



Comparative Thermal Performance of Perforated Absorber Shapes in a Solar Air Heater

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Abstract- This paper compares semi-circular and parabolic perforated absorber shapes for a forced-convection solar air heater. Regular and zigzag patterns in inward and outward orientations were assessed from 11:00 to 15:00 using temperature, airflow and solar-irradiance data. A simple numerical comparison was also used to check the observed performance trend. The parabolic zigzag-outward absorber gave the best result, with 28.70% measured efficiency and a heat-transfer rate of 75 W/m² at 14:00. At the same condition, the semi-circular zigzag-outward design reached 27.07% efficiency and 53 W/m². The numerical estimate for the best parabolic case was 31.10%, which was 2.40 percentage points above the measured value. The results show that curved shape, staggered placement and outward orientation can improve air mixing and useful heat output without making the collector arrangement unnecessarily complex.

Keywords- solar air heater; perforated absorber; parabolic absorber; semi-circular absorber; thermal efficiency; computational fluid dynamics.

I. INTRODUCTION

Solar air heaters convert incident solar radiation into sensible heat and are used in crop drying, space heating and low-temperature industrial processes. Their simplicity is attractive, but conventional smooth absorbers develop a thermal boundary layer that limits convective heat transfer. Surface shaping, ribs, baffles and perforations can disturb this layer and increase contact between the heated surface and the flowing air [1–6].

Previous investigations have reported performance gains from V-shaped roughness, wavy fins, spiral baffles and perforated elements [2–8]. Curved surfaces offer an additional route to enlarge the exposed area and redistribute the flow. However, direct experimental–numerical comparisons of semi-circular and parabolic perforated matrices, including regular/zigzag placement and inward/outward orientation, remain limited. The present work compares eight configurations under the same daytime test protocol and validates the observed ranking using CFD.

1. Related research and study contribution

Artificial roughness improves a solar air heater by interrupting the low-velocity layer next to the absorber. V-shaped ribs, corrugations, wavy fins and perforated baffles have therefore been studied as



passive heat-transfer devices. Kumar et al. [2] reported that V-shaped roughness improved convective exchange, while Sharma et al. [3] showed that the pitch and height of sine-wave baffles strongly influenced the performance. Amara and Bouabidi [4] combined experiments and three-dimensional simulations to evaluate spiral baffles. These studies demonstrate that the geometry must create useful mixing without producing an excessive pressure penalty.

Perforations offer a different mechanism because part of the air can interact with the openings and the curved feature edges. Khanlari et al. [8] found that plus-shaped perforated baffles increased heat transfer in a drying collector. Semi-circular surfaces and parabolic ribs have also been reported as promising geometries [9,11]. However, their performance cannot be compared directly when collector size, airflow, irradiance and reporting methods differ between studies.

The contribution of the present study is a controlled comparison within one dataset. It evaluates two curvature families, two row patterns and two orientations, giving eight absorber configurations. The analysis uses the measured inlet and outlet temperatures, airflow velocity, solar irradiance, heat-transfer rate and thermal efficiency at five daytime conditions. Reynolds number, Nusselt number and numerical efficiency are used as supporting indicators. This structure makes it possible to separate the effects of absorber shapes, row arrangement and orientation.

II. LITERATURE REVIEW

1. Heat Transfer Enhancement in Solar Air Heaters

The low thermal conductivity and heat capacity of air make convective heat transfer the main limitation in a conventional solar air heater. Researchers have used ribs, fins, baffles, corrugations and porous inserts to interrupt the boundary layer and increase mixing. Rajendran et al. [6] evaluated V-shaped baffles for domestic air heating and reported improved heat exchange through repeated flow separation. Haldar et al. [5] used CFD to examine artificial wavy roughness and showed that the modified surface changed both the velocity field and absorber-to-air heat transfer. These findings support the use of passive surface modification when the additional pressure loss remains manageable.

2. Perforated and Curved Absorber Surfaces

Perforated elements allow the moving air to interact with both the main surface and the edges of the openings. Khanlari et al. [8] studied plus-shaped perforated baffles and found that the arrangement was suitable for improving a solar collector used in drying. Priyam and Chand [7] investigated wavy-fin absorbers and showed that surface geometry affected the thermal response. Al-Bakri et al. [11] later examined a semi-circular solar collector with metal foams and reported favourable thermal and thermo-hydraulic behaviour. Together, these studies show that curvature and perforation can be combined to enlarge the effective exchange region.

3. Numerical and Experimental Comparison

Numerical modelling is widely used to screen solar collector geometries before fabrication. Sutar et al. [9] numerically investigated parabolic rib turbulators, while Barrón-Díaz et al. [12] combined finite-element and CFD analysis with experiments on compound parabolic collectors. Amara and Bouabidi [4] also combined experiments with three-dimensional simulation for spiral baffles. Numerical models normally reproduce the main ranking of alternative designs but may predict higher performance because of idealized inlet conditions, uniform material properties and simplified heat losses. Experimental comparison is therefore required before selecting the final design.



Table 1. Summary of literature related to absorber geometry and solar air-heater enhancement.

Authors	method	Main finding	Relevance to present work
Kumar et al. [2]	V-shaped roughness	Surface roughness improved convective exchange	Supports geometric enhancement
Sharma et al. [3]	Sine-wave baffles	Baffle dimensions affected thermal performance	Shows importance of pattern
Amara and Bouabidi [4]	Spiral baffles with 3D simulation	Experiment and simulation showed similar trends	Supports combined validation
Haldar et al. [5]	Artificial wavy roughness using CFD	Modified flow field improved heat transfer	Supports numerical screening
Priyam and Chand [7]	Wavy-fin absorber	Absorber geometry influenced thermal output	Supports curved surfaces
Khanlari et al. [8]	Perforated baffles	Perforations enhanced collector performance	Supports perforated matrices
Sutar et al. [9]	Parabolic rib turbulators	Parabolic elements improved thermo-hydraulic response	Supports parabolic geometry
Al-Bakri et al. [11]	Semi-circular collector and metal foam	Curved design improved thermal behaviour	Supports semi-circular comparison

4. Research Gap

Earlier studies generally examined one roughness shape or compared designs under different collector sizes and operating conditions. A limited number of studies compare semi-circular and parabolic perforated absorbers using the same test period, airflow range and calculation procedure. The combined influence of regular versus zigzag placement and inward versus outward orientation also requires clearer comparison. The present study addresses this gap by evaluating eight arrangements using a common experimental dataset and a supporting numerical efficiency series.

Table 2. Experimental design factors used for the comparative study.

Design Factor	Design Parameters	Thermal effect
Absorber curvature	Semi-circular and parabolic	Changes exposed area and flow guidance
Row pattern	Regular and zigzag	Zigzag pattern increases repeated flow disturbance
Orientation	Inward and outward	Changes wake formation and air-surface contact
Time	11:00 to 15:00	Represents changing irradiance and inlet condition

III. MATERIALS AND METHODS

1. Absorber Configurations and Test Rig

The absorber plate measured $1000 \times 200 \times 20$ mm. Each perforation had a nominal diameter of 20 mm and depth of 10 mm; reported center spacing was 6 mm horizontally and 3 mm vertically. Semi-circular and parabolic features were arranged in regular or zigzag matrices and oriented inward or outward. The

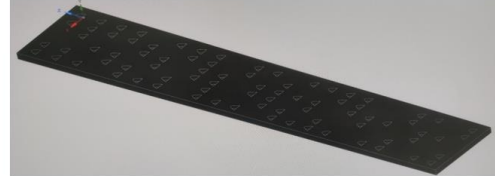


collector used a glass cover, blackened high-conductivity absorber, insulated wooden casing and a forced-air passage. It was installed at a 30° south-facing tilt.

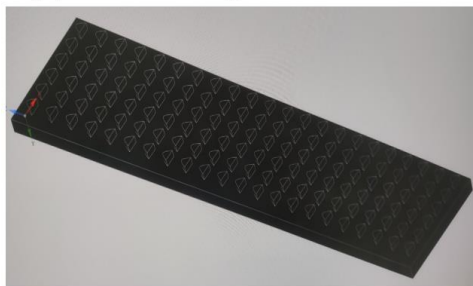
(a) Semi-circular regular



(b) Semi-circular zigzag



(c) Parabolic regular



(d) Parabolic zigzag

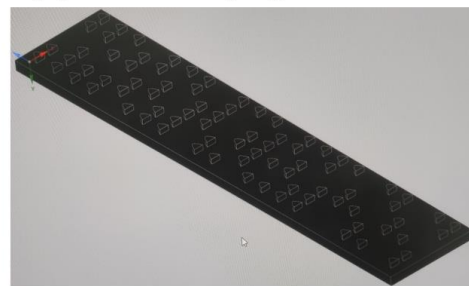


Figure 1: Absorber-plate models used in the study for regular and zigzag arrangements

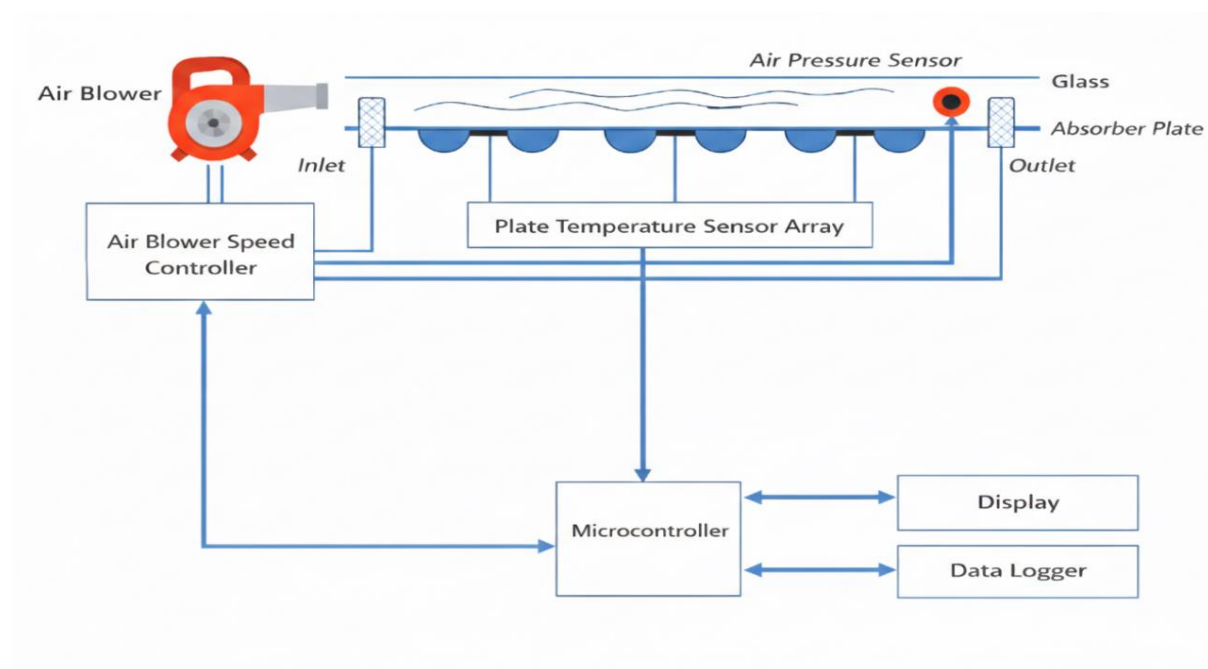


Figure 2: Working-principle and instrumentation diagram of the solar air-heater system

A 650 W blower (220–230 V; rated speed 13,000 rpm) supplied the air stream. Outlet velocity was measured with a METRAVI AVM01 Mini anemometer, temperature with a plate/inlet/outlet sensor array



and Sunsui DL-35W data logger, and solar irradiance from the recorded Solcast series. Readings were taken hourly from 11:00 to 15:00.

2. Test Matrix and Recorded Variables

For each absorber shapes, regular-inward, regular-outward, zigzag-inward and zigzag-outward arrangements were evaluated. The semi-circular dataset covered inlet temperatures from 28 to 44°C, outlet temperatures from 31 to 47°C, air velocities from 1.7 to 2.6 m/s and irradiance from 700 to 1350 W/m². The parabolic dataset covered inlet temperatures from 28 to 44°C, outlet temperatures from 32 to 48°C, the same velocity interval and irradiance from 750 to 1350 W/m². The hour-by-hour values were retained rather than replacing them with a single daily average.

Table 3. Recorded variables and their use in the analysis.

Variable	InstrumentS	Observed Range	Role in analysis
Inlet and outlet temperature	Sensor array and data logger	28–48°C	Temperature rise and useful heat
Air velocity	METRAVI AVM01 Mini	1.7–2.6 m/s	Flow condition and Reynolds number
Solar irradiance	Recorded solar series	700–1350 W/m ²	Incident energy input
Time	Hourly observation	11:00–15:00	Daytime performance trend

3. Performance Equations

The useful heat gain and thermal efficiency were evaluated from Eqs. (1) and (2):

$$Q_u = \dot{m} C_p (T_o - T_i) \quad (1)$$

$$\eta_{th} = [\dot{m} C_p (T_o - T_i)] / (I A) \times 100 \quad (2)$$

where $\dot{m}$ is mass-flow rate, C_p is air specific heat, T_o and T_i are outlet and inlet temperatures, I is solar irradiance and A is collector area. The reported calculation used $\dot{m} = 0.02$ kg/s and $C_p = 1005$ J kg⁻¹ K⁻¹. Reynolds and Nusselt numbers were used to interpret the flow and convection trends. CFD agreement is reported both as percentage-point difference and relative error to avoid confusing the two measures.

4. Numerical Comparison

A steady numerical model was used to compare the temperature and airflow trends of the absorber arrangements. The inlet velocity was set to 1 m/s, the outlet was maintained at atmospheric pressure and the bottom wall was treated as insulated. The numerical results were used only to check whether the predicted configuration ranking followed the measured trend. They were not used as a replacement for experimental performance data.

IV. RESULTS AND DISCUSSION

1. Peak performance and configuration ranking

Table 4: Peak-hour comparison of representative configurations.

Absorber PlateS Arrangement	Time	I (W/m ²)	Q (W/m ²)	η_{exp} (%)	η_{CFD} (%)
Semi-circular regular inward	14:00	1200	49	23.53	25.76
Semi-circular zigzag outward	14:00	1350	53	27.07	29.70
Parabolic regular inward	14:00	1200	62	23.72	26.40
Parabolic zigzag outward	14:00	1350	75	28.70	31.10



At 14:00, parabolic zigzag-outward delivered the highest experimental efficiency (28.70%) and heat-transfer rate (75 W/m²). Relative to semi-circular zigzag-outward, its heat-transfer rate was 41.5% higher, while measured efficiency was 1.63 percentage points higher. The regular inward configurations were consistently lower, supporting the combined benefit of curvature, staggered placement and outward orientation.

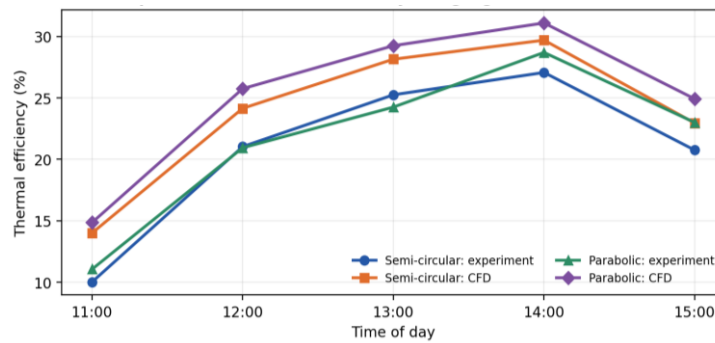


Figure 3. Experimental and CFD efficiency trends for the best orientation of each absorber shapes

All four efficiency series rose toward 14:00 and then declined as irradiance decreased. CFD preserved the experimental ranking but overpredicted the magnitude. For the best configuration at 14:00, the gap was $31.10 - 28.70 = 2.40$ percentage points, equivalent to an 8.36% relative overprediction. Idealized wall conditions, uniform inlet specification and omission of outdoor losses likely contributed to this difference.

2. Heat Transfer and Solar Input

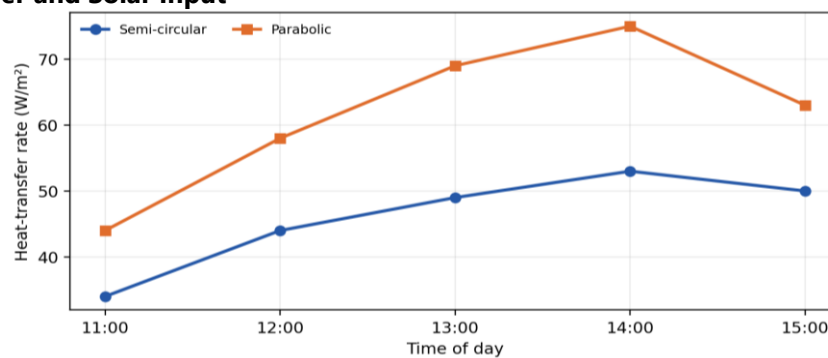


Figure 4: Heat-transfer rate of the zigzag-outward semi-circular and parabolic absorbers

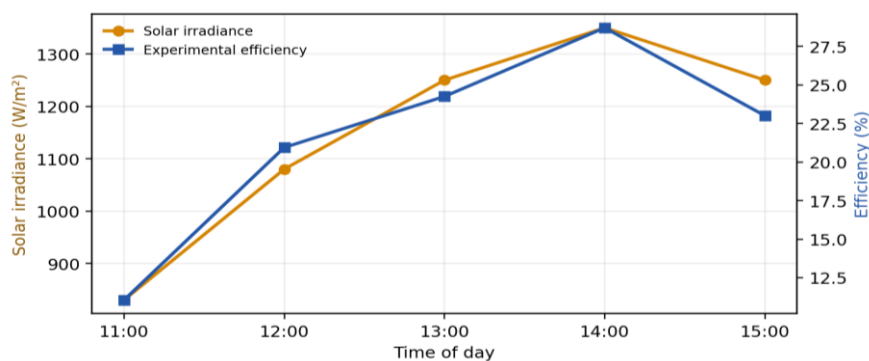


Figure 5: Relationship between irradiance and measured efficiency for the parabolic zigzag-outward configuration.



The parabolic absorber maintained the larger heat-transfer rate throughout the observation period. Its gain over the semi-circular form ranged from 10 W/m^2 at 11:00 to 22 W/m^2 at 14:00. Efficiency did not scale linearly with irradiance because useful heat gain also depends on the inlet–outlet temperature difference, mass flow and losses. Nevertheless, both variables reached their maximum at 14:00, identifying the same peak operating condition.

3. Temperature and flow indicators

Table 5: Outlet temperature and dimensionless indicators for zigzag-outward configurations

Time	Semi-circular T_{out} ($^{\circ}\text{C}$)	Parabolic T_{out} ($^{\circ}\text{C}$)	Semi-circular Re	Parabolic Re	Semi-circular Nu	Parabolic Nu
11:00	34	36	14,268	14,283	16.88	17.45
12:00	44	45	16,353	16,280	19.68	20.15
13:00	46	47	18,938	19,011	21.19	21.59
14:00	47	48	20,328	20,402	22.31	22.63
15:00	43	44	17,548	17,548	20.39	20.39

Parabolic zigzag-outward produced an outlet temperature 1°C above the corresponding semi-circular case at every time point. Reynolds and Nusselt numbers generally increased up to 14:00, indicating stronger forced convection at the peak condition. The outward zigzag pattern likely promotes repeated boundary-layer disruption; this mechanism agrees with earlier ribbed and baffled solar-air-channel studies [2–8].

4. Effect of shapes and Orientation

Measured efficiency of all eight configurations

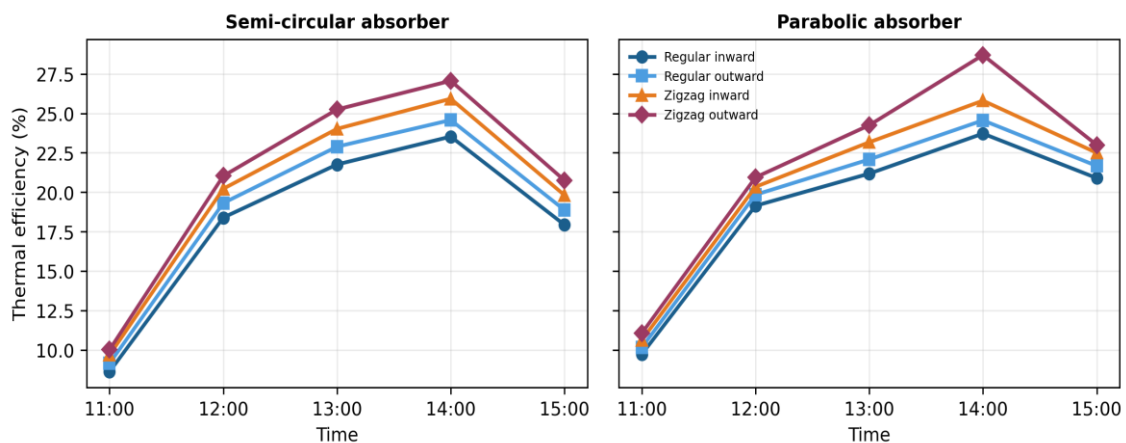


Figure 6. Measured thermal efficiency of all semi-circular and parabolic configurations

The complete efficiency series confirms that the ranking was not limited to the peak hour. In the semi-circular shapes, zigzag-outward had the largest efficiency at every observation, followed by zigzag-inward, regular-outward and regular-inward. At 14:00, the sequence was 27.07%, 25.93%, 24.58% and 23.53%, respectively. The parabolic shapes followed the same general order, with 28.70%, 25.81%, 24.56% and 23.72%. Thus, changing from regular inward to zigzag outward improved peak measured efficiency by 3.54 percentage points for semi-circular absorbers and 4.98 percentage points for parabolic absorbers.

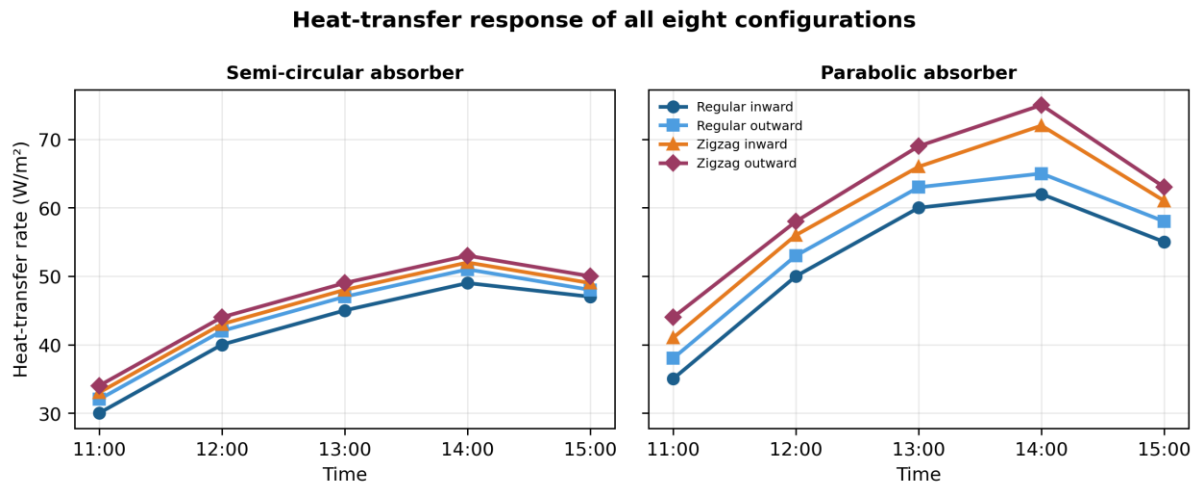


Figure 7. Heat-transfer rate of all absorber configurations from 11:00 to 15:00.

Heat-transfer rate displayed a clearer separation between the two absorber families than thermal efficiency. At 14:00, the parabolic configurations ranged from 62 to 75 W/m², whereas the semi-circular configurations ranged from 49 to 53 W/m². The largest value, 75 W/m², occurred for parabolic zigzag-outward. The regular-to-zigzag increase was also stronger for the parabolic plate, suggesting that its curved perforations benefited more from staggered placement.

5. Heat transfer mechanism and validation

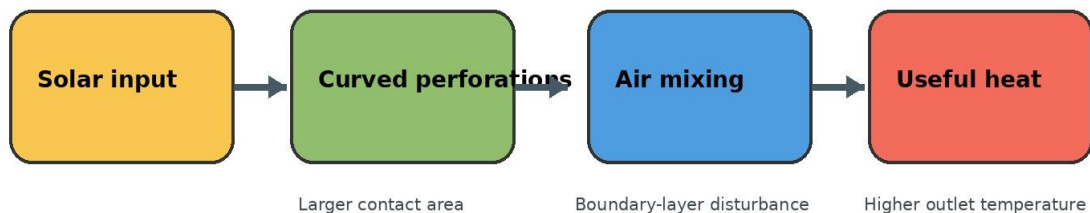


Figure 8: Simplified mechanism linking absorber geometry with useful heat gain

Table 6. Experimental–CFD validation summary

Metric	Experiment	CFD	Difference
Peak efficiency (%)	28.70	31.10	+2.40
Semi-circular peak efficiency (%)	27.07	29.70	+2.63
Best configuration	Parabolic zigzag outward	Parabolic zigzag outward	Same ranking

The curved perforations increase the available contact area, while the zigzag arrangement repeatedly redirects the air stream. This combination disturbs the boundary layer and improves mixing near the heated plate. The numerical comparison correctly identified the best design in both absorber families. Its small overprediction is useful for comparative screening, although a complete uncertainty and mesh-independence study would be required for stronger validation.

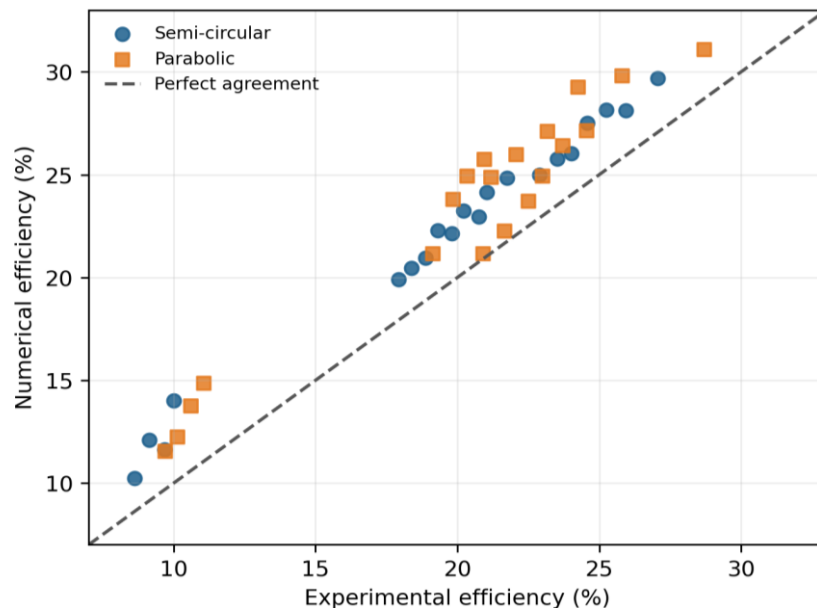


Figure 9: Agreement between measured and numerical efficiencies for all operating point

All numerical points lie above the line of perfect agreement, showing a systematic positive bias rather than random scatter around the measurements. This pattern is consistent with idealized numerical boundaries that do not reproduce every outdoor loss. Even with this bias, the close clustering and preserved configuration ranking support the model as a comparative design tool. The peak differences were 2.63 percentage points for semi-circular zigzag-outward and 2.40 percentage points for parabolic zigzag-outward.

6. Engineering Interpretation

The parabolic zigzag-outward absorber provides the strongest thermal result, but thermal efficiency alone is not sufficient for a final product decision. Increased turbulence can also increase pressure drop and fan energy. Those quantities were not included in the available dataset, so the present result identifies the best thermal arrangement rather than a complete thermo-hydraulic optimum. For low-cost drying or space-heating systems, the preferred design should therefore be checked at the intended mass-flow rate and evaluated for fabrication effort, fouling and cleaning access.

The hourly profiles also show that a single noon measurement may miss the best operating condition. Both families reached their maximum measured efficiency at 14:00, when the largest irradiance and outlet temperatures were recorded. A longer seasonal test would be required to determine whether this peak time remains stable under different weather, tilt angles and ambient temperatures.

V. CONCLUSIONS

An experimental and CFD comparison of eight perforated absorber configurations led to the following conclusions:

- The parabolic zigzag-outward absorber achieved the highest measured thermal efficiency, 28.70%, and heat-transfer rate, 75 W/m^2 , at 14:00 under 1350 W/m^2 irradiance.
- The semi-circular zigzag-outward design reached 27.07% efficiency and 53 W/m^2 at the same peak condition; the parabolic form increased heat-transfer rate by 41.5%.



- Zigzag and outward arrangements generally outperformed regular and inward arrangements, indicating that geometric disruption and orientation improve air–surface interaction.
- CFD reproduced the configuration ranking but predicted 31.10% for the best case, 2.40 percentage points above the experiment.
- Future work should report sensor uncertainty, pressure drop and fan power, perform mesh-independence testing, and evaluate year-round operation at controlled mass-flow rates.

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Declarations

Conflict of interest: The authors declare no conflict of interest.

Data Availability: The experimental dataset is contained in the underlying thesis record and may be shared by the corresponding author. Author contributions and funding statements should be completed before journal submission.

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