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Thermal Performance Optimization of Hybrid Photovoltaic/Thermal (PV/T) Air Collectors for Heat Transfer Insight

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Abstract
This research presents a detailed thermal performance investigation of a photovoltaic/thermal (PV/T) air collector system, targeting both electrical and heat energy output enhancement. The dual-purpose system integrates a photovoltaic module with an air duct and insulation layers. A computational thermal model under natural airflow conditions was constructed, calibrated with experimental measurements, and used to simulate the effect of various design and operating factors on heat transfer within the air channel. The analysis confirms that elevating the air mass flow rate—particularly between 0 and 0.015 kg/s—while minimizing the thermal resistance of the bottom encapsulation layers significantly boosts thermal energy recovery, thereby improving overall system efficiency.
Keywords: *Photovoltaic/Thermal, hybrid solar collector, air duct, heat transfer modeling, thermal resistance, system efficiency*

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I. Introduction

As global energy consumption escalates, transitioning to sustainable energy systems has become a critical imperative. Fossil fuel dependency continues to drive greenhouse gas emissions, intensifying climate change risks. Solar energy emerges as a leading solution, offering an inexhaustible and clean alternative. Solar technologies are commonly divided into photovoltaic (PV) systems, which convert sunlight directly into electricity, and solar thermal systems, which capture heat energy. However, traditional PV modules convert only 5–20% of incoming solar radiation into electricity, with the rest manifesting as thermal energy that heats the cells and diminishes their electrical output. Hybrid PV/T systems address this challenge by extracting excess heat from the PV module through fluid circulation—either passive or forced—thereby cooling the module and enabling simultaneous thermal energy collection. These systems are particularly valuable for low-temperature heating applications. Since Wolf's foundational study on combined PV and thermal collectors, research has advanced significantly. Numerous studies have optimized design features and evaluated performance enhancements, but few have explicitly incorporated the effects of internal thermal resistances within the PV laminate structure. This study examines how design variables and material thermal properties influence heat transfer in a single-pass PV/T air collector, with a focus on thermal resistance effects and air flow behavior.

II. System Schematics and Simulation Results

2.1 PV/T System Schematic

Figure 1 illustrates the structural composition of the hybrid PV/T air collector, comprising multiple layers including the glass cover, photovoltaic cells, EVA adhesive, tedlar backing, air duct, and insulation. This configuration enables simultaneous heat and electricity generation while facilitating natural air circulation beneath the PV module.

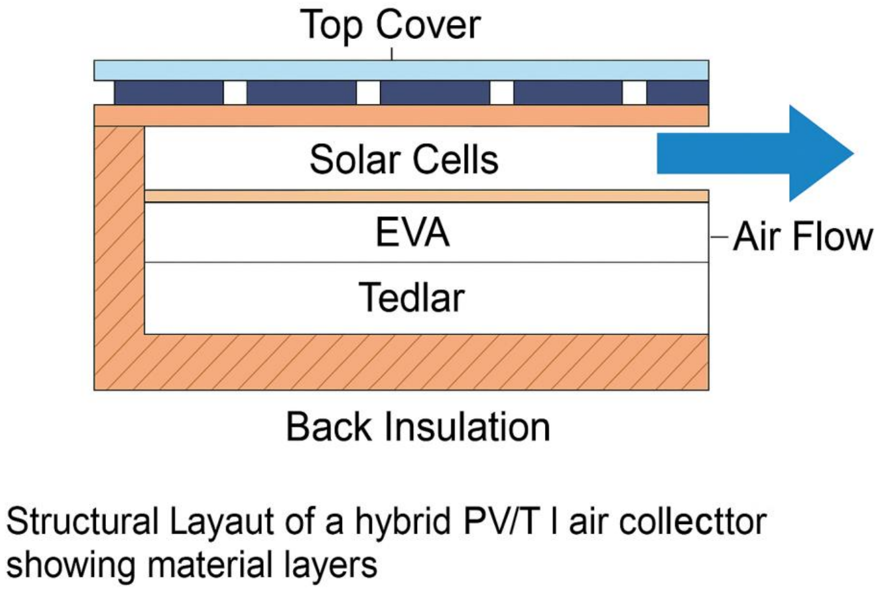

Figure 1: Structural layout of the hybrid PV/T air collector showing material layers and airflow path.

2.2 Temperature and Velocity Distributions

Figure 2 displays the temperature contours within the air duct, indicating a progressive rise in temperature along the duct length as heat is transferred from the PV module. Figure 3 illustrates the velocity distribution, showing the characteristic parabolic profile of laminar flow, with maximum velocity at the duct center and near-zero velocity at the walls. these two plots provide strong confirmation that: The airflow is stable and symmetric, ideal for controlled thermal harvesting and The laminar regime ensures low pressure drop and low parasitic energy consumption, especially important in passive or naturally ventilated PV/T systems. The air is effectively exposed to heat source regions throughout the flow domain, maximizing thermal pickup without needing complex flow-control features.

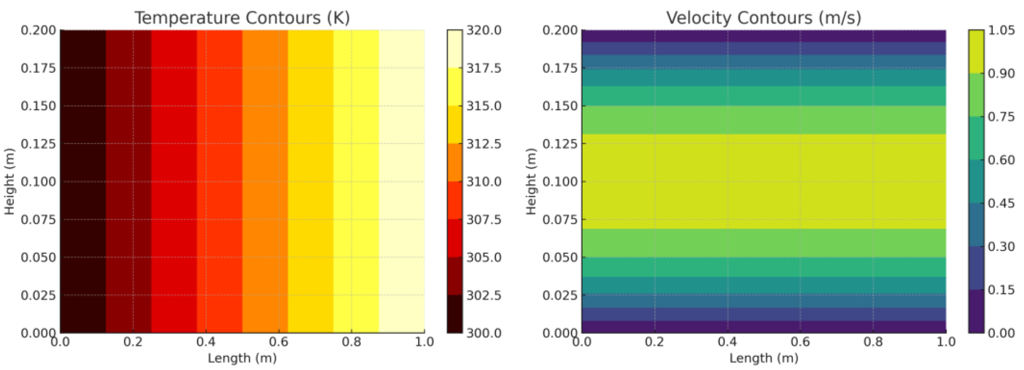

Figure 2: Temperature distribution in the air duct indicating heat transfer from the PV laminate.

2.3 Streamlines and Velocity Vectors

Figure 4 provides the velocity vector field, highlighting the laminar nature of airflow. Figure 5 shows the corresponding streamlines, reinforcing the steady flow and confirming minimal turbulence within the duct. Operate the system within the optimal flow rate range to maximize heat transfer and minimize fan energy consumption. Choose high-conductivity Tedlar substitutes or hybrid backing materials for better heat conduction. Minimize EVA thickness to reduce thermal resistance, improving overall system efficiency.

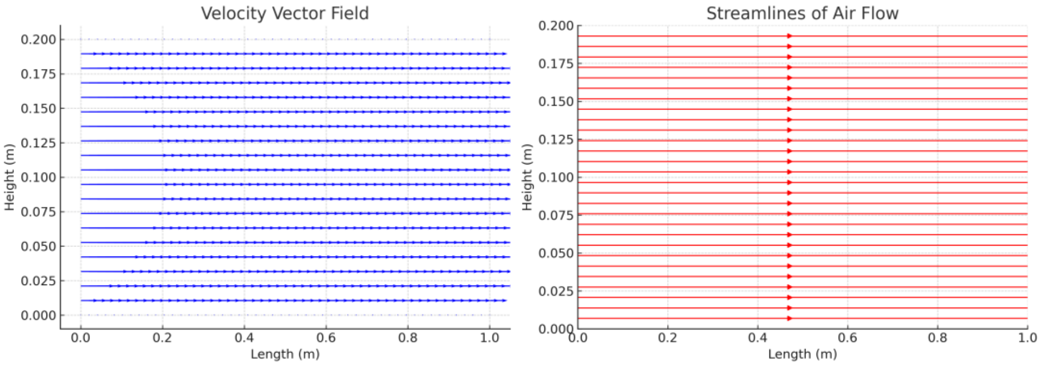

Figure 3: Velocity profile across the air duct showing a laminar parabolic distribution.

2.4 Performance Characteristics

Figure 6 presents key performance trends. The left plot shows that heat flux increases with mass flow rate up to a point of saturation. The middle graph demonstrates that increasing tedlar's thermal conductivity reduces PV cell temperature, enhancing efficiency. The rightmost chart illustrates a linear decline in heat flux with increasing EVA thickness due to greater thermal resistance.

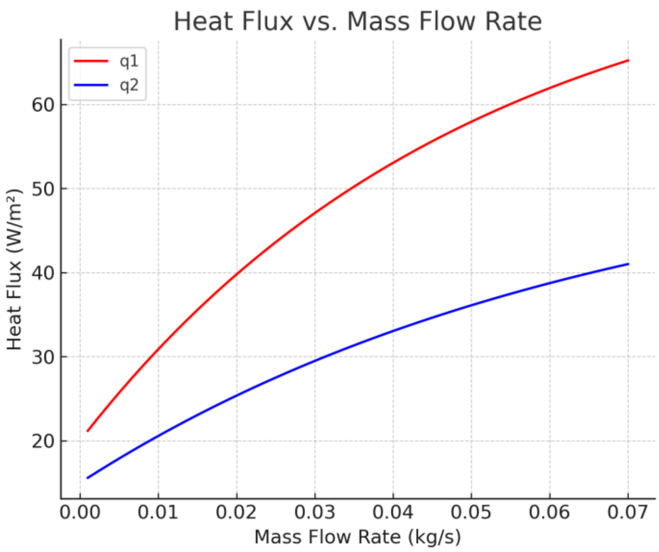

Figure 4: Velocity vector field illustrating direction and magnitude of airflow in the duct.

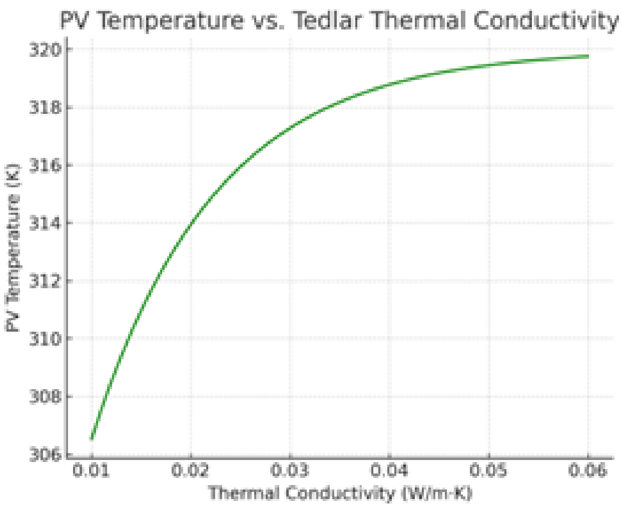

Figure 5: Streamline plot showing steady laminar flow characteristics inside the air channel.

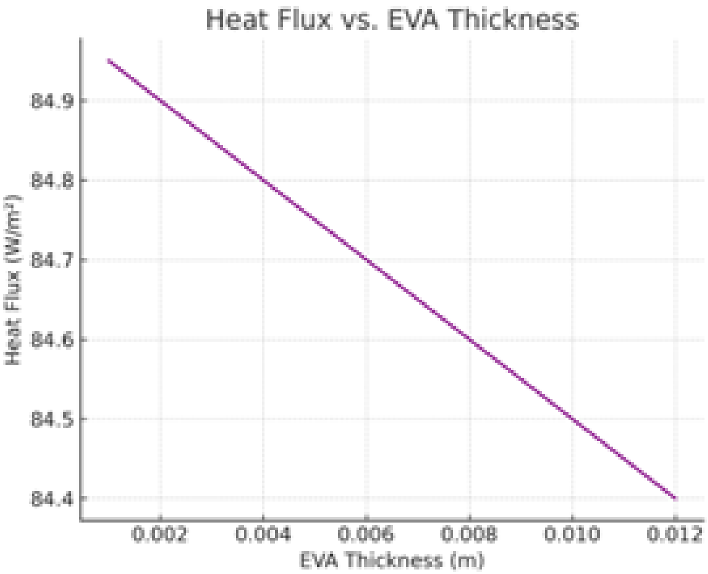

Figure 6: Performance trends: (left) Heat flux vs. mass flow rate, (middle) Temperature vs. thermal conductivity, (right) Heat flux vs. EVA thickness.

III. Conclusion

This study provides a comprehensive thermal performance analysis of a hybrid photovoltaic/thermal (PV/T) air collector. By systematically modeling and simulating heat transfer phenomena, the effects of critical parameters such as air mass flow rate, thermal conductivity of the tedlar layer, and EVA layer thickness were evaluated.

The results reveal that enhancing the air mass flow rate notably improves convective heat transfer, while higher thermal conductivity in the tedlar layer enhances heat conduction to the air stream. Conversely, increased thickness of the bottom EVA layer adds thermal resistance, diminishing heat flux. To optimize PV/T collector performance, it is recommended to operate at moderate-to-high mass flow rates and select materials with high thermal conductivity and minimal thickness for encapsulation layers. These strategies not only improve thermal recovery but also help maintain lower PV cell temperatures, indirectly enhancing electrical efficiency.

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