phase change, surface tension, viscous forces, and internal pressure differences (Panda, Nayak, & Mahanta, 2023). When heat is applied to the evaporator section, the working fluid undergoes boiling, forming vapor plugs that expand and push the liquid slugs. Concurrently, in the condenser section, the vapor condenses, creating a pressure drop that pulls the liquid slugs. This continuous cycle of evaporation and condensation, coupled with the pressure imbalances along the serpentine channel, drives the oscillatory motion and enables effective heat transfer from the hot to the cold section (Zhang, Cui, & Zhao, 2017). The intricate dynamics involved, however, make their design and performance prediction challenging, often necessitating a combination of experimental and numerical approaches. A study conducted by Chen et al. (2024) indicates that the integration of PHP with PCM is capable of lowering the peak PV temperature by more than 10–15 °C and increasing the electrical conversion efficiency by 4–8% due to temperature stabilization during the day-night cycle. Furthermore, the absence of moving components and external energy requirements makes PHP a low-cost and environmentally friendly solution for cooling solar panel systems and other electronic devices. In a thermodynamic perspective, PHPs (Pulsating Heat Pipes) leverage heat transfer through two simultaneous mechanisms: latent heat transfer due to vapor-liquid phase change and sensible heat transfer through the movement of liquid slugs. The combination of these mechanisms gives PHPs a

significantly higher effective thermal conductivity compared to conventional metal materials. This makes PHPs one of the most efficient heat management technologies in various applications, including electronics cooling, electric vehicle batteries, micro-reactors, and hybrid solar systems such as photovoltaic/thermal (PV/T). Thus, a Pulsating Heat Pipe can be understood as a high-performance thermal device that operates based on the oscillatory dynamics of two-phase fluid within a capillary structure. The primary advantages of PHPs lie in their design simplicity, passive operation, intensive heat transfer capability, and ease of integration with modern energy systems. In the context of renewable energy research, PHPs play a strategic role in enhancing PV panel performance, stabilizing operating temperatures, and extending device lifespan, thereby making a significant contribution to the efficiency of future energy systems.

Technological Challenges

The integration of heat pipe systems with photovoltaic (PV) modules, whether through direct mounting or behind-PV configurations, presents a promising avenue for enhancing overall system efficiency by simultaneously generating electricity and recovering thermal energy (PV/T systems) (Tripanagnostopoulos & Nousia, 2012). However, this seemingly straightforward concept is fraught with significant technological challenges that demand careful consideration during the design phase. Foremost among these is the critical issue of thermal contact resistance at the interface between the heat pipes and the PV module. Poor thermal contact can severely impede heat transfer from the PV cells to the working fluid within the heat pipes, leading to suboptimal cooling of the PV module and consequently, reduced electrical efficiency and less effective heat recovery (Chow et al., 2010). The design of the heat pipe evaporator section, particularly its geometry and material compatibility with the PV module, is crucial for maximizing heat capture while minimizing structural stress on the delicate PV cells. The selection of an appropriate working fluid is also paramount, as its thermophysical properties (e.g., latent heat of vaporization, boiling point) must align with the operational temperature range of the PV module to ensure efficient phase change and heat transport (Jafari et al., 2015). Without careful optimization, issues such as dry-out in the evaporator or excessive pressure drop in the system can arise, compromising the long-term performance and reliability of the PV/T system (Tyagi et al., 2012).

Another significant hurdle lies in the intricate balance between effective heat removal and maintaining the structural integrity of the entire PV/T system. Directly mounting heat pipes can add considerable weight and complexity, potentially impacting the installation process and long-term durability of the PV array (Shahsavari & Sarrafi, 2018). Moreover, the thermal expansion and contraction cycles experienced by the heat pipes and PV module during operation can induce mechanical stresses, potentially leading to material fatigue or delamination of the PV encapsulants over time. Therefore, sophisticated mechanical design and material selection are essential to ensure the longevity and robustness of these integrated systems (Sardarabadi et al., 2014). The dynamic and often unpredictable nature of solar irradiance and ambient temperatures introduces further challenges in maintaining optimal operating conditions for heat pipe-based PV/T systems. Designing a system that can effectively manage transient thermal loads and varying heat fluxes requires a deep understanding of fluid dynamics and heat transfer principles. The capacity of the heat pipe to adapt to these fluctuating conditions without experiencing performance degradation or instability is a key factor in its successful implementation (Xu et al., 2019). Existing research often highlights the theoretical potential, yet practical application demands robust solutions to these complex thermal and mechanical challenges.

Future Prospects

Exploration into advanced heat pipe designs, such as pulsating heat pipes (PHPs) and micro heat pipes, offers pathways to overcome existing limitations in thermal resistance and integration complexity (Akbarzadeh et al., 2018). These next-generation heat transfer devices boast superior thermal conductivity and compact form factors, making them ideal candidates for seamless integration within the confined spaces of PV/T modules. The ability of PHPs, for instance, to operate without external power input and across various orientations makes them particularly attractive for decentralized energy applications where robust and low-maintenance solutions are paramount. Consequently, research efforts are increasingly focused on developing hybrid systems that leverage these sophisticated heat transfer mechanisms to unlock higher energy conversion efficiencies and broader application potential. A critical aspect of advancing heat pipe integration in PV/T systems involves meticulous system design and optimization, particularly concerning the interface between the heat pipe evaporator section and the PV cells, as well as the condenser section and the thermal energy storage or heat utilization mechanism (He et al., 2019). The thermal contact resistance at these interfaces significantly influences the overall heat transfer

effectiveness and, consequently, the PV/T system's performance. Therefore, future designs must prioritize novel manufacturing techniques and material selections that minimize thermal resistance while ensuring mechanical integrity and long-term durability. This includes exploring phase change materials (PCMs) integrated with heat pipes to manage transient thermal loads and provide more stable thermal output. Moreover, the economic viability and scalability of heat pipe-integrated PV/T systems will largely depend on reducing manufacturing costs and improving system longevity. Current research indicates a strong correlation between optimized heat pipe geometry, working fluid selection, and overall system cost-effectiveness (Huang et al., 2020). Future developments are expected to leverage computational fluid dynamics (CFD) and advanced simulation tools to rapidly prototype and test various designs, thereby accelerating the development cycle and reducing experimental costs. Such rigorous theoretical and empirical investigations are essential to transition these advanced PV/T technologies from laboratory settings to widespread commercial application, offering a sustainable solution for integrated energy generation.

CONCLUSION

The integration of heat pipe technology into solar photovoltaic/thermal (PV/T) systems represents a strategic advancement in holistically improving solar energy conversion efficiency. This review demonstrates that heat pipes, through their passive and efficient two-phase heat transfer mechanism, successfully address the fundamental issue of PV modules: the decline in electrical efficiency due to rising operating temperatures. By cooling PV cells, this technology not only enhances electrical output but also recovers thermal energy that can be utilized for water heating, space heating, or industrial processes, thereby yielding higher overall energy output and exergy efficiency compared to standalone PV or thermal systems. Various design configurations, from conventional heat pipes and Loop Heat Pipes (LHPs) to Pulsating Heat Pipes (PHPs), each offer distinct advantages in terms of ease of integration, long-distance heat transport capability, or heat flux density.

However, widespread adoption of this technology still faces several technical and economic challenges. Thermal resistance at interfaces, material compatibility, design optimization for dynamic climatic conditions, and relatively high initial costs remain primary obstacles to overcome. Looking ahead, innovations in working fluid materials such as nanofluids, smart integration with phase change materials (PCMs), computational fluid dynamics (CFD)-based modeling, and the development of standardized testing protocols and long-term performance data will be key drivers. Thus, PV/T systems integrated with heat pipes hold promising prospects for making significant contributions to the renewable energy transition, offering a space-efficient and sustainable solution for simultaneous electrical and thermal energy production.

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