International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 6 [June. 2025] PP: 298-300

Future Research Directions for Enhancing Solar Air Heater Performance

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Abstract: *Solar air heaters (SAHs) have gained significant traction as sustainable thermal energy systems, but many challenges still inhibit their full potential in real-world applications. This study presents an expanded and structured roadmap for next-generation research directions. The roadmap integrates advanced absorber geometries, innovative working fluids (e.g., nanofluids), turbulence enhancement devices, hybrid configurations, AI-driven optimization, and techno-economic frameworks. In addition to reviewing the current state of SAH technologies, the paper provides detailed discussions on methodology, physical mechanisms, potential industrial applications, and system limitations. The integrated strategies outlined herein are designed to significantly enhance SAH performance, paving the way for more efficient, intelligent, and adaptable solar thermal solutions.*
Keywords: *Solar air heater; Future research; Nanofluids; Hybrid systems; Artificial intelligence; Turbulence enhancement; CFD; PCM; Techno-economic analysis; AI control.*

Date of Submission: 14-06-2025 Date of acceptance: 29-06-2025

I. Introduction:

The accelerating demand for renewable heating systems has positioned SAHs as essential technologies for both residential and industrial sectors. Despite notable progress in geometry, material science, and control strategies, limitations persist in terms of thermal performance, energy losses, adaptability, and economic feasibility. An interdisciplinary research approach is now required to integrate advances in fluid mechanics, thermal modeling, materials, and artificial intelligence.

This paper expands upon previous studies, such as Rahman et al. (2016), which emphasized nanofluid effectiveness, and Sun et al. (2021), which discussed AI applications in thermal systems. The need to address unresolved design inefficiencies, ensure dynamic adaptability, and optimize life-cycle performance is more pressing than ever.

II. Research Framework and Methodology

A multi-tiered approach was adopted to define the roadmap:

- Review of over 100 publications (2010–2024).
- Classification of innovation areas based on impact potential.
- Identification of integration challenges and technology readiness levels.
- Proposal of experimental and simulation strategies for future studies.

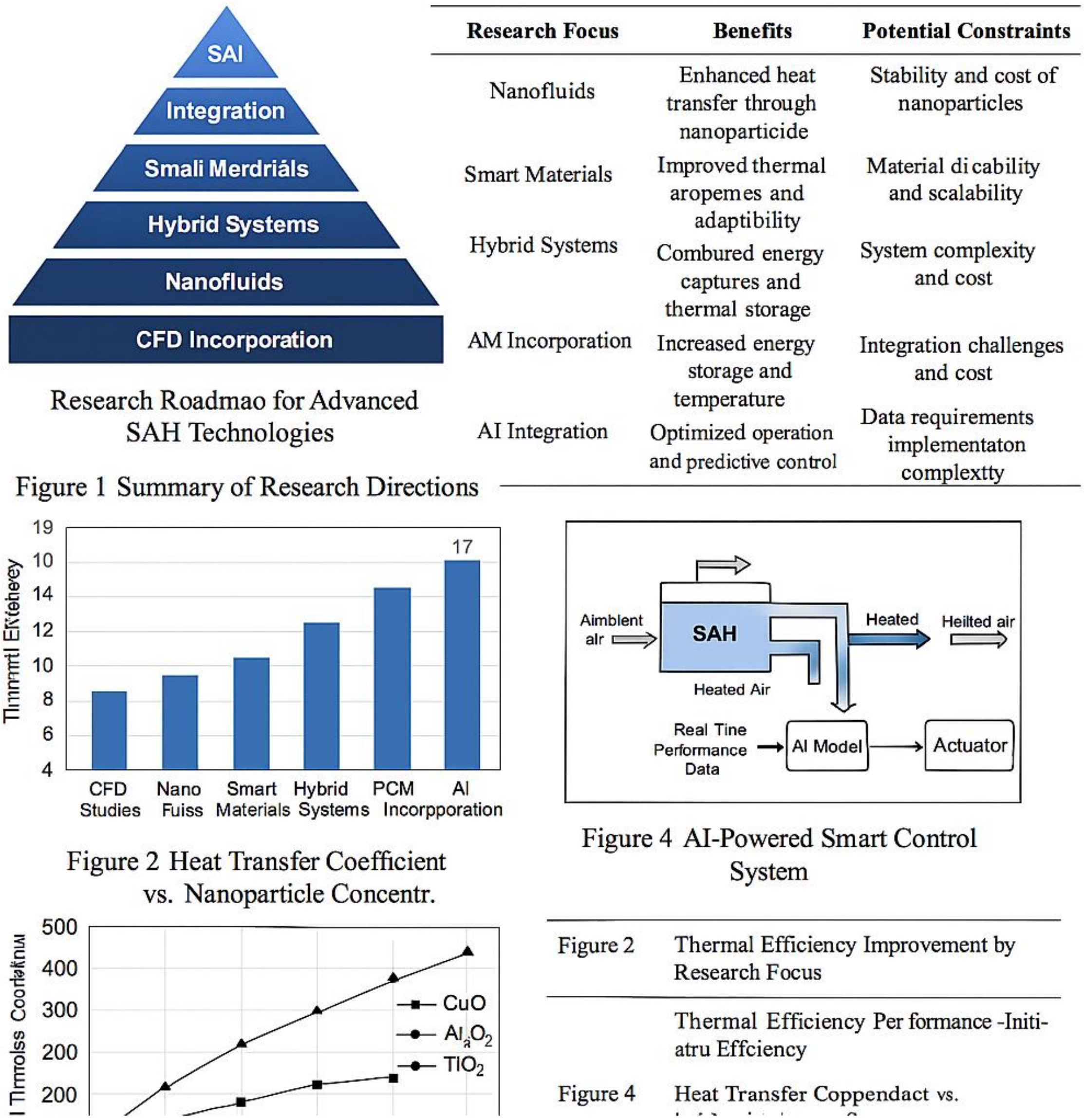

Figure 1: Hierarchical Structure of SAH Research Domains. Figure 1

III. Key Research Areas:

3.1 Advanced Absorber Geometries: Innovative surface designs significantly improve heat transfer and turbulence: - Biomimetic surfaces (e.g., shark-skin texture). - Fractal and hierarchical patterns. - V-groove and wavy designs for increased area and flow disturbance.

3.2 Working Fluid Innovations: - Nanofluids doped with Al2O3, CuO, or hybrid particles improve thermal conductivity and convective heat transfer. - Stability, dispersion uniformity, and long-term behavior must be studied. - Hybrid nanofluids combine materials for tailored thermal properties.

3.3 Turbulence Inducing Elements: - Use of ribs, dimples, and vortex generators. - Perforated baffles and twisted tape inserts. - Enhancement of internal mixing without significantly increasing pressure loss.

3.4 Alternative Flow Configurations: - Counterflow and multi-pass systems increase thermal contact time. - Z-shaped and double-pass flow designs enhance heat transfer.

3.5 Hybrid SAH Systems: - PV/T modules generate both thermal and electrical energy. - PCM layers stabilize thermal output and store excess energy. - Integration with desiccant wheels for air dehumidification.

3.6 High-Fidelity CFD and Experimental Validation: - Grid refinement and turbulence model optimization (e.g., SST k-ω). - Multi-climate simulations across seasonal variations. - Lab-scale testing with IR thermography and flow visualization.

3.7 Artificial Intelligence Applications: - Predictive modeling using machine learning (ML). - Neural networks for thermal performance forecasting. - Adaptive control systems based on weather and load inputs.

IV. Techno-Economic and Environmental Assessments:

Figure 2: Projected Efficiency Gains (%) vs. Research Focus Area. Figure 2
Figure 3: Impact of Nanofluids on Heat Transfer Coefficient (HTC). Figure 3
Figure 4: Smart Control System Feedback Loop in AI-Driven SAHs. Figure 4

Table 2: Sample Economic Analysis for Hybrid SAH Configurations.

Configuration	Initial Cost (USD/m²)	Thermal Efficiency (%)	Payback Period (years)	Carbon Savings (kg CO_2/year)
Standard Flat SAH	80	45	6.5	110
SAH + Nanofluids	120	62	5.2	145
SAH + PCM Layer	135	68	4.8	160
SAH + PV/T + AI Control	180	75	3.9	190

Table 1: Comparative Summary of Research Directions, Benefits, and Constraints.

Research Area	Benefit	Potential Constraint
Advanced Geometries	Improved heat transfer via flow disruption	Increased fabrication complexity
Nanofluids	Enhanced thermal conductivity	Stability and long-term dispersion
Turbulence Inducers	Greater mixing, better Nu number	Higher pressure drop
Alternative Flow Paths	Higher thermal contact time	Larger space requirements
Hybrid Systems (PV/T, PCM)	Combined outputs, better temperature control	Cost, integration complexity
CFD + Experimental Validation	Accurate predictions, design validation	High computational cost, time-consuming
AI Integration	Intelligent control, fault prediction	Data requirement, algorithm complexity

V. Assumptions and Limitations:

- Idealized simulations may neglect dust accumulation, fouling, and real-time degradation.
- Nanofluid models often assume single-phase homogeneity.
- PCM behavior may be oversimplified due to computational constraints.
- AI models require large datasets for reliable training.

VI. Conclusion:

This expanded roadmap articulates a multi-pronged strategy to elevate the performance, adaptability, and sustainability of solar air heaters. By leveraging developments in absorber design, hybrid integration, intelligent control, and thermal modeling, future SAH systems can offer higher efficiency and resilience across varied operating conditions.

Practical Recommendations:

- Use of hybrid nanofluids in high-sunlight regions to maximize gain.
- Deployment of AI-integrated SAHs for building HVAC control.
- Prioritization of modular, retrofittable designs for scalability.

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