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CRITICAL ISSUES AND NOVEL CONCEPTS OF COOLING BIPVT AND ITS INTEGRATION WITH LOW-TEMPERATURE HEATING

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ABSTRACT: The efficiency of photovoltaic (PV) modules is inversely correlated with their operating temperature. Extensive research has shown that cooling PV systems to maintain a stable and low surface temperature enhances PV efficiency, power generation and prolongs the life span of the modules by limiting the degradation caused by thermal fatigue. This applies particularly for Building Integrated Photovoltaic-Thermal (BIPVT) systems where the extracted heat can be potentially recovered by the rest part of building energy services. To implement this, BIPVT systems can be integrated with low temperature heating systems, such as existing heating and ventilation installations, running on low temperature level, or integrated with heat pumps. The effective cooling of such systems can be instrumental for meeting nearly Zero Energy Building (nZEB) standards, by enhancing their overall conversion efficiency, while meeting both the electrical and thermal demand of buildings. In this study, key challenges related to this topic are outlined and crucial parameters for thermal management concepts are presented. Practical aspects of the design and integration processes are explored as well, alongside the cost-effectiveness, sustainability and aesthetics of said systems. Meeting such criteria plays a vital role for the penetration of the next generation of BIPVT to the market, yet current literature does not address these implementations comprehensively. In view of these characteristics, new BIPVT cooling concepts are proposed along with methods for simulating their thermal behavior utilizing numerical solutions, i.e., computational fluid dynamics (CFD).
Keywords: BIPVT, cooling, solar air heater

Nomenclature		Symbols	
		A	Area (m^2)
BIPVT	Building Integrated PVT	Cp	Specific heat of air (J/Kg K)
PV	Photovoltaic	Dh	Hydraulic Diameter (m)
PVT	Photovoltaic-Thermal	f	Friction Factor
TEF	Thermal Enhancement Factor	h	Convective heat transfer Coefficient (W/m^2K)
VG	Vortex Generator	L	Length (m)
		$\dot{m}$	Mass flow rate (kg/s)
		Nu	Nusselt number
		Pr	Prandtl number
		Re	Reynolds number
		T	Temperature (K)
		U	Free flow Velocity (m/s)
		$\dot{V}$	Volumetric flow rate (m^3/s)
		ΔP	Pressure drop (Pa)
		ν	Kinematic viscosity (J.s/kg)
		ρ	Density (kg/ m^3)

1 INTRODUCTION

Only a fraction of the total incident radiation on a photovoltaic (PV) panel is converted directly to electrical energy. The rest is either transmitted to the surroundings or absorbed by the PVs material, in the form of thermal energy [1]. This results in an increase of PV modules temperature. Studies have shown that this causes an almost linear drop in efficiency of up to 0.5 %/C° and attribute this to electrical resistance losses in the cells [2]. Additionally, the effective lifecycle of the modules is reduced due to thermal fatigue. Therefore, cooling PV systems is beneficial in multiple aspects: e.g., by enhancing the generation efficiency and prolonging their lifespan. PVT/BIPVT systems generate electrical and thermal energy simultaneously, by utilizing various forms of cooling.

Previous studies have explored different cooling configurations, some particularly focusing on using air as the cooling medium [3]. Although great interest is detected, no significant breakthroughs have been made lately, with no sound solutions penetrating the market [4]. This is partly due to the insufficient increase in either electrical or thermal energy generation. Solar air heaters have shown potential to be suitable for dealing with this challenge, given that the physical conditions, heat transfer mechanism and overall purpose are of very similar nature. Thus, in this study, heat transfer enhancement designs of solar air heaters, with proven performance, are discussed and their suitability for BIPVT systems is explored. Further improvements and novel concepts compatible with such systems are suggested.

2 NUMERICAL DESCRIPTION

Assuming an adiabatic backplate, the convective heat transfer between the PV surface and the stream of air is:

$$Q = hA\Delta T = \dot{m}C_p(T_{out} - T_{in}) \tag{1}$$

In the case of utilizing ambient air as the cooling medium, it is not sensible to cool the stream beforehand (therefore increasing ΔT) or increasing the mass flow $\dot{m}$

significantly, since those operations require active power consumption. In contrast, increasing the heat transfer coefficient h and heat transfer area A only increases the load of the fan, which requires energy, albeit significantly less that the former methods. Nusselt number is widely used in the investigations which indicates the ratio of convective over conductive heat transfer :

$$Nu = \frac{hD_H}{k} \qquad (2)$$

D_H is the hydraulic diameter and k the conductivity of air. The friction factor of the channel plays a crucial role as well, since it is directly responsible for the pressure drop that the fan blower must provide.

$$f = \frac{\Delta P}{\frac{1}{2}\left(\frac{L}{D_H}\right)\rho U^2} \qquad (3)$$

The goal here is to improve Nu with minimum friction penalty. To effectively compare methods with a single metric, studies in similar applications use the thermal enhancement factor TEF (or thermohydraulic parameter) as an indicator, which combines the heat transfer improvement and subsequent friction increase. A definition was proposed by Webb and Kim [5] in which it assumed that the pumping power of the channels are equal:

$$P_0 = P \rightarrow \left(\dot{V}\Delta P\right)_0 = \dot{V}\Delta P \ \rightarrow \ (fRe^3)_0 = fRe^3 \qquad (4)$$

Where values with the subscript 0 indicate a smooth channel and those without the configuration/geometry analyzed.

With $Re = \frac{UD_H}{\nu}$ being the Reynolds number which describes the turbulent nature of the flow.

Both sides of Eq. 4 are multiplied by $1/f_{0,Re}$ which is the friction factor of the smooth duct but for the Reynolds number of the modified one.

$$Re_0^3 \frac{f_0}{f_{0,Re}} = Re^3 \frac{f}{f_{0,Re}} \qquad (5)$$

The Blasius equation for friction in smooth ducts $f_0 = \frac{C1}{Re^{m1}}$ is used to get:

$$\left(\frac{Re_0}{Re}\right)^3 \left(\frac{C1/Re_0^{m1}}{C1/Re^{m1}}\right) = \left(\frac{f}{f_0}\right)_{Re} \rightarrow \left(\frac{Re_0}{Re}\right)^{3-m1} = \left(\frac{f}{f_0}\right)_{Re} \qquad (6)$$

TEF is defined as : $TEF = \frac{Nu}{Nu_0}$ for equal pumping power. The Dittus-Boelter equation can be then used to predict the Nu in smooth ducts: $Nu_0 = CRe_0^{m2}Pr^n$. Inserting it to the former equation gives:

$$TEF = \frac{Nu}{CRe_0^{m2}Pr^n} = \frac{Nu}{CRe_0^{m2}Pr^n(Re^{m2}/Re^{m2})}$$

$$= \frac{\frac{Nu}{Nu_0}}{\frac{Re_0^{m2}}{Re^{m2}}}$$

Combining with Eq. 6 gives:

$$TEF = \left(\frac{Nu}{Nu_0}\right)_{Re} \Bigg/ \left(\frac{f}{f_0}\right)_{Re}^{\frac{m2}{3-m1}}$$

A simpler definition is commonly found in existing literature:

$$TEF = \frac{\frac{Nu}{Nu_0}}{\left(\frac{f}{f_0}\right)^{0.33}}$$

Most studies validate their mathematical models or CFD analyses with the known Dittus-Boelter equation $Nu = 0.023Re^{0.8}Pr^{0.4}$ (for heating of fluid) or the Gnielinski equation:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}(Pr^{0.66} - 1)}$$

3 HEAT ENHANCEMENT DESIGNS

3.1. Principles of heat enhancement designs

Solar air heating studies primarily address the limitation of utilizing air as a cooling medium, specifically the much lower thermal capacity of air in comparison to water. However, water shows disadvantages for certain applications, leading to investigations into the efficient heating of air through solar energy. Among the heat enhancement mechanisms possible, emphasis has been given to mostly two aspects: the disruption of the thermal boundary layer and the increase of turbulence of the flow [6]. Turbulent flow displays higher convection heat transfer rates due to its tumultuous movement which distributes heat further. In applications of forced convection above surfaces or in piping, surfaces exert friction on the particles adjacent, impending their movement and transmission of heat. In such manner, a boundary layer and an equivalent thermal one are formed, hindering efficient heat transfer. Different strategies have been reported that attempt to disturb this layer at short intervals and obtain the thermal characteristics of the free flow. Rashidi et al. [7] reviewed the prospective utilization of inserts in solar thermal energy systems, which covered twisted tapes, wired coils, vortex generators and baffles. Various numerical and experimental studies were evaluated, giving insight into the specifics of each concept and recommendations for future research was given. However, it was reported that hardly any studies performed economic assessments of these systems, which is a vital factor for their wider adoption as a viable solution.

Given the development, selected high-performing methods and designs are presented in further detail. Given the infancy of this technology, the terminology used is still hazy. A straightforward and comprehensible designation was given by Promvonge and Skullong [8] who define baffles and winglets as extremely thin ribs. They distinguish the former from the latter when their height is equal or more than 25% of the height of the channel and their angle of attack is equal or more than 30°.

In summary, solar air heating technology has seen significant developments, which could potentially cover the gap found in PVT/BIPVT performance enhancement, which is reflected in this study.

3.2 Development of Baffles

Baffles are surfaces that direct the airflow with the primary aim of interrupting the thermal and laminar boundary layer. Shapes vary from rectangular, triangular to trapezoid profiles. Starting from the edge of the baffle, the flow separates, creates recirculation zones and impinges back on the surface. This, in combination with secondary flows formed, results in better mixing of the fluid and subsequently in improved heat transfer, though with an increased pressure drop. Combinations of factors like height, width, and position need to be tested to procure optimum thermohydraulic behavior. The key parameters can be summarized as blockage ratio, pitch ratio and angle of attack. Baffles can be further subdivided according to their shapes and arrangements. Some early studied adopted shapes in terms of such baffles, such as : Z-shaped [9], U-shaped [10] and cuboid-shaped [11].

The sub-category of baffles which continuously outperform other designs, by achieving higher and consistent TEF values, is the V-shaped baffle and its multiple derivations. Researchers have detected its potential and dedicate efforts to develop its performance further. V-shaped designs break the main flow at regular intervals and create secondary flow jets, which progress from the leading edge up to the trailing one, eventually boosting heat transfer. Kumar et al. [12] investigated a discretized broken V-shape baffle arrangement. The idea with the utilization of discretized baffles instead of continuous ones, is to direct and join the main and secondary flows through these gaps. This results in the latter accelerating the former, energizing its slowed-down boundary layer. Optimal values of parameters like the position and size of the gaps were identified. Promvonge and Skullong [8], motivated by perforated designs, aimed for a configuration that would decrease the pressure drop penalty as well as introduce impingement jets right behind the baffles that cool the adjacent surface. It was made possible with the forming of flaps from square shaped cuts on the baffles. Air flows unobstructed though the cavity and is directed by the flap towards the heated surface, creating a jet that impinges on it. Tests delivered promising results and specified optimal flap angles and pitch ratios. Eiamsa-ard et al. [13] further developed this concept by employing semi-circular flaps (or hinges) instead, with the intend of reducing dead zones behind the baffle.

From the channel design perspective, Tamna et al. [14] performed one of the few studies exploring staggered an in-line configurations of baffles on both sides of the air channel. It was shown that an arrangement on a single wall (that of the absorber) provides higher TEF values in comparison to a double sided configuration. This difference was attributed to the lower blockage ratio of the single arrangement. Should a double arrangement be chosen, the in-line version achieved only slightly better results. Fawaz et al. [15] analyzed an in-line arrangement in a numerical simulation and found out that TEF values increase as the blockage ratio is decreased. Furthermore, fully developed periodic flow behavior was detected a few characteristic lengths in.

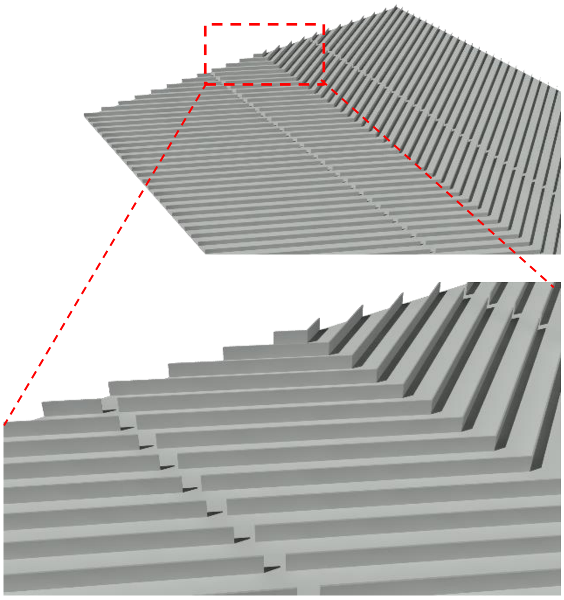

Figure 1: Example of a discrete V-shaped baffle with two gaps.

3.3 Vortex Generators

An alternative critical design element, Vortex generators (VGs), as the name suggests, are meant to create vortices in the main flow, resulting in increased turbulence and mixing. As described previously, turbulent flows transfer heat more effectively because they prevent thermal and mass layers from forming. Similarly to baffles, vortex generators with various shapes have been investigated, such as rectangular [16], trapezoidal [17], delta shaped, curved [18] or even truncated half conical [19]. Increase of the pressure drop due to the blockage of the flow is always present. VGs are commonly protrusions on surfaces, that initially disturb the boundary layer and the wake created from their trailing edges hinder it from forming again.

Sawhney et al. [20] inspected the performance of wavy delta winglets. The aim was for the wavy shape to create pairs of counter rotating vortices, which interacted with each other, superimposing them towards one direction. Thus, the effect on the surface heat transfer is multiplied. To fully take advantage of this concept, critical pitch ratios were investigated, so as to strengthen the vortices at regular intervals before they break down. Some studies incorporated perforated designs as well. In this case, openings are created in the VGs, through which the flow enters. A lower pressure drop is achieved due to the overall smaller blockage. Baissi et al. [21] investigated the thermal and friction profiles of perforated and non-perforated curved delta shaped vortex generators. All perforated cases showed reduced friction rates and improved TEF values. Skullong et al. [22] tested perforated rectangular and trapezoidal winglets and compared different hole diameters on those configurations. The study was further developed for the combination of grooves on the surface with VGs [23]. Zhao et al. [24] explored the combination of VGs and baffles by placing delta winglet VGs in front of V-shaped continuous ribs. It was reported that longitudinal vortices are able to alter the direction of the back flow produced by such ribs with a positive effect on heat transfer. Optimization of nine parameters, related to delta shaped winglet design, for flow-up and flow-down arrangements, was performed by Dezan et al. [25]. It was concluded that the most impactful parameters were chord and angle of the first row, followed by their equivalents in the third and first rows. Flow-up configurations displayed marginally improved results only with low Reynolds numbers. Optimized setups tended to generate and maintain longitudinal vortices along the main flow direction and close to the heated surface, while their corner vortices were of reduced size and dissipated rather quickly.

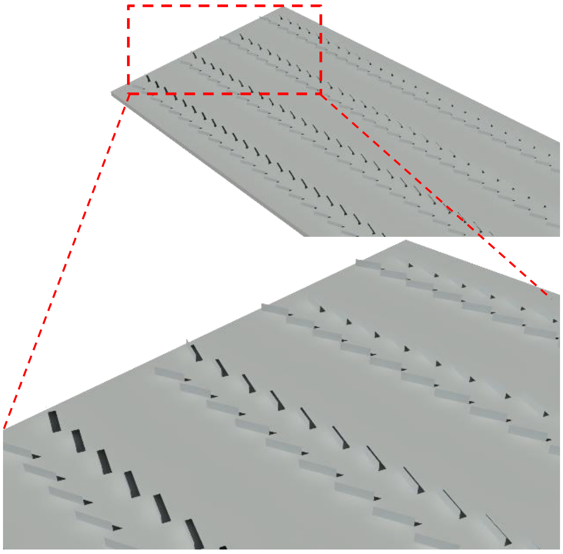

Figure 2: Example of rectangular vortex generators.

3.4 Impingement jets and ribs

To combat the pressure drop increase caused by the addition of inserts in solar air heaters as introduced in Section 3.2 and 3.3, researchers have attempted to minimize their size considerably. One strategy is to focus mainly on the disruption of the thermal boundary layer through minute extrusions, called usually ribs, and artificial roughness on the heated surface. The result is separation and reattachment of the flow that enhance heat transfer. Such configurations can potentially be combined with the technique of impingement flow cooling. Impingement jets strike the selected surface, enhancing the heat transfer coefficient locally and maintain a slim thermal boundary layer.

A selection of rib profiles were analyzed numerically by Ngo and Phu [26], regarding their heat transfer and friction factor. The highest thermohydraulic performance was achieved by the hyperbolic ribs. The smoother profile of the hyperbolic ribs resulted in smaller zones of ineffective convection, particularly upstream. Deo et al. [27] applied the broken V-shape to their rib arrangement and complemented it with staggered rib units that disrupted the flow between the gaps. Optimal rib geometry parameters were identified, which lead to higher TEF values. Multiple studies investigated the arc shape for ribs with broken, staggered and multi-arrangements [28–30].

Nayak and Singh [31] examined the effect of channel spacing and mass flow rates of a non-conventional cross-flow jet plate solar air heater. Longer spacing and larger mass flow rates were favored. It was determined that, even though the friction factor did not change considerably in the proposed configuration, its thermal behavior was improved and was therefore deemed more fit for solar air heating than the typical setup. N. Kumar et al. [32] constructed conical ring obstacles for enhancing the cooling ability of impingement jets. Due to the longer swirl flow path and the greater mixing rate caused by the rings, the heat transfer was improved.

Table I: Studies investigating heat transfer enhancements in solar air heaters

Study	Type	Max TEF	Critical parameter
Promvonge and Skullong (2021) [8]	Flapped V-shaped baffle	2.5	Pitch, flap angle
Sriromreun et al. (2012) [9]	Z-shape baffle	2.98	Height, Pitch
Bopche and Tandale (2009) [10]	U-shape baffle	1.97	Pitch
Pasra et al. (2021) [11]	Cuboid baffle	3.28	Height
Eiamsa-ard et al. (2022) [13]	V-shaped w/ circular hinges	2.6	Hinge angle
Tamna et al. (2014) [14]	Multi V-shape baffle	1.83	Pitch
Fawaz et al. (2018) [15]	V-shape baffle	0.78	Blockage ratio
Depaiwa et al. (2010) [16]	Rectangular winglet VGs	1.17	Re number
Xiao et al. (2020) [17]	Trapezoidal VGs	1.89	Upwind arrangement
Zhou and Ye (2012) [18]	Curved VGs	1.6	Attack angle
Bezbaruah et al. (2021) [19]	Truncated half conical VGs	2.04	Re number
Sawhney et al. (2017) [20]	Wavy delta-shaped VGs	2.09	Pitch
Baissi et al. (2020) [21]	Perforated VGs	2.26	Pitch
Skullong et al. (2018) [22]	Perforated VGs	2.01	Hole diameter
Skullong et al. (2017) [23]	Grooves + VGs	2.12	Groove Pitch
Zhao et al. (2021) [24]	Ribs + VGs	1.4	Shape of ribs
Ngo and Phu (2020) [26]	Conic ribs	1.56	Conic constant
Deo et al. (2016) [27]	V-shaped, staggered ribs	2.45	Rib height

4 PVT AND BIPVT APPLICATIONS

Currently, studies regarding Air-cooled PVTs mainly aimed to increase the heat transfer through the addition of fins, which increase the total heat exchange area. Unsurprisingly, sub-optimal arrangements cause significant pressure drop, thereby reducing the efficiency of the system. So far, studies omitted this impact with limited evidence on the performance and do not investigate its effectiveness by having such a high pumping power demand. This can be illustrated in the study of Shrivastava et al. [33] where multiple fin and baffle combinations for a PVT system were tested, regarding their thermal performance, but the overall cost-effectiveness was not reported. PVT/BIPVT research primarily focused on heat transfer related to water, Phase Change materials and nanofluids as shown by the comprehensive review on PVT of Chandrasekar et al. [3]. Those that did employ air as the cooling medium mostly investigated regular air channels and the addition of fins but did not explore the impact of inserts found in solar air heater studies.

The aforementioned heat transfer enhancement strategies indicate the proven performance increase for solar air heaters. It is sensible to extend their conclusions to PVT/BIPVT collectors too, based on the similarity of these technologies. There is strong potential for improving their efficiency, by applying the further adapted techniques, with the aim of maximizing the cooling of the PV modules and the generation of thermal energy. Operational and differences do exist though that will determine which methods are most appropriate for these applications.

From the module level, one critical impactful decisive parameter is to maintain a uniform temperature reduction, specifically avoid large temperature gradients along the PV surface. This causes the cells to operate at different maximum power points, reducing their electrical efficiency and lifespan. Thus, a form of cooling is required that would avert hot and cold zones from forming or at least minimize them. Flapped or perforated baffles are able to counter that aspect, by reducing the total area of the dead transfer zones behind the installed baffle arrangement. In that sense, the combination of both cooling mechanisms, the increased rate of vortices and the presence of impingement jets can provide spatially even heat extraction.

It should be noted that in most solar air heater applications, the surface of the absorber could be modified by various manufacturing processes, in order to attain the desired morphology that would enhance heat transfer. For instance, ribs and protrusions can be either be added or manufactured directly on the absorber material. In the case of PVT, it is the photovoltaic panel area that is heated by radiation. The backsheet of this is usually made of tedlar material and is hard to process. Future designs should take this difference of materials into consideration.

For the case of BIPVT, key challenges lie in the weight of the systems. Installations in the residential sector require low weight solutions, given the risk of damage on building envelopes. Heavy weight materials, such as metals, shows limitations for practical applications. Polymers, on the other hand, are a lightweight solution suitable for such applications. 3D additive manufacturing has progressed rapidly the past years, now being able to construct complex geometries with greater ease and in a shorter timeframe. Metals, polymers and composites are presently employed. Vortex generators in general require less material than baffles, thus are more fit for instances where low weight is critical.

In the end, it is of outmost importance for prospective designs to keep friction levels low, thus reducing pumping power demand. Although different methods might have similar TEF values, options with less severe pressure drop ought to provide better results, even if other solutions perform better thermally.

5 CONCLUSIONS

This study presents the prospective enhancements to the performance of PVT/BIPVT systems, with a thorough summary of key operational aspects in the development of solar air heater technology. The study concluded that:

- A parallel between solar air heaters and Air-based PVT technologies was drawn, emphasizing that methods employed for enhancing heat transfer in the former show potential for the latter as well.
- A thorough description of heat transfer improvement techniques that are apt for PVT and BIPVT systems was compiled based on literature review, mainly focusing on baffles, vortex generators, impingement jets and ribs
- Characteristics specific for such applications were described as well, with suggestions on how to counter them using novel approaches such as 3D printing or the utilization of polymers instead of metals.
- The study also pointed the challenges of optimizing pressure drop increase with any heat transfer enhancement method, to discover those solutions with minimum friction, in order for the system to be cost-effective.

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