



Numerical Simulation of Solar Air collectors: A Review

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Abstract: Solar air heaters have emerged as an efficient and sustainable solution for harnessing solar energy to meet heating requirements in various applications. This study presents a numerical simulation approach to analyze the performance and optimize the design parameters of a solar air heater. The simulation is based on computational fluid dynamics (CFD) techniques, enabling accurate modeling of the complex heat transfer phenomena occurring within the system. The numerical model incorporates the fundamental principles of fluid flow, heat transfer, and solar radiation absorption to predict the thermal performance of the solar air heater. The geometry of the air heater, including the absorber plate, duct design, and insulation materials, is discretized into a computational grid to solve the governing equations. The simulation accounts for factors such as solar radiation intensity, ambient temperature, airflow velocity, and inlet air properties to calculate the temperature distribution and heat transfer rates. By conducting a parametric study using the numerical model, various design parameters are investigated, including the dimensions of the duct, the inclination angle of the absorber plate, and the properties of the heat-absorbing materials. The simulation results provide insights into the impact of these parameters on the system's thermal efficiency, heat transfer performance, and overall energy output. Furthermore, optimization techniques such as genetic algorithms or response surface methodology are employed to identify the optimal configuration of the solar air heater. This optimization process aims to maximize the thermal efficiency and heat transfer rates while considering practical constraints such as cost and space limitations. The proposed numerical simulation serves as a powerful tool for engineers, researchers, and designers involved in the development and improvement of solar air heating systems. It enables a comprehensive evaluation of the system's performance under various operating conditions and facilitates the exploration of innovative design strategies to enhance energy efficiency and sustainability.

Keywords: Solar air heater, numerical simulation, computational fluid dynamics (CFD), heat transfer, optimization, thermal efficiency.

I. INTRODUCTION

Numerical simulation plays a crucial role in the design and analysis of solar air heaters (SAH), which are innovative devices used for harnessing solar energy to heat air. These devices are widely employed in various applications, including space heating, drying processes, and ventilation systems (Fudholi, Sopian, & Othman, 2013). Numerical simulation (NS) of SAH involves the application of computational methods and mathematical models to simulate the complex fluid flow, heat transfer, and energy conversion processes that occur within these systems. The NS method optimizes the performance of SAHs before constructing the physical prototypes, leading to cost and time savings. (Shukla, Buddhi, & Sharma 2016). The simulation process begins with the construction of a virtual model that represents the geometry and physical characteristics of the SAH. This model includes components such as the absorber plate, ducts, insulation materials, and glazing. The simulation software then applies the governing equations to the model, taking into account boundary conditions, solar radiation input, and the properties of the working fluid (Kayiem et al., 2012). By solving these equations iteratively over a defined time or spatial domain, the software predicts the behavior of the system under various operating conditions. The NS provides valuable insights into the performance of SAHs, allowing engineers to assess factors such as thermal efficiency, heat loss, and pressure drop. These simulations can aid in the design optimization of the system, enabling the selection of appropriate dimensions, materials, and operating parameters. Additionally, simulations can help in the identification of potential issues or inefficiencies, allowing for the implementation of improvements prior to the actual manufacturing and testing stages (Chen & Hu, 2016). Singh et al. (2018) carried out the numerical simulation and performance analysis of a SAH with V-shaped roughness elements. Investigates the effect of V-shaped roughness elements on the thermal performance of a SAH through numerical simulations using ANSYS Fluent. The SAH consisted of a rectangular duct with an absorber plate, glass cover, and insulation material. V-shaped roughness elements were placed on the absorber plate to enhance heat transfer.



1.1 Role of numerical simulation in solar air heater research

NS plays a crucial role in the design, optimization, and performance evaluation of SAHs and it can be summarized as follows (El-Sebaai et al., 2012):

- **Design Optimization:** It allows for the exploration and optimization of various design parameters and configurations. By modeling the fluid flow, heat transfer, and thermal performance of different designs, simulations can identify the most efficient geometry, materials, and operating conditions for SAH. This helps in maximizing heat transfer, reducing pressure drop, and improving overall system performance.
- **Performance prediction:** It provides accurate predictions of the performance of SAH under different operating conditions. By modeling the thermal behavior of the system, simulations can estimate important performance parameters such as outlet air temperature, thermal efficiency, heat transfer rates, and pressure drop. This information is crucial for assessing the effectiveness and suitability of solar air heaters for specific applications.
- **Visualization of flow and temperature distributions:** It enables the visualization of flow patterns, temperature distributions, and thermal stratification within SAH. This visual information helps in understanding the complex fluid dynamics and heat transfer phenomena occurring within the system. It allows for the identification of areas of high or low flow velocities, regions of heat accumulation or stagnation, and potential areas of heat loss or inefficiency.
- **Sensitivity analysis:** It facilitates sensitivity analysis by investigating the impact of various design parameters and operating conditions on system performance. By systematically varying parameters such as collector tilt angle, flow rate, absorber plate properties, and insulation thickness, simulations can identify the sensitivity of the system to these factors. This analysis helps in understanding the relative importance of different parameters and assists in design optimization.
- **Validation and verification:** It validates and verified against experimental data to ensure their accuracy and reliability. By comparing simulation results with experimental measurements, simulations can be validated for different solar air heater configurations and operating conditions.
- **Cost and time efficiency:** It offers a cost-effective and time-efficient approach compared to experimental testing. Instead of building and testing multiple physical prototypes, simulations allow for virtual testing and optimization of various design alternatives. This significantly reduces the cost and time required for design iterations and improvements.
- **Future development and innovation:** It provides a platform for exploring new ideas, innovative designs, and emerging technologies in SAH. It allows for the investigation of advanced concepts, such as nanofluids, phase change materials, and hybrid systems, by modeling their performance and potential benefits.

1.2 Mathematical Modeling

Mathematical modeling forms the foundation of numerical analysis in the study of SAH. It involves formulating the governing equations that describe the physical phenomena occurring within the system and it typically consists of the following key components (Fudholi, Sopian, & Othman, 2013):

Energy balance equations: The energy balance equations represent the conservation of energy within the SAH system. These equations account for the various heat transfer mechanisms, including conduction, convection, and radiation. The energy balance equations relate the energy inputs (solar radiation) and outputs (convective and radiative heat losses) to the temperature distribution within the system as shown in Fig. 1.

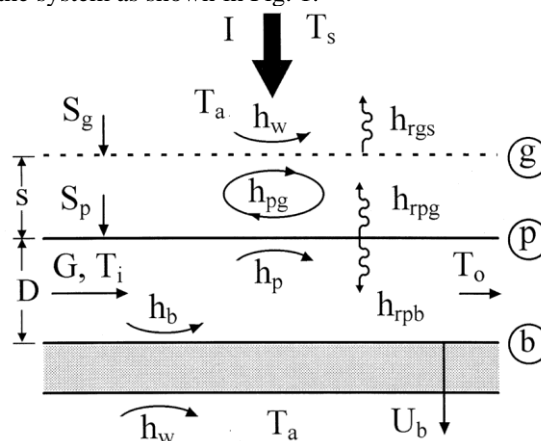


Fig. 1 Energy distribution (Fudholi, Sopian, & Othman, 2013).



- **Fluid flow equations:** The fluid flow equations describe the motion of the air within the SAH. The most commonly used equations are the Navier-Stokes equations, which represent the conservation of mass, momentum, and energy in the fluid flow. These equations capture the fluid flow behavior, velocity distribution, and pressure drop within the system.
- **Radiative heat transfer equations:** Radiative heat transfer plays a significant role in SAH due to the presence of solar radiation. The radiative heat transfer equations, such as the radiation heat transfer equation or the radiative transfer equation, describe the exchange of thermal radiation between surfaces and the absorption of solar radiation by the absorber plate as mentioned in Fig. 3. These equations account for factors such as surface emissivity, absorptivity, and reflection.
- **Turbulence modeling equations:** Turbulence is often present in the fluid flow within SAH. Turbulence modeling equations, such as the Reynolds-averaged Navier-Stokes (RANS) equations or large eddy simulation (LES) equations are used to capture the turbulent flow behavior. These equations incorporate additional terms to account for the effects of turbulent fluctuations in velocity and temperature.
- **Equation of state:** The equation of state relates the properties of the air, such as density, pressure, and temperature. Different equation-of-state models, such as the ideal gas law or more complex formulations, is used depending on the specific requirements of the simulation.
- **Boundary conditions:** Boundary conditions define the values of variables at the system boundaries. They include the solar radiation incident on the collector, inlet, and outlet conditions (such as mass flow rate and temperature), and boundary conditions for temperature and velocity at the surfaces of the SAH.
- **Material properties:** Material properties, such as thermal conductivity, specific heat capacity, and emissivity, are essential for accurately modeling heat transfer and energy conversion processes within the solar air heater. These properties are typically specified based on the materials used in the system, such as the absorber plate, insulation materials, and glazing.
- **Once the mathematical model is established, numerical methods such as finite volume method (FVM), finite element method (FEM), or finite difference method (FDM) are employed to discretize the governing equations and solve them numerically. These methods convert continuous mathematical equations into discrete equations that can be solved iteratively on a computational grid or mesh.**

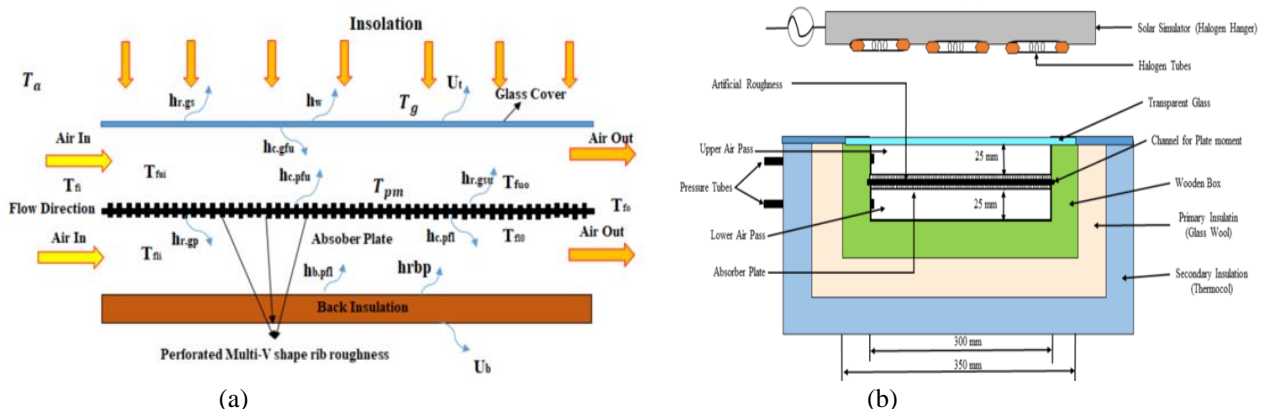


Fig. 3 Schematic of heat transfer (Khadrawi and Muzychka, 2013)

1.3. Boundary Conditions and Input Parameters

Boundary conditions and input parameters are essential components of numerical analysis in the study of SAH. They define the values of variables at the boundaries of the computational domain and provide information about the operating conditions and system characteristics. The following are the key boundary conditions and input parameters typically considered in the numerical analysis of SAH (Khalifa & Yilbas, 2017).

- **Solar radiation:** The incident solar radiation is a crucial input parameter in SAH simulations. It defines the intensity and distribution of solar radiation incidents on the absorber plate as presented in Fig. 4.



- **Inlet boundary conditions:** The inlet boundary conditions specify the properties of the incoming air entering the SAH. This includes the mass flow rate, temperature, and composition (if applicable) of the inlet air. The mass flow rate can be determined based on the desired flow rate or obtained from experimental measurements or simulations.
- **Outlet boundary conditions:** The outlet boundary conditions define the properties of the air leaving the SAH. These conditions typically include the outlet temperature, pressure, and velocity. The outlet temperature can be prescribed based on the desired outlet air temperature or obtained from experimental measurements or simulations.
- **Wall boundary conditions:** The wall boundary conditions specify the properties of the surfaces within the SAH. These conditions include the temperature, heat transfer coefficients, and thermal properties (such as conductivity and emissivity) of the absorber plate, glazing, insulation materials, and other components. The heat transfer coefficients can be estimated based on correlations or obtained from experimental data.
- **Ambient conditions:** Ambient conditions represent the environmental conditions surrounding the SAH. These conditions include the ambient temperature, wind speed, and solar radiation incident on the surroundings. They influence the convective heat transfer from the SAH surfaces and can be obtained from weather data or measurements.
- **Geometry and dimensions:** The geometric parameters and dimensions of the SAH are important input parameters. These include the dimensions of the absorber plate, channel dimensions, spacing between channels, and overall dimensions of the system. The geometry can be defined based on the specific design and configuration of the SAH.
- **Material properties:** Material properties, such as thermal conductivity, specific heat capacity, density, and emissivity, are input parameters that describe the thermal behavior of the materials used in the SAH.
- **Time step and simulation duration:** The time step and simulation duration are important input parameters in transient simulations. The time step determines the temporal resolution of the simulation, and the simulation duration determines the length of time for which the simulation is run.

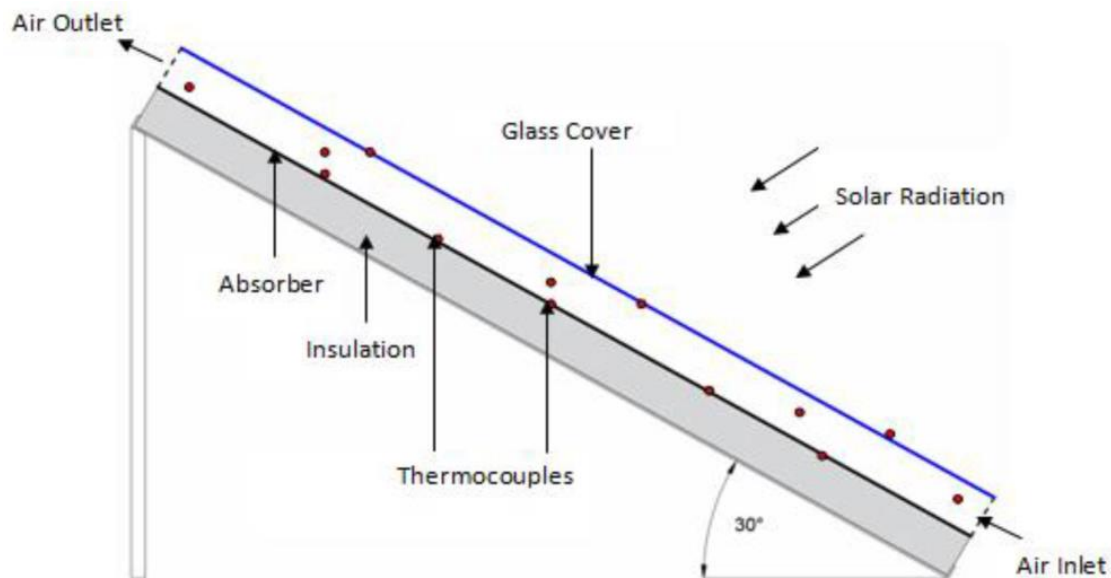


Fig. 4 Schematic of incident solar radiation (Kumar & Mullick, 2017)

1.4 Validation Techniques

Validation techniques are used to assess the accuracy and reliability of numerical simulations of SAH by comparing the simulation results with experimental data or analytical solutions. These techniques help validate the numerical model and ensure that it accurately captures the physical behavior of the system (Mathur & Tiwari, 2015). The following are common validation techniques used in NS of SAH:

- **Experimental data comparison:** One of the most straightforward validation techniques is comparing the simulation results with experimental data obtained from physical testing of a SAH. This involves measuring relevant



parameters such as outlet air temperature, heat transfer rates, pressure drop, and thermal efficiency in an experimental setup and comparing them with the corresponding values predicted by the NS.

- Analytical solutions: It exist for specific configurations of SAH. These analytical solutions are derived based on assumptions and simplifications but provide a benchmark for validating the numerical simulation results. By comparing the simulation results with analytical solutions, discrepancies can be identified, and any necessary adjustments or refinements can be made to the numerical model.
- Grid convergence study: It involves performing simulations with different grid sizes to assess the sensitivity of the results to the grid resolution. By systematically refining the computational grid and comparing the results, one can determine if the solution has converged and if further grid refinement is necessary. Grid convergence studies help ensure that the numerical simulation is not significantly affected by the grid resolution and provide confidence in the accuracy of the results.
- Sensitivity analysis: It involves varying input parameters or system conditions within a reasonable range to evaluate their impact on the simulation results. By systematically changing parameters such as solar radiation intensity, ambient temperature, flow rate, or material properties, the sensitivity of the simulation results can be assessed. Sensitivity analysis helps identify the most influential parameters and their impact on the system performance, and it provides insights into the robustness of the simulation model.

1.5. Optimization Strategies

Optimization strategies in numerical simulation of solar air heaters aim to improve the system's performance and efficiency by finding the optimal design and operating conditions. These strategies utilize mathematical optimization algorithms to search for the best configuration that maximizes desired objectives or minimizes certain constraints. The following are common optimization strategies employed in numerical simulation of SAH (Naphon, 2016):

- Design parameter optimization: It include dimensions, geometries, materials, and other characteristics of the system. By varying these parameters within defined ranges, numerical simulations coupled with optimization algorithms, such as genetic algorithms, particle swarm optimization, or simulated annealing, can be used to find the combination that yields the best performance in terms of parameters like outlet air temperature, thermal efficiency, or heat transfer rate.
- Flow optimization: It focuses on optimizing the flow characteristics within the SAH. This includes optimizing the inlet/outlet configurations, duct geometries, flow rates, and distribution within the system. By simulating different flow scenarios and using optimization algorithms, the flow patterns that minimize pressure drop, enhance heat transfer, and ensure uniform temperature distribution can be identified.
- Material selection and optimization: It involves selecting or optimizing the properties of the materials used in the SAH. This can include selecting materials with higher thermal conductivity or specific heat capacity to enhance heat transfer, optimizing surface coatings with high absorptivity and low emissivity for the absorber plate, or choosing suitable insulation materials to minimize heat loss.
- Multi-objective optimization: It considers multiple conflicting objectives simultaneously. It may include maximizing thermal efficiency, minimizing pressure drop, and reducing material cost of SAH.
- Sensitivity analysis and optimization: It identifies the parameters that significantly influence the performance of the SAH. By conducting sensitivity analyses, the most influential parameters can be identified. Subsequently, optimization strategies can be applied to these parameters to find the optimal values that maximize performance or minimize certain constraints.
- Control strategy optimization: Control strategy optimization involves optimizing the control parameters or strategies of the solar air heater system. This can include optimizing the tracking algorithm for solar radiation, control of flow rate or temperature set-points, or optimizing the operation schedule to match energy demand.

II. MODELLING METHODS

2.1 CFD (Computational Fluid Dynamics) analysis is a powerful tool for studying the fluid flow and heat transfer characteristics of various systems, including SAH. By using NS, CFD allows engineers and researchers to analyze and optimize the design and performance of SAH without the need for costly and time-consuming physical prototypes as shown in Fig.5 (Nejat, Jomehzadeh & Taheri, 2016).

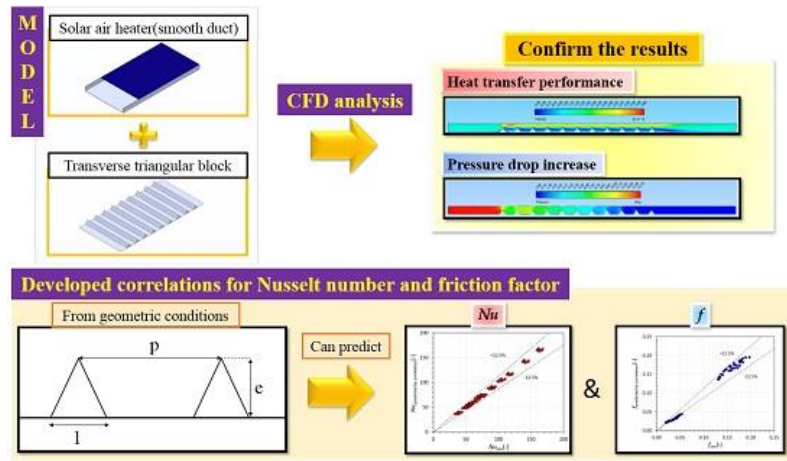


Fig. 6 CFD Modelling (Nejat, Jomehzadeh & Taheri, 2016).

To perform a CFD analysis of a SAH following steps are followed:

1. **Geometry creation:** A 3D model of the SAH geometry using CAD (Computer-Aided Design) software or a dedicated CFD pre-processing tool is created. The model should include all the relevant components, such as the absorber plate, transparent cover, ducts, and inlet/outlet openings.
2. **Mesh generation:** Divide the geometry into a mesh of small control volumes or cells. The mesh quality and resolution are critical for accurate results. Use meshing software or the CFD software's built-in meshing capabilities to generate a structured or unstructured mesh.
3. **Boundary conditions:** Define the boundary conditions for the simulation. Specify the fluid properties, such as air density, viscosity, and specific heat. Set the inlet boundary conditions, such as the air velocity, temperature, and composition. Define the outlet conditions, which can be either fixed values or pressure-driven.
4. **Physics modeling:** Select the appropriate physical models to represent the fluid flow and heat transfer phenomena in the solar air heater. These may include models for turbulence, radiation, conduction, and convection. The selection of models depends on the specific characteristics of the solar air heater being analyzed.
5. **Solver setup:** Configure the solver settings, such as the numerical schemes, convergence criteria, and time step (for transient simulations). The choice of solver depends on the CFD software being used. Common solvers include finite volume, finite element, or finite difference methods.
6. **Simulation execution:** Run the simulation and monitor its progress. Depending on the complexity of the model and the available computational resources, the simulation may take several hours or even days to complete. During the simulation, the software will solve the governing equations iteratively until convergence is achieved.
7. **Post-processing:** Once the simulation is complete, analyze the results using post-processing tools provided by the CFD software. Generate visualizations of variables such as temperature, velocity, pressure, and heat flux distributions. Calculate performance metrics, such as heat transfer efficiency, pressure drop, and temperature rise.
8. **Validation and optimization:** Compare the simulation results with available experimental data or analytical solutions to validate the accuracy of the CFD model. If discrepancies exist, refine the model or adjust the boundary conditions accordingly. Use the validated model to perform optimization studies, exploring different design parameters to improve the performance of the solar air heater.

2.1 Performance Effect

Numerical simulations of SAH can provide valuable insights into their performance. By analyzing various parameters and variables, these simulations can help evaluate and optimize the efficiency and effectiveness of solar air heaters. Here are some of the performance effects that can be studied through numerical simulations (Yadav, Saini, & Varun, 2015):

1. **Heat transfer efficiency:** Numerical simulations can determine the heat transfer characteristics of the SAH, such as the temperature distribution on the absorber plate and the convective heat transfer coefficient. This information helps assess how effectively the SAH transfers heat from the absorber plate to the airflow.
2. **Thermal losses:** Simulations can identify and quantify thermal losses in a SAH, including conduction through the components, radiation losses, and convective losses to the surroundings. Understanding these losses enables engineers to optimize the design and reduce energy wastage.



3. **Flow distribution:** Simulations allow for the analysis of airflow distribution within the SAH. This helps determine if there are any areas of low velocity or recirculation zones that may hinder heat transfer or cause inefficiencies. Optimizing the flow distribution can lead to more uniform heat transfer and improved performance.
4. **Pressure drop:** Numerical simulations can evaluate the pressure drop across the solar air heater, providing insights into the resistance encountered by the airflow as it passes through the system. Minimizing pressure drop is crucial to maintain a sufficient airflow rate and reduce the energy required for air movement.
5. **Optimal design parameters:** Through parametric studies and optimization techniques, numerical simulations can assess the impact of various design parameters on the solar air heater's performance. These parameters include the size and shape of the absorber plate, the inclination angle, the spacing between fins, and the dimensions of the ducts. By optimizing these parameters, engineers can enhance the overall efficiency of the SAH.
6. **Transient behavior:** Numerical simulations can also capture the transient behavior of SAH, considering changes in solar radiation, ambient temperature, and airflow rate over time. This enables the analysis of the system's response under different operating conditions and helps identify dynamic performance characteristics.
7. **Comparison and validation:** Numerical simulations can be used to compare different SAH designs or configurations, allowing engineers to evaluate the performance of various options before physical prototyping. Simulations can also be validated against experimental data to ensure the accuracy and reliability of the numerical models. By studying these performance effects through numerical simulations, engineers can gain insights into the behavior of solar air heaters and make informed decisions to optimize their design, maximize heat transfer efficiency, minimize energy losses, and improve overall performance.

III. SCOPE FOR FUTURE PERSPECTIVES

Numerical simulation of solar air heaters offers valuable insights into their performance, design optimization, and operational characteristics. However, several challenges and future perspectives exist in this field. Here are some key challenges and potential future directions:

- **Model Validation:** Ensuring accurate validation of numerical models is crucial for reliable simulations. Obtaining comprehensive experimental data for validation can be challenging due to complex heat transfer phenomena, uncertainties in material properties, and variations in environmental conditions. Future research should focus on developing more comprehensive experimental data sets for model validation to enhance the reliability of numerical simulations.
- **Complexity of Physical Phenomena:** Solar air heaters involve complex heat transfer mechanisms, including radiation, convection, and conduction, coupled with fluid flow dynamics. Capturing all these phenomena accurately in numerical models can be challenging. Future research should aim to develop more sophisticated numerical models that can account for these complexities and provide a more accurate representation of the physical behavior of solar air heaters.
- **Uncertainties in Input Parameters:** Accurate determination of input parameters, such as solar radiation data, ambient temperature, and wind conditions, is crucial for reliable simulations. However, uncertainties in these parameters can significantly affect the accuracy of the results. Future research should focus on improving the accuracy of input parameter measurements and developing techniques to account for uncertainties in numerical simulations.
- **Computational Efficiency:** Numerical simulations of solar air heaters often require significant computational resources and time, particularly for complex geometries and detailed modeling of heat transfer processes. Enhancing computational efficiency through algorithmic improvements, parallel computing techniques, and model simplification methods will enable faster and more practical simulations, making them more accessible to researchers and engineers.
- **Integration with System-Level Simulations:** Solar air heaters are typically part of larger energy systems, such as solar thermal systems or building HVAC systems. Integrating the numerical simulation of solar air heaters with system-level simulations will provide a more comprehensive understanding of the overall system performance, energy interactions, and potential optimization strategies. Future research should focus on developing integrated simulation platforms that can model and optimize the interactions between solar air heaters and other system components.
- **Optimization under Dynamic Conditions:** Most numerical simulations of solar air heaters assume steady-state conditions. However, in real-world applications, solar radiation, ambient temperature, and airflow conditions are dynamic and vary over time. Future research should explore the optimization of solar air heaters under dynamic operating conditions to account for transient behavior, control strategies, and response to changing environmental conditions.
- **Advanced Materials and Designs:** The development of advanced materials, such as nanostructured surfaces, selective coatings, and phase change materials, opens up new possibilities for improving the performance of solar air heaters. Numerical simulations can aid in the design and optimization of these advanced materials and novel geometries to enhance heat transfer, increase energy capture, and improve system efficiency.



- **Sustainability and Environmental Impact:** Future perspectives in numerical simulation of solar air heaters should also focus on evaluating and optimizing the sustainability and environmental impact of these systems. Simulations can be used to assess the life cycle analysis, energy payback time, and carbon footprint of solar air heaters, helping identify areas for improvement and sustainable design practices.

IV. CONCLUSIONS

Numerical simulation plays a critical role in the design and optimization of solar air heaters, providing valuable insights into their performance and aiding in the development of more efficient and reliable systems. By simulating fluid flow, heat transfer, and radiation within the solar air heater, engineers and researchers can assess the system's behavior under various operating conditions and make informed design decisions. The accuracy and reliability of numerical simulations have significantly improved over time, thanks to advancements in computational power and modeling techniques. High-fidelity modeling allows for the inclusion of finer details and complexities in the simulation, resulting in more accurate predictions. Techniques such as computational fluid dynamics (CFD) and advanced radiation models enable a deeper understanding of the fluid flow patterns, heat transfer mechanisms, and the influence of solar radiation on the system. The future of numerical simulation in solar air heaters looks promising. One of the key trends is the integration of multi-scale modeling techniques, which will enable the representation of phenomena at different length scales.

This will facilitate a more comprehensive understanding of the system's behavior, considering micro scale effects, such as particle behavior within the absorber material or local heat transfer variations. Another important aspect is the incorporation of machine learning and artificial intelligence techniques. These approaches can be employed to optimize system design parameters, predict performance, and reduce computational costs. Machine learning algorithms can assist in identifying patterns and relationships within simulation data, enabling more efficient and accurate predictions. Additionally, artificial intelligence algorithms can automate model calibration, improving the reliability of the simulation results. The integration of real-time monitoring and control systems with numerical simulation is another exciting prospect. This integration allows for continuous monitoring of the system's performance and the adjustment of operating parameters in real-time. By coupling simulation models with sensor data and control algorithms, it becomes possible to optimize system operation, maximize energy utilization, and identify potential issues before they occur. Furthermore, the assessment of environmental impact is gaining importance in the field of numerical simulation for solar air heaters. Evaluating the carbon footprint, life cycle analysis, and sustainability of the system will help in making environmentally conscious decisions and promoting the adoption of renewable energy technologies.

In summary, numerical simulation has proven to be an invaluable tool for designing and optimizing solar air heaters. With ongoing advancements in computational power, modeling techniques, and integration with emerging technologies, simulations will become even more accurate, efficient, and versatile. These advancements will contribute to the wider adoption of solar air heaters, fostering sustainable energy practices, reducing environmental impact, and driving the transition to a cleaner and more sustainable future.

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