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SCIENTIFIC AND TECHNICAL REVIEW OF HEAT AND HYDRODYNAMIC PROCESS INTENSIFICATION IN SOLAR WATER AND AIR COLLECTORS

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Abstract. Hybrid water–air solar collectors (HSCs) enhance the performance of conventional flat-plate collectors by simultaneously utilizing water and air as heat transfer media. This study reviews recent developments in collector configurations and thermo-hydrodynamic enhancement techniques, including modified air channels, ribbed geometries, porous media, and optimized mass flow rates. The analyzed literature shows that combined air–water operation significantly improves thermal and exergetic efficiency compared to single-purpose collectors, with efficiencies exceeding 70% under optimal conditions. Additionally, the integration of HSCs into solar desalination systems has demonstrated promising freshwater productivity and improved overall thermal performance. The findings confirm that thermo-hydrodynamic intensification is essential for expanding the application range and energy efficiency of hybrid solar collectors in sustainable heating and desalination systems.

Keywords: hybrid renewable energy systems, residential buildings, energy efficiency, near-zero energy building, sustainable heating, energy storage.

At present, one of the most practical and reliable approaches to improving the efficiency of flat-plate solar collectors is the integration of water and air collectors into a combined system. The primary objective of merging two different solar energy technologies is to expand the range of applications and to increase the energy potential obtained per unit area occupied by the collector. A clear example of such a multi-purpose collector is the integration of photovoltaic technology with a solar thermal collector.

The hybrid water–air solar collector was developed as a solution for operation in cold climate regions. In such areas, when sufficient solar radiation is available, the system can provide domestic hot water at temperatures of 50–60°C, while during winter it can be used for preheating air up to approximately 30°C. This combined configuration significantly increases the annual solar energy yield and extends the operational period of the system. As a result, the economic performance of the hybrid unit is higher compared to conventional single-purpose water or air collectors.

Several configurations of hybrid solar collectors (HSCs) have been proposed based on the arrangement of water tubes and air flow channels. Assari et al. [1] developed a mathematical model of a water–air solar collector using the efficiency method. The model was experimentally validated, and three types of air channels were investigated to analyze the performance of the HSC: rectangular ribs, triangular ribs, and a smooth channel without ribs. According to the modeling results, the rectangular ribbed channel demonstrated superior performance characteristics compared to the other configurations.

Djafari et al. [2] conducted an energetic and exergetic analysis of an HSC with a triangular-shaped air channel. Their findings indicated that the hybrid collector exhibited significantly better energetic and exergetic performance compared to conventional single-purpose water or air collectors. Ma et al. [3] performed both theoretical and experimental investigations of an HSC with L-shaped ribs in the air channel and concluded that the air flow velocity is a key parameter influencing thermal efficiency. Subsequently, Mokhaddar et al. [4] reported similar findings.

Arun and Arun [5] investigated the application of porous media in hybrid solar collector (HSC) configurations and reported that the incorporation of porous materials enhanced the thermal efficiency of the collector. Nematollahi et al. [6] experimentally compared a conventional water solar collector with an HSC. The results indicated that the hybrid collector exhibited significantly higher efficiency. Venkatesh and Christraj [7] conducted an experimental investigation of an HSC and found that its performance was superior to that of a single-fluid solar collector. According to their findings, when the water mass flow rate in the solar water heater was 0.015 kg/s, the thermal efficiency reached 67.69%, whereas for the solar air heater, at an air mass flow rate of 0.0104 kg/s, the thermal efficiency was 85%. For the HSC, the thermal efficiency was approximately 70%.

Tabrizi et al. [8] designed and conducted both theoretical and experimental investigations of an HSC. Various tests were performed to determine outlet temperatures and thermal efficiencies under different operating conditions. The theoretical and experimental results showed good agreement. The authors identified optimal minimum mass flow rates that ensured maximum outlet temperature and efficiency. It was observed that a triangular air channel configuration increased collector efficiency and outlet air temperature by approximately 10% compared to conventional designs.

Considerable research interest has been directed toward HSCs. Ma et al. [9] modified the classical HSC configuration by redesigning the water flow tubes into a G-shaped geometry, thereby improving heat transfer to the air channel. According to their findings, the system was capable of heating 100 liters of water per day up to 30°C. The daily thermal efficiency was 50% for water heating and 52% for air heating.

In a subsequent study, Ma et al. [10] performed experimental and numerical investigations of a wall-mounted HSC under controlled and uncontrolled indoor temperature conditions. The results showed that during winter, indoor temperature increased by 3.34°C, and the collector provided 3.5 kWh of thermal energy to maintain an indoor temperature of 18°C. The daily thermal efficiency of the HSC was reported to be 44.3%.

Zhang et al. [11] conducted both experimental and theoretical studies on an HSC under three operating modes: air heating, water heating, and combined air–water heating. A mathematical model was developed to analyze the effect of working fluid mass flow rates in the first two modes. The thermal efficiencies for air heating and water heating modes were 51.3% and 51.4%, respectively, while in the combined mode the efficiency reached 73.4%. The study also demonstrated that the mass flow rate significantly influences outlet temperature and overall collector performance. The authors recommended optimal operating ranges of 0.02–0.25 kg/s for air and 0.06–0.08 kg/s for water to achieve higher efficiency.

Rajaseenivasan et al. [12] experimentally investigated the application of an HSC in a solar desalination system. During the experiments, the air flow rate varied between 50.4 and 64.8 kg/h, and the water flow rate ranged from 60 to 120 kg/h. The maximum freshwater productivity of the solar still was reported to be 14.14–15.23 kg/m² per day, with an overall thermal efficiency of approximately 68%.

The analysis of the reviewed literature indicates that hybrid solar collectors enable simultaneous production of hot water and heated air. Furthermore, integrating HSCs with other thermal systems can significantly enhance overall system efficiency and operational performance.

Conclusion The conducted scientific and technical analysis demonstrates that hybrid water–air solar collectors (HSCs) exhibit higher energy conversion efficiency compared to conventional single-fluid collectors, enabling more effective utilization of absorbed solar heat flux. The simultaneous operation of air and water streams facilitates improved thermal distribution within the collector, reduces heat losses, and enhances the annual energy yield of the system.

The reviewed literature confirms that constructive and operational strategies aimed at thermo-hydrodynamic intensification — including ribbed and porous absorber surfaces, triangular and L-shaped air channels, optimization of flow velocity and mass flow rates, and modification of tube geometry — lead to increased Nusselt numbers and enhanced convective heat transfer. Consequently, both thermal and exergetic efficiencies of the collector are significantly improved, with performance exceeding 70% under optimal operating conditions.

Furthermore, the integration of HSCs into solar desalination systems contributes to the intensification of evaporation–condensation processes, thereby improving overall energy utilization and freshwater productivity. Therefore, thermo-hydrodynamic optimization approaches represent a strategically important research direction for advancing hybrid solar collector technologies in sustainable energy systems and solar-driven water supply applications.

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