Impact of Thermal Absorber Design on the Performance and Manufacturing Viability of PVT Collectors

Summary

This work investigates the role of thermal absorber design in flat-plate and low-concentrating photovoltaic–thermal (PVT) collectors using a Computational Fluid Dynamics (CFD) based assessment approach. Three absorber configurations were analyzed for each collector type and compared with the reference design, with the results validated against experimental data to evaluate thermal efficiency, heat-loss behavior, and hydraulic performance. Flat-plate PVT collectors targeting heat pump integration benefit from absorber designs that enhance heat extraction, resulting in improved thermal efficiency and a higher heat-loss coefficient. For low-concentrating PVT collectors intended for low- to medium-industrial applications, absorber geometry primarily influences heat-loss reduction and zero-loss thermal efficiency. An optimized cost-based analysis of manufacturing processes comparing vacuum forming and extrusion routes highlights a production volume threshold at which extrusion becomes economically favorable for both applications. The results demonstrate the importance of application-specific absorber design and manufacturing-aware optimization. Experimental validation within the PVT4EU project and extended analyses of electrical, economic, and environmental aspects are planned for future journal publication.

Keywords: Flat Plate Collectors (FPCs), Concentrating Photovoltaic thermal collectors (CPVTs)

Field of application for the findings: Heat pump integration (FPCs) & High temperature applications (CPVTs)

Addressed audience: PVT researchers, system designers, and manufacturers involved in PVTs.

1. Introduction

The thermal absorber is a key component of photovoltaic–thermal (PVT) collectors, as it governs heat extraction, overall efficiency, and the practical feasibility of system deployment. (Kurniawati and Sung, 2024) Absorber design also directly affects manufacturability and production cost, making it a critical factor for scaling PVT technologies across different applications. However, comparative studies differentiating flat-plate and low-concentrating PVT absorber designs with respect to their application domains remain limited. In addition, manufacturing-aware design considerations, including production processes and cost implications, are rarely integrated into performance-oriented PVT studies (Ramezani *et al.*, 2024).

This study evaluates the role of thermal absorber design in determining the numerical performance and manufacturing viability of photovoltaic–thermal (PVT)collectors across different application domains using a CFD model-based assessment approach. Two representative categories of collectors were considered: a flat-plate PVT collector targeting heat pump integration and a low-concentrating PVT collector intended for low high-temperature industrial applications (up to 140°C), see Figure 1. For the flat-plate configuration, a polymer double-plate absorber based on ABS/polycarbonate was used as the reference geometry, with an absorber area of 0.910 m² and an operating temperature range of approximately −10 °C to 40 °C. For the low-concentrating configuration, a reference collector, employing a compound parabolic concentrator (CPC) and a bifacial receiver, was considered. In both cases, different channel geometries were evaluated to assess their impact on heat-extraction effectiveness under application-relevant thermal loads.

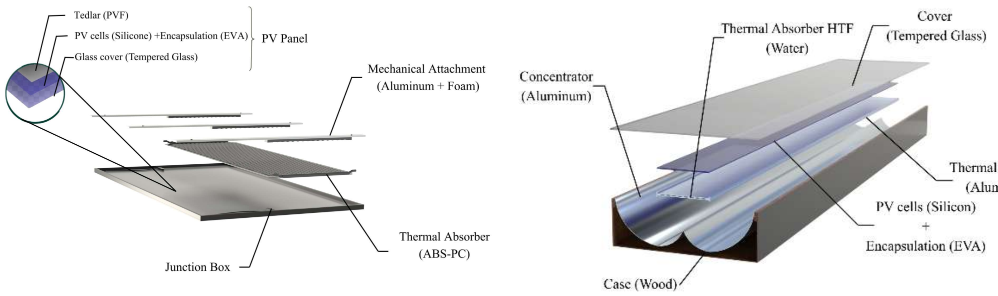

Figure 1: Conceptual schematic representation of the investigated PVT collector concepts and their main components. Left: Flat-plate PVT. Right: Low-concentrating PVT collector.

2. Methodology

2.1. Model Approach:

A COMSOL CFD numerical modeling approach was used to assess the influence of thermal absorber design on flat-plate and low-concentrating PVT collectors. For each collector type, three alternative channel configurations were evaluated and compared against a reference validated design (See Figure 2). Configuration names reflect the intended manufacturing process, where EXT denotes extrusion-based channel designs, and VAC denotes vacuum-formed geometries. For flat-plate PVT collectors, three-dimensional steady-state simulations with laminar flow and conjugate heat transfer were performed.

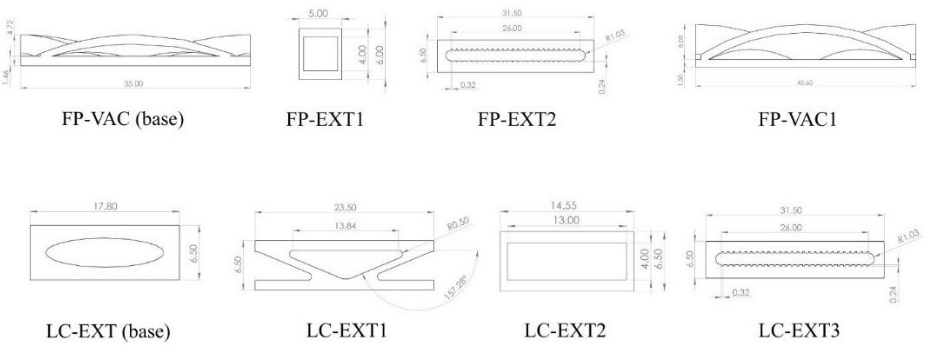

Figure 2: Cross-sectional geometries of the investigated thermal absorber channel configurations for flat-plate (FP) and low-concentrating (LC) PVT collectors. The top row shows the flat-plate configurations, including the reference vacuum-formed design (FP-VAC) and the modified extrusion-based (FP-EXT1, FP-EXT2) and vacuum-formed (FP-VAC1) designs. The bottom row presents the low-concentrating PVT absorber configurations, including the reference extrusion-based design (LC-EXT) and the modified extrusion-based designs (LC-EXT1, LC-EXT2, LC-EXT3) considered in this study.

For low-concentrating PVT collectors, a two-step approach was adopted: two-dimensional simulations were first used to evaluate the convective heat transfer coefficient based on the local heat flux and the temperature difference between the absorber wall and the tempered glass (Eq. 1), followed by three-dimensional simulations to capture the coupled thermal and electrical behavior.

$$h_{(conv)}[Wm^{-2}K^{-1}] = q/T_{(wall)} - T_{(glass)} \quad \text{(eq. 1)}$$

Thermal performance was assessed by thermal efficiency using (Eq. 2 & 3)

$$P_{th}\ [W/m_2] = \left(m_f \dot{c}_p \Delta T\right)/A_c \quad \text{(eq. 2)}$$

$$\eta_{(th)} = P_{(th)}/G \quad \text{(eq. 3)}$$

2.2. Boundary Conditions:

In both cases, photovoltaic electrical performance was assumed to be temperature dependent. Standard testing conditions were adopted to enable comparative evaluation. For flat-plate collectors, simulations were conducted at an irradiance of 800 W/m², an ambient temperature of 25 °C, and a wind speed of 1.3 m/s. For the low-concentrating collector, irradiance distributions obtained from optical simulations were applied to the absorber surfaces, with ambient and wind conditions kept consistent.

2.3. Manufacturing cost comparison:

A manufacturing cost analysis was performed for the PVT-SP absorber, using essential parameters collected from companies associated with vacuum forming and extrusion. A linear cost model was used, where x is the number of units produced, m is the unitary manufacturing cost, and n represents the initial tooling CAPEX. (see Eq. 4)

$$C(x) = mx + n \quad \text{(eq.4)}$$

3. Results

Figure 3 shows that for the flat-plate PVT collectors targeting heat pump integration, all modified absorber configurations outperform the reference design. Extrusion-based configurations FP-EXT1 and FP-EXT2 show the highest thermal efficiency improvements of approximately 8% and 7%, respectively, while the vacuum-formed configuration FP-VAC1 achieves an improvement of about 3%. Since low-temperature heat recovery is desired, an increased heat loss coefficient is advantageous; FP-EXT2 exhibits the largest increase, 26%, followed by FP-VAC1 21% and FP-EXT1, 15%. All flat-plate configurations also show reduced pressure loss relative to the base case, with FP-EXT1 and FP-EXT2 achieving reductions of approximately 77% and 80%, respectively, and FP-VAC1 showing a reduction of about 29%, reflecting the influence of channel geometry and manufacturing approach on hydraulic performance. For the low-concentrating PVT collectors intended for high-temperature industrial applications, thermal efficiency improvements are more moderate, with increases of approximately 3.9% for LC-EXT1, 3.0% for LC-EXT2, and 2.0% for LC-EXT3. In this case, reducing heat loss is desirable; LC-EXT3 reduces the heat loss coefficient by approximately 5.0%, whereas LC-EXT1 and

LC-EXT2 increase it by about 7.7% and 4.9%, respectively. However, LC-EXT3 also experiences a substantial increase in pressure loss of approximately 121% due to the use of micro-grooved channels, illustrating a clear trade-off between reduced thermal losses and increased hydraulic penalty.

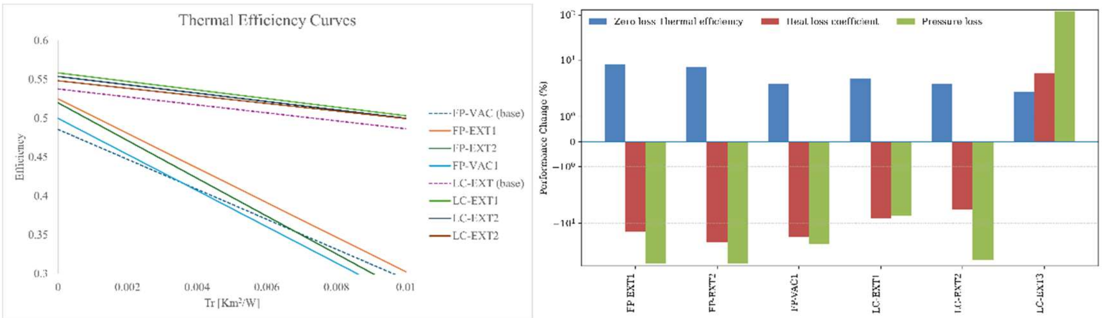

Figure 3: Thermal performance comparison of flat-plate and low-concentrating PVT absorber configurations. (a) Thermal efficiency curves as a function of reduced temperature for the investigated flat-plate (FP) and low-concentrating (LC) PVT designs. (b) Relative percentage changes in thermal efficiency, heat loss coefficient, and pressure loss for all configurations with respect to their respective base cases, highlighting the trade-off between thermal performance and hydraulic behavior.

A manufacturing cost comparison was performed for both flat-plate and concentrating PVT absorbers using a linear cost model. For the flat-plate PVT absorber, vacuum forming is characterized by a lower initial tooling investment (25 k€) but a higher unitary cost (47 €/unit), making it more suitable for low production volumes. In contrast, extrusion requires a higher initial capital expenditure (CAPEX) of 129 k€ but offers a lower unitary cost of 33 €/unit. The cost curves intersect at approximately 7,300 PVT units, below which vacuum forming remains the more economical option, whereas extrusion becomes preferable at higher production volumes due to its reduced unitary cost. A similar trend is observed for the concentrating PVT absorber, where vacuum forming involves the same initial tooling cost (25 k€) but a unitary cost of 23 €/unit, while extrusion requires a higher CAPEX of 129 k€ with a lower unitary cost of 16 €/unit. In this case, the cost curves intersect at approximately 15,000 units, indicating that vacuum forming is more cost-effective at lower production volumes, while extrusion becomes the preferred manufacturing route for large-scale production. (see Figure 4).

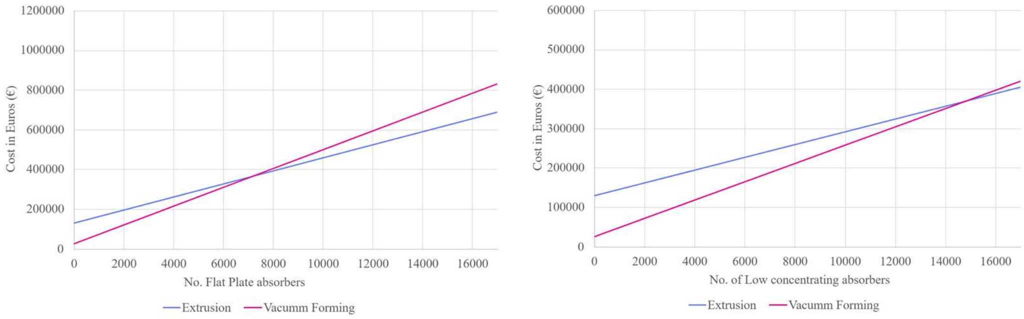

Figure 4. Comparison of total manufacturing cost for the Flat-Plate and Low-concentrating PVT absorber produced using extrusion and vacuum forming as a function of production volume.

4. Conclusion

This study investigated the role of thermal absorber design in flat-plate and low-concentrating PVT collectors using a CFD model-based assessment combined with a simplified manufacturability analysis. The results demonstrate that absorber geometry optimization has a strong impact on thermal performance and hydraulic behavior, with application-specific trade-offs observed between heat extraction, heat loss, and pressure loss. For flat-plate PVT collectors targeting heat pump integration, designs with higher heat loss coefficients and improved thermal efficiency were found to be advantageous, while for low-concentrating PVT systems, absorber design primarily influenced thermal loss reduction and hydraulic penalties.

The reference designs investigated in this work are experimentally validated within the PVT4EU project. Future work will include experimental results, an extended assessment of the influence of absorber design on electrical efficiency, and an enhanced techno-economic analysis incorporating payback time and environmental impact for journal publication.

5. References

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