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Experimental and Simulation Analysis of Single-Pass Solar Air Collector Performance

QUANKUN ZHU[1], JANOS BUZAS[2], ISTVAN FARKAS[3]

[1]Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, Hungary
[2]Institute of Technology, Hungarian University of Agriculture and Life Sciences, Hungary
Email: zhu.quankun@phd.uni-mate.hu

ABSTRACT

The solar air collector is a key technology for utilizing solar energy, and many studies focus on improving its efficiency to enhance overall solar energy utilization. This study investigates the thermal performance of a single-channel solar air collector through both experimental and simulation methods, aiming to identify ways to enhance its performance. The Multiphysics software is used to model and evaluate the collector's performance. Computational fluid dynamics (CFD) techniques are applied to simulate heat transfer in both solid and fluid regions, as well as the laminar flow field. The results indicate that the maximum absorber plate temperature of the solar air collector reached 87.8 °C, and the maximum outlet temperature was 52 °C during the experiments. The simulation results show good agreement with the experimental data, with the percentage error within 8.2%, which is considered acceptable.

Keywords: computational fluid dynamics, COMSOL software, thermal efficiency, solar air collector

ABSTRAK

Kolektor surya pemanas udara (kolektur udara surya) merupakan teknologi penting dalam pemanfaatan energi surya, dan berbagai studi umumnya fokus pada peningkatan efisiensinya sebagai representasi meningkatnya pemanfaatan energi surya secara keseluruhan. Studi ini menyelidiki kinerja termal kolektor udara surya saluran tunggal melalui metoda eksperimental dan simulasi, sebagai identifikasi untuk meningkatkan kinerjanya. Perangkat lunak Multiphysics digunakan untuk memodelkan dan mengevaluasi kinerja kolektor. Teknik Komputasi Dinamika Fluida diterapkan untuk mensimulasikan perpindahan panas pada bagian padat (plat) dan fluida, serta medan aliran laminar. Hasil penelitian menunjukkan bahwa suhu pelat penyerap tertinggi yang tercatat dalam eksperimen kolektor udara surya mencapai 87,8 °C, dengan suhu keluaran maksimum 52 °C. Hasil simulasi menunjukkan konsistensi yang wajar dengan data eksperimental, dengan persentase kesalahan dalam kisaran 8,2%, yang dianggap dapat diterima.

***Kata kunci**: Teknik Komputasi Dinamika Fluida, perangkat lunak COMSOL, efisiensi termal, kolektor udara surya*

1. INTRODUCTION

With the continuous depletion of conventional energy sources, solar energy, as a renewable alternative, has garnered significant attention in both research and application. Solar air collector is a device that harnesses solar energy and converts it into heat. It typically consists of a transparent cover, an absorber plate, an air channel, and an insulation layer. With its energy-saving, eco-friendly, and pollution-free advantages, it is widely used in agricultural drying, building heating, and industrial preheating applications **(Chakraborty and Nath, 2025).** The primary challenge faced by solar air collectors is their relatively low efficiency. Consequently, numerous studies have focused on various types of air collectors, evaluating their performance differences.

Karwa and Maheshwari (2009) compared the heat transfer performance of fully perforated and semi-perforated rectangular baffle ducts. Their findings revealed that, compared to the Nusselt number of a smooth duct, the fully perforated baffle increased heat transfer by 79–169%, while the semi-perforated baffle resulted in an even greater enhancement of 133–274%. **Alam et al. (2014)** investigated the effect of geometric parameters of V-shaped perforated blocks on the heat transfer performance of rectangular ducts. Experimental results showed that, compared to solid blocks, V-shaped perforations increased the Nusselt number by an average of 33% and improved the thermohydraulic performance by 50%. Furthermore, when compared to a smooth duct, the Nusselt number of the V-shaped perforated blocks was enhanced by up to 6.76 times. **Sharma et al. (2017)** found that, under optimal parameter settings, the use of discrete V-shaped obstacles significantly enhanced performance compared to an unobstructed configuration. Specifically, thermal efficiency increased by 4.2 to 6.2 times, hydraulic efficiency improved by 5.9 to 8.4 times, and collector efficiency was boosted by 1.23 to 1.47 times. **Abhay et al. (2018)** conducted a simulation study on the airflow and heat transfer characteristics inside a solar air collector with roughened square ribs. Compared to a smooth duct, the heat transfer coefficient and friction factor (fr) increased by 2.13 times and 3.54 times, respectively. Additionally, the average Nusselt number (Nu) of the roughened plate improved from 37.84% to 112.85%.

Bahrehmand and Ameri (2015) conducted an experimental study on the energy and exergy efficiency of solar air collectors with rectangular and triangular longitudinal fins. The results indicated that the triangular fin collector exhibited higher energy efficiency compared to the rectangular fin collector. **Arul Kumar et al. (2016)** investigated the thermodynamic performance of solar air collectors with two different configurations: a flat plate absorber and a finned plate absorber. The study revealed that, compared to the flat plate absorber, the finned plate absorber increased the outlet air temperature by 2–5°C and improved thermal efficiency by 3–35%. **Mojumder et al. (2016)** introduced a thin rectangular fin-type single-pass PV/T air collector system. At a mass flow rate of 0.14 kg/s, the highest thermal efficiency with four fins reached 56.19%, representing an 18.37% improvement compared to a collector without fins. **Bhattacharyya et al. (2017)** investigated the performance of finned-plate solar air heaters. The optimal design parameters were found to be 80 fins, a high aspect ratio of 0.6, and a fin thickness of 2 mm, under which the solar air heater achieved its best performance. **Fan et al. (2017)** developed a dynamic model to investigate the system performance of a hybrid photovoltaic-thermal (PVT) solar air heater with longitudinal fins. The dynamic model provided a more accurate assessment of the system's thermal performance, with the model results showing a high level of consistency with the measured data, as indicated by the RMSD values.

Aboghrara et al. (2017) compared the performance of corrugated and flat plate absorbers under jet impingement at different air velocities and solar radiation levels. The study found that, compared to smooth surface absorbers, the corrugated plate absorber system achieved an approximately 14% increase in average thermal efficiency. **Zheng et al. (2017)** used a mathematical model to study the thermal efficiency of a novel metal corrugated packing solar air collector (MCPSAC) and compared it with unglazed evaporative, glazed evaporative, and iron filings-filled solar collectors. The results indicated that MCPSAC featured a large heat transfer area and a high heat transfer coefficient, with thermal efficiency ranging from 47% to 66%. **Poongavanam et al. (2018)** conducted a comparative study on the thermal performance of conventional solar air heaters and V-shaped corrugated SAH. Experimental results indicated that, compared to conventional absorber plates, shot-peened V-shaped corrugated absorber plates facilitated better airflow beneath the plate and exhibited higher Nusselt number values. **Abdullah et al. (2018)** investigated the performance of a novel dual-pass solar air heater (DPSAH) utilizing aluminum cans as turbulence promoters. The results showed that at a mass flow rate of 0.05 kg/s, the alternating DPSAH configuration achieved a maximum daily efficiency of 68%.

Solar air collectors are essential tools for harnessing solar energy. Single-pass solar air collectors have a simple structure and low cost, and are widely used in applications such as solar drying and building heating. However, their thermal efficiency is generally low, which limits their practical performance. Therefore, it is necessary to carry out systematic simulation and analytical studies on single-channel solar air collectors to identify the key influencing factors and evaluate their thermal performance. This article investigates the performance of a single-channel solar air collector through experiments and COMSOL simulations. By comparing experimental results with simulation results, this study analyzes the relevant performance characteristics of the solar air collector.

2. METHODS

The experiment in this study were conducted at the Solar Energy Laboratory of the Hungarian University of Agriculture and Life Sciences (MATE) in Gödöllő, Hungary. The solar air collector used in the experiments consists of a transparent cover, an absorber plate, an air channel, and an insulation layer, as shown in Fig. 1. The experiments were conducted under clear weather conditions from 10 a.m. to 3 p.m. Relevant instruments were used to record the experimental data.

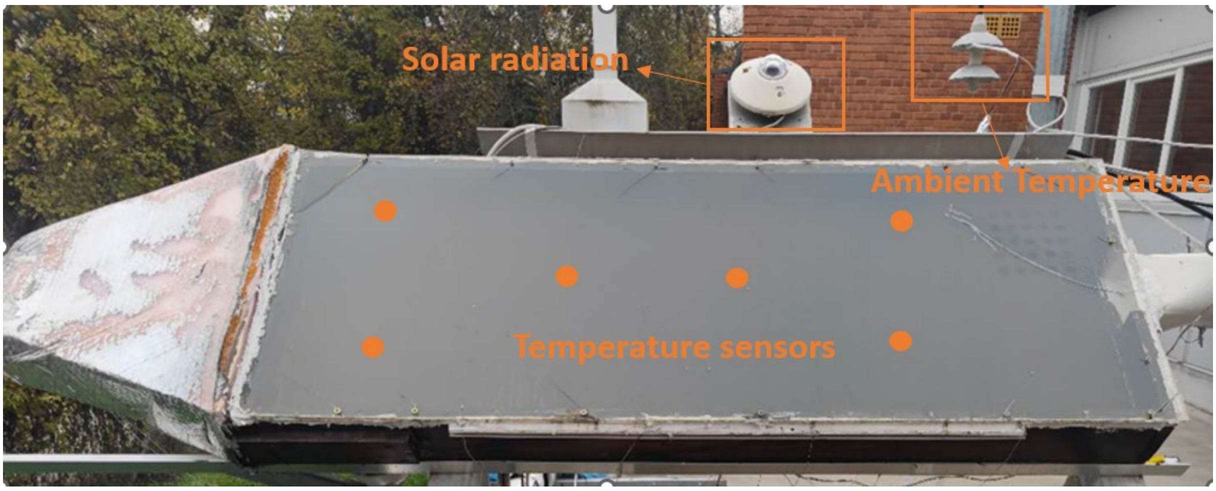

Figure 1. Solar air collector for the experiment

Table 1 presents the measurement instruments used in the experiments and their specifications. The instruments were mainly used to collect data on temperature, solar radiation intensity, and pressure difference during the experiments. The instruments were connected to a computer system to store the relevant experimental data for subsequent analysis.

Table 1. Specification of the measurement instruments

Instruments	Type	Accuracy
Thermocouples	T-type	±0.5 °C
Pyranometer	Kipp & Zonen CM11	<0.6%
Data logger	Advantech ADAM 4017	±0.1%
Differential pressure sensor	SENSIRION SDP-810	±3%

The solar air collector was modeled in 3D using COMSOL Multiphysics software, as shown in the Fig. 2. During simulation, the quality of mesh generation plays a crucial role in influencing the results. High-quality mesh generation facilitates the convergence of simulation results. In this paper, using the finer method for mesh the single pass solar air collector, the number of elements is 3597437, minimum element quality is 0.1026 and the average element quality is 0.6709. A part of meshing of the single pass solar air collector shown Fig. 3.

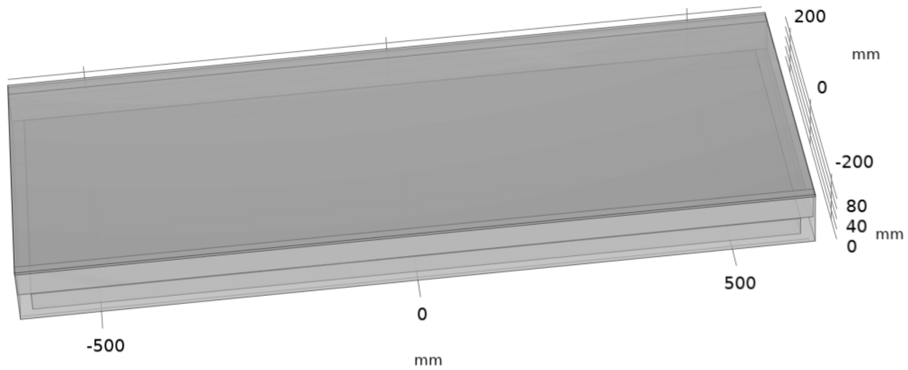

Figure 2. The solar air collector model in comsol software

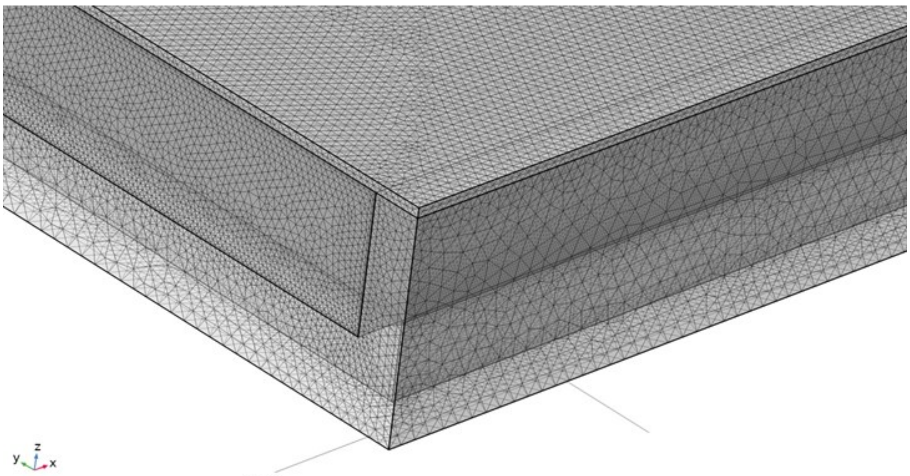

Figure 3. A part of meshing of the single pass solar air collector

In a solar air collector, ambient air enters the collector and gets heated by the absorber plate, which absorbs solar radiation. This process is governed by air temperature changes, airflow behavior, and heat transfer principles. The flow regime of gas in the collector can be determined based on the Reynolds number (Re). When Re < 2300, the gas flow is laminar, when Re > 6000, it is turbulent. Flow between these two ranges is transitional. The specific calculation formula is as follows:

$$Re = \frac{\dot{m}\, D_h}{A\, \mu}, \tag{1}$$

where, A is area of collector (m^2), $\dot{m}$ is air mass flow rate (kg/s), μ is dynamic viscosity of air (kg/m.s). D_h is hydraulic diameter of the ducts, can be calculated as follow:

$$\mathrm{D_h} = \frac{4\,\mathrm{H\,W}}{2\,(\mathrm{H+W})}, \tag{2}$$

where, H is the air channel hight (m), W is the width of solar air collector (m).

Thermal efficiency is an important indicator for evaluating solar air collectors and can typically be calculated using the following formula:

$$\eta = \frac{Q_u}{I\, A_p}, \tag{3}$$

$$Q_u = \dot{m}\, C_p (T_{\mathrm{out}} - T_{\mathrm{in}}), \tag{4}$$

$$C_p = 1.0057 + 0.000066\,(\mathrm{T} - 300), \tag{5}$$

where, T_{out} is the outlet temperature (°C), T_{in} is inlet temperature (°C), C_p denotes air specific heat (J/kg°C), Q_u represents useful energy gain (W), I is solar radiation (W/m²) and A_p denotes the collector surface area (m^2).

When using COMSOL software for simulation, initial and boundary conditions are critical factors determining the success of the simulation. In this study, experimental measurements of ambient temperature, wind speed, and solar radiation were employed as boundary conditions for the simulation. Table 1 presents detailed information on the initial conditions, boundary conditions, and other properties of the computational system.

Table 2. Boundary conditions used during the simulation

Parameter	Value
Density of air (kg/m^3)	1.16
Walls	Adiabatic
Air velocity (m/s)	1.169
Outlet pressure	Assumed gauge pressure
Transmittance of glass	0.93
Absorbance of glass	0.07
Absorbance of absorber	0.95
Inlet temperature (°C)	Experimental data
Solar radiation (W/m²)	Experimental data

In computational fluid dynamics (CFD) simulations, certain simplifications and assumptions are usually made to the governing equations to reduce computational time. Common assumptions include that the air collector operates under steady-state conditions, with no internal heat loss or air leakage, and that the air density remains constant regardless of temperature variations. The walls are adiabatic, there is no heat transfer with the external environment.

In this simulation study, a steady-state study was chosen, employing the physics interface of heat transfer in solids and fluids, with the fluid region modeled as laminar flow. Corresponding initial and boundary conditions were then defined to obtain simulation results, which were subsequently compared and analyzed against experimental data.

3. RESULTS AND DISCUSSION

The experiment was conducted on a clear day in August 2024. Figure 4 illustrates the trends in solar radiation intensity and ambient temperature. The maximum solar radiation intensity reached 898.9 W/m². Figure 5 illustrates the variation of inlet temperature, absorber plate temperature, and outlet temperature over time for the single-pass air collector tested on a clear day. The inlet temperature gradually increased over time, reaching a maximum of 36 °C. The absorber plate temperature initially increased and then decreased over time, peaking at approximately 87.8°C around 13:00. Similarly, the outlet temperature first increased and then decreased, with a maximum temperature of about 52 °C.

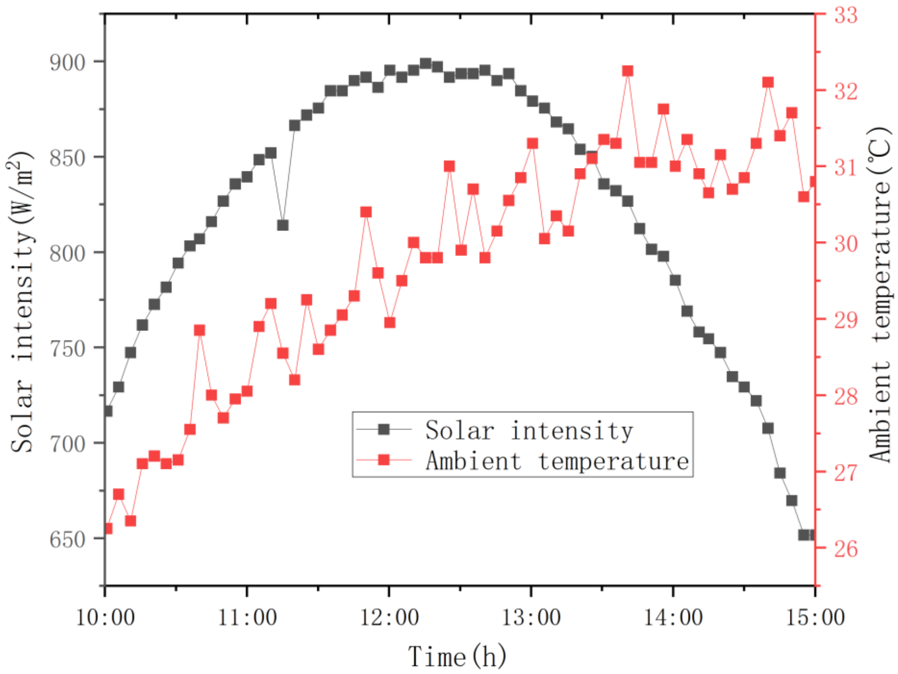

Figure 4. Solar radiation intensity and the ambient temperature

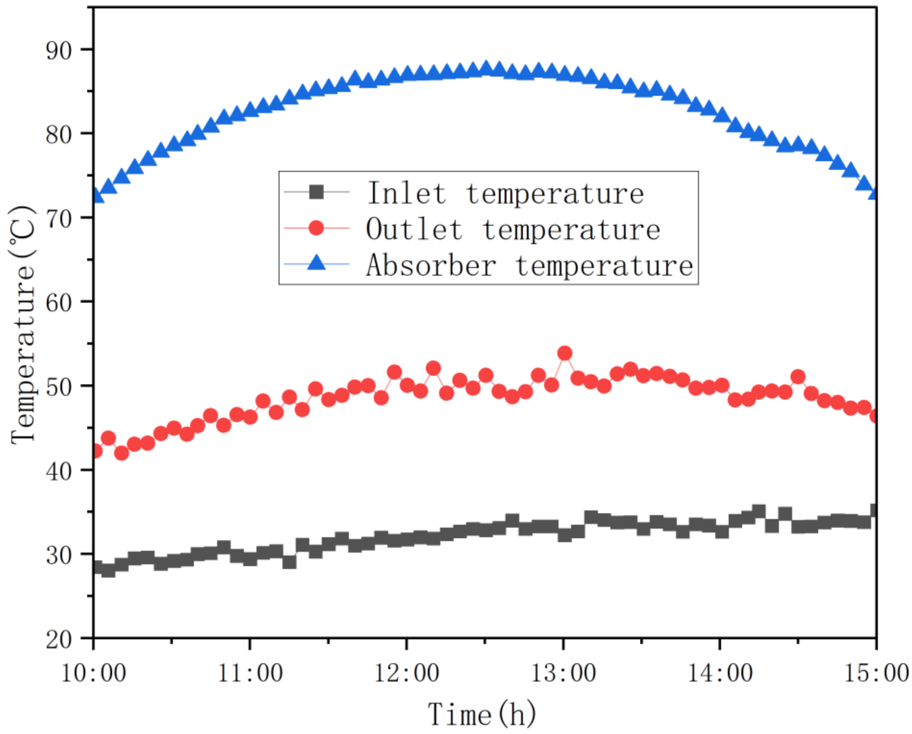

Figure 5. Temperature Distribution in Solar Air Collector

The experimental data were applied as boundary conditions for the simulation. Figure 6 presents the simulated temperature distribution in the solar air collector, with the color distribution representing temperature variations across the collector. In the software, numerical values of the temperature distribution can be intuitively visualized by selecting the surfaces of the model.

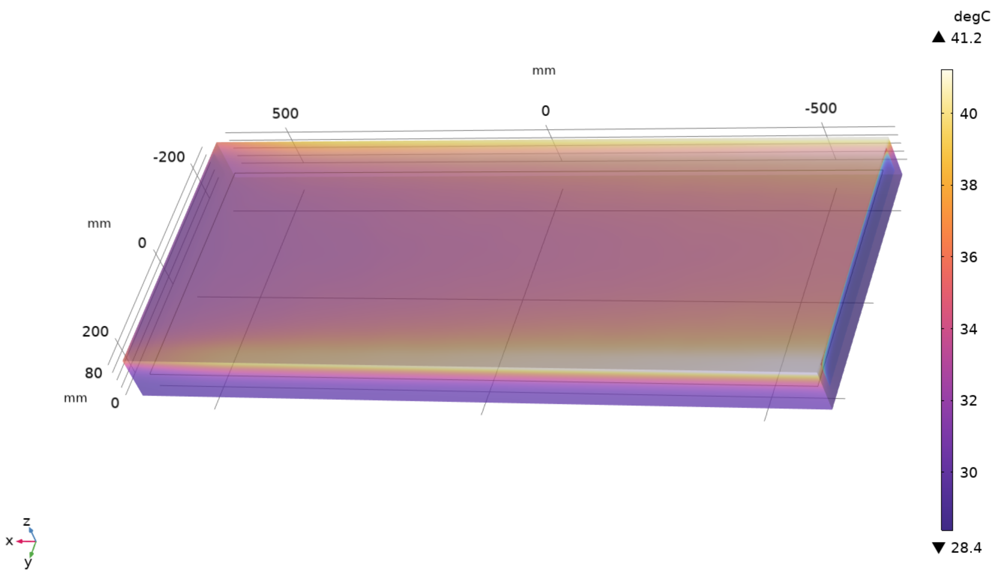

Figure 6. Temperature distribution of a simulated solar air collector

Figure 7 shows a cross section of the air velocity inside the air collector. Different colors on the cross-sectional planes represent the velocity distribution, with variations in color across different sections. Comparing the color changes between sections provides insight into the flow characteristics to some extent.

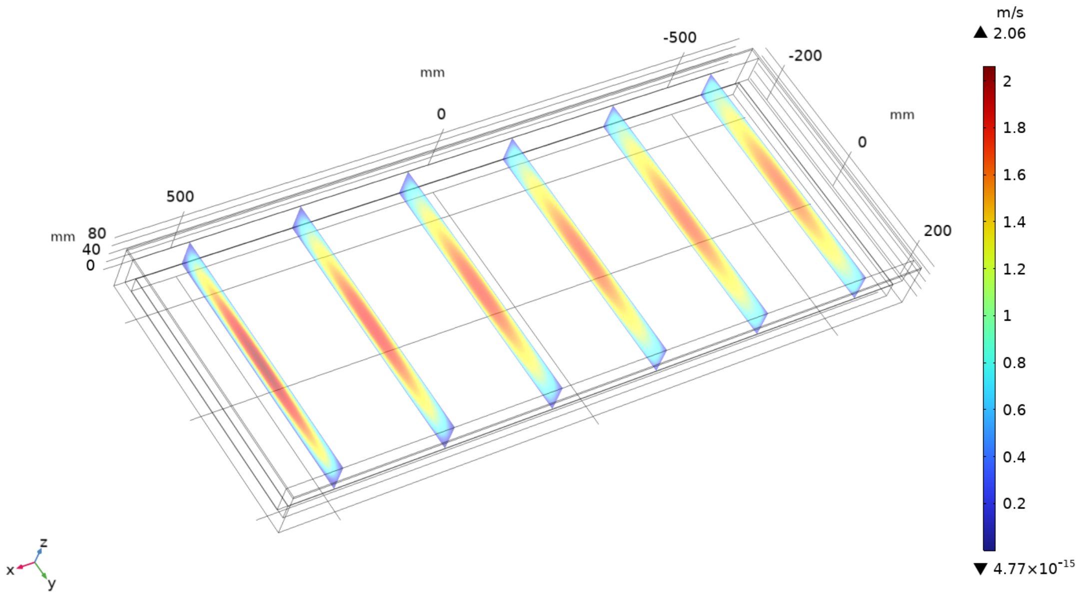

Figure 7. Velocity distribution inside a solar air collector during simulation

According to Equations (3)–(5), the thermal efficiency of the solar air collector can be calculated. Figure 8 presents a comparison of the thermal efficiency between experimental and simulated results for the solar air collector. The efficiency curves of experiment and simulation exhibit a similar trend. The maximum thermal efficiency recorded in the experiment is 40.33%, while the highest efficiency obtained from the simulation is 37.04%. Calculations indicate that the percentage error between the experimental and simulated efficiencies remains within 8.2%, which is an acceptable range.

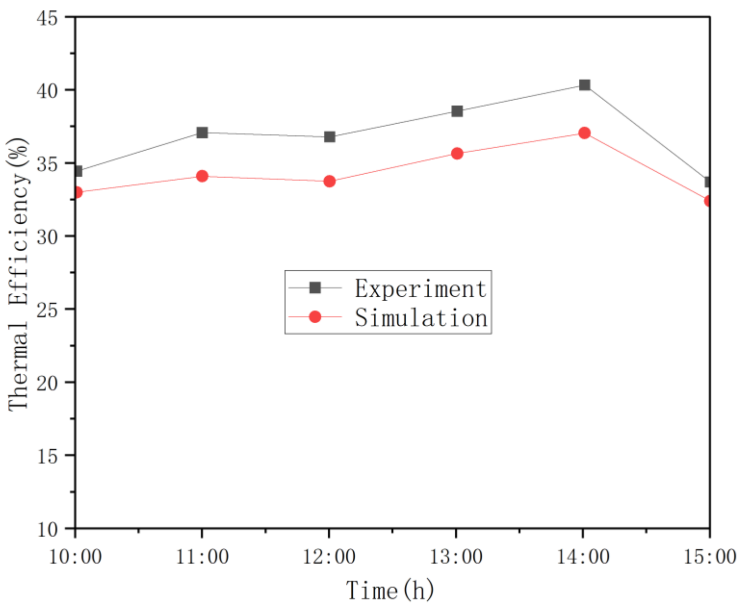

Figure 8. Comparison of experimental and simulated efficiency of solar air collector

4. CONCLUSIONS

This study investigates the thermal performance of a single-channel solar air collector using both experimental and simulation methods. The simulation is conducted using COMSOL software, employing computational fluid dynamics (CFD) to model the solar air collector. The simulation results are compared with experimental data, showing that the maximum inlet temperature of the collector reaches 36 °C, the highest absorber plate temperature is 87.8 °C, and the maximum outlet temperature is 52 °C. The maximum thermal efficiency obtained in the solar air collector experiments was 40.33%. By using experimental data as boundary conditions for the simulation, the percentage error between experimental and simulated results is found to be within 8.2%, which is considered acceptable. The simulation results demonstrate that the proposed model and methodology are effective. The software can therefore be used for further simulations to identify more effective approaches for improving the performance of the solar air collector.

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