Fins vs No Fins: A Comparative Experimental Analysis of Novel Box-Channel Photovoltaic/Thermal Collector Prototypes for Ground Source Heat Pump Integration

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Abstract

This study compares the thermal performance of two novel box-channel PVT collectors, assessing the impact of fins in low temperature operating conditions. This work will contribute the understanding of how PVT collectors can be integrated with GSHPs for borehole regeneration in cold climates. The two prototype PVT collectors were tested simultaneously at an outdoor testing facility in Stockholm, Sweden. The outdoor testing environment allows for the analysis of a variety of different weather conditions under different fluid flow rates as well as different roof installations. It was found that the finned PVT collector displayed a potential annual thermal energy output 11% higher than that of the non-finned one at the optimal flow rate of 77 l/h m2. At the optimal flow rate, fluctuations in wind speed also significantly impacted the observed specific thermal energy of the PVTs, mainly the finned PVT collector, with an increase of 93% being observed due to a 2.5 m/s increase in wind speed.

Keywords: Solar PV/thermal, PVT collector, heat pump, thermal performance, fins

1. Introduction

In recent years, the integration of photovoltaic/thermal (PVT) collectors with ground source heat pumps (GSHP) has been the interest of many research studies. This is because of the system's ability to decarbonise domestic heating while also regenerating the borehole field (Sommerfeldt et al., 2020) and reducing their length and spacing needs (Sommerfeldt and Madani, 2019).

One key feature of these systems is the low working fluid temperature, allowing for simultaneous cooling of the PV panel as well as heat extraction from ambient air. This allows for an increase in both thermal and electrical efficiencies of the PVT collector.

While the sheet and tube absorber is the most prevalent in literature as well as among commercially available PVTs, studies show that collectors with a box-channel absorber design outperform those with sheet and tube absorbers (Herrando et al., 2019). This is because of the increased heat transfer area between the fluid and the absorber plate. The addition of fins to the back of the absorber further increases the heat transfer area between the low temperature fluid and the higher temperature ambient air (Giovannetti et al., 2019).

However, the addition of fins serves to increase the PVT collector mass and cost. Therefore, to obtain a better understanding of the trade-offs between increased thermal performance and the associated increase in collector cost, it is necessary to conduct a comparative analysis of a specific PVT collector with and without fins. While previous studies have assessed the performance of finned PVT collector designs, to the best knowledge of the authors, there has not been a study that concurrently compares the effect of fins on the same absorber design through outdoor laboratory experiments. The results of this study will help in refining the design of PVT collectors specifically for GSHP integration.

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2. Objectives

The objective of this study is to compare two box-channel PVT collector prototypes, one finned and the other non-finned, under low operating temperatures and a wide range of ambient weather conditions. This will provide a better understanding of the effect of fins on energy and power outputs of PVT collectors. The aim of the work is achieved by answering the following research questions:

1. How do varying ambient weather conditions, such as wind and solar irradiance, affect the thermal output and U-value of the finned and non-finned designs?
2. How do varying flow rates of the working fluid impact the thermal performance of the finned and non-finned designs?
3. How do different roof installation types affect the thermal performance of the finned and non-finned designs?

3. Methods

The experiments performed are under outdoor dynamic conditions on a south facing testing array located at KTH Royal Institute of Technology, Stockholm, see the right panel of Figure 1. The testing facility includes two PVT collectors, identical apart from fins, designed specifically for heat pump integration. They consist of a harp-shaped box-channel absorber, with a manifold at either end for the inlet and outlet connection. The PVT design can be seen in Figure 2. Both PVTs are connected to a 12 kW variable speed HP with a 300 L cold storage tank, left of Figure 1. This allows for the simultaneous operation of the two PVTs with separate temperature and mass flow rate measurements from installed heat meters. The system diagram can be found in Figure 3. The HP can provide supply temperatures as low as -5°C during the summer, enabling low temperature operation. The collected heat is dissipated through a hot water tank and a 10 kW air-to-water heat exchanger. Ambient conditions at the collectors are measured by a weather station and a reference cell at the same tilt, 45°, as the PVT collectors.

Fig. 1: Left) Mechanical room containing the HP and hot and cold storage tanks, as well as the circulation pumps and their monitoring system. Right) Test rig with the PVT collectors being tested.

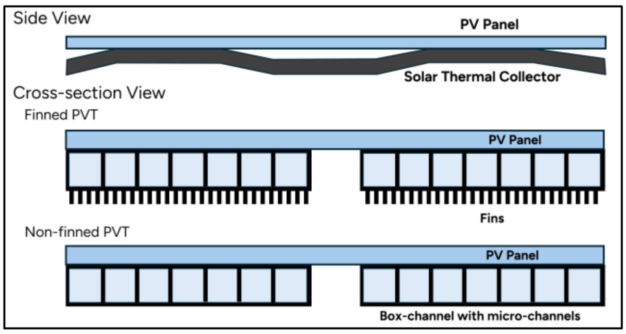

Fig. 2: Schematic of the prototype PVT absorbers, not to scale.

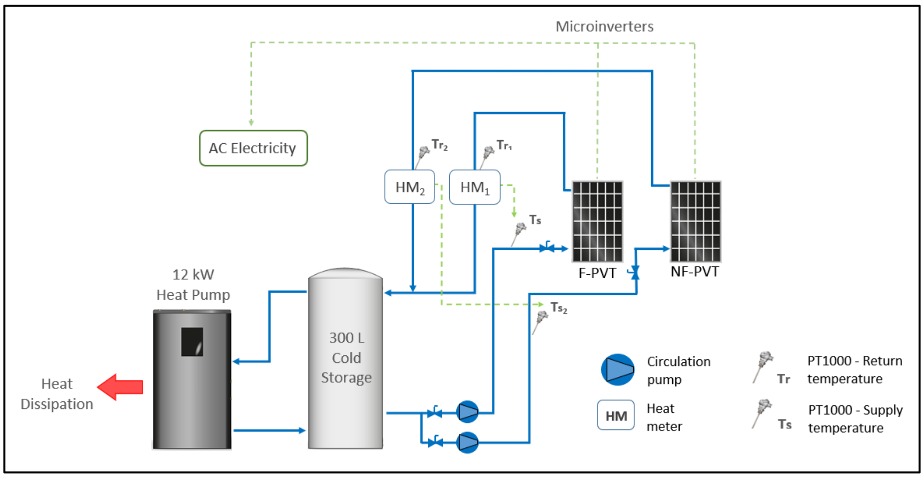

Fig. 3: System diagram of the testing rig.

Experiments are carried out over several days in spring 2024, between 11th March and 31st May, to obtain data in a variety of ambient conditions. This will allow for the investigation of the impact of ambient weather conditions, answering Question 1. The range of mass flow rates studied is approximately 50 to 100 l/h per meter^2, based on the manufacturer's recommended mass flow rate for the PVT collectors. This will provide data to answer Question 2. To answer Question 3, sheets of corrugated plastic and thin metal are used to construct side and back panels for the PVTs, see Figure 4. This final set of tests will be carried out at a constant flow rate of 51 l/h per m^2, however, as the tests are performed outdoors, a range of ambient conditions will be used.

Fig. 4: Left) Side panels attached behind the PV panel. Right) Back panel attached 14.5 cm behind the absorber of the PVT.

The mass flow rate along with the temperature difference between the inlet and outlet temperatures of the working fluid will be used to calculate the specific thermal power (W/m^2) of the PVT collectors. To compare the performance of the finned and non-finned designs, the thermal performance coefficients of the PVT collectors will be calculated using a simplified version of the specific thermal power output equation presented in ISO 9806:2017 for solar thermal collectors, see Equation 1. The coefficients and their errors are calculated using multivariable regression analysis.

$$\dot{q} = \eta_0 G + a_1(T_a - T_m) + a_3 u(T_a - T_m) - a_6 uG \qquad \text{(eq. 1)}$$

Additionally, the U-value of the PVTs will be calculated along with the potential annual thermal energy output per m^2. The U-value will be calculated at wind speeds of 1 m/s using Equation 2 below and the potential annual thermal energy output will be calculated by summing the hourly heat output of the PVT collectors. The hourly heat output is calculated using the obtained hourly thermal performance coefficients from the regression model, the monthly average mean brine temperature and hourly weather data of a typical meteorological year in Stockholm. The method is described in greater detail in Beltran et. al. (2024) and gives an estimation for the potential annual thermal energy output when a PVT is connected in series to a GSHP system in a Nordic climate.

$$U = a_1 + a_3 \times u \qquad \text{(eq. 2)}$$

4. Results

4.1. Result Validation

Tables 1 and 2 show the obtained thermal performance coefficients for the two prototype PVT collectors when considering different brine flow rates and different roof installation types, respectively. The calculated coefficient of determination of the regression, R^2, is also shown. Below in Figure 5, the empirical data can be seen for the baseline flow rate of 51 l/h per m^2 at different irradiance levels.

Tab. 1: Thermal performance coefficients for the finned and non-finned PVTs at the three flow rates tested.

Brine flow rate [l/h per m^2]	51		77		103	
Thermal performance coefficient	**Finned PVT**	**Non-finned PVT**	**Finned PVT**	**Non-finned PVT**	**Finned PVT**	**Non-finned PVT**
η_0	0.506	0.423	0.523	0.470	0.326	0.267
a_1	34.105	38.460	27.032	29.206	45.419	45.979
a_3	4.251	3.001	12.304	9.951	4.313	1.939
a_6	0.000	0.000	0.064	0.062	0.000	0.000
R^2	0.92	0.94	0.90	0.90	0.86	0.87

Tab. 2: Thermal performance coefficients for the finned and non-finned PVTs for the three roof installations tested.

Roof installation	Side panels		Back panels		Side and back panels	
Thermal performance coefficient	**Finned PVT**	**Non-finned PVT**	**Finned PVT**	**Non-finned PVT**	**Finned PVT**	**Non-finned PVT**
η_0	0.562	0.478	0.554	0.488	0.506	0.507
a_1	21.626	26.708	28.197	29.857	21.382	21.899
a_3	4.773	4.773	3.224	2.041	1.943	2.786
a_6	0.016	0.012	0.014	0.004	0.019	0.015
R^2	0.97	0.97	0.96	0.96	0.97	0.97

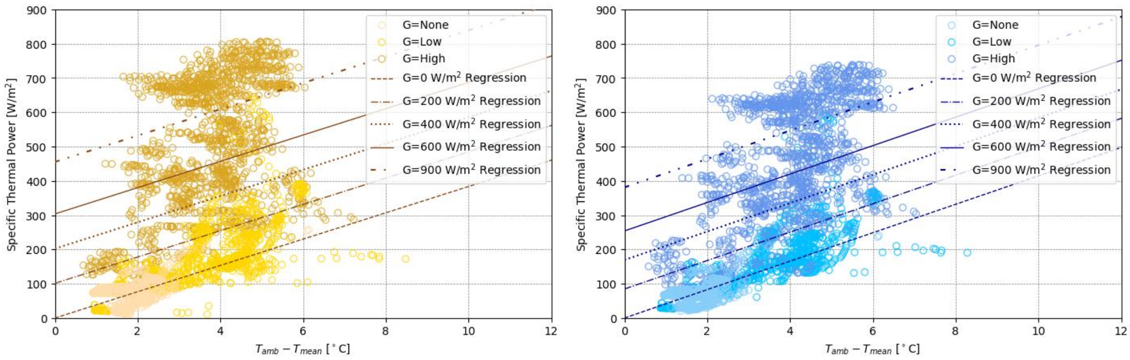

Fig. 5: Empirical data of the baseline flow rate of 51 l/h per m^2 with the corresponding regression line for the irradiance level for the finned PVT collector (yellow) on the left and the non-finned PVT collector (blue) on the right.

4.2. Ambient Weather Conditions

As the experiments were conducted outdoors between March and May of 2024, a broad range of ambient conditions was observed. This range is presented in Table 3.

Tab. 3: Range of ambient weather conditions experienced throughout experimental period.

Ambient Conditions	Unit	Minimum	Maximum
Irradiance	W/m^2	0	1286
Wind speed	m/s	0	9.1
Ambient Temperature	°C	-4.1	28

In conjunction with previous literature, it was found that a higher irradiance level leads to a higher specific thermal power output of both PVT collectors as the thermal efficiency of the absorber is constant, see Figure 6.

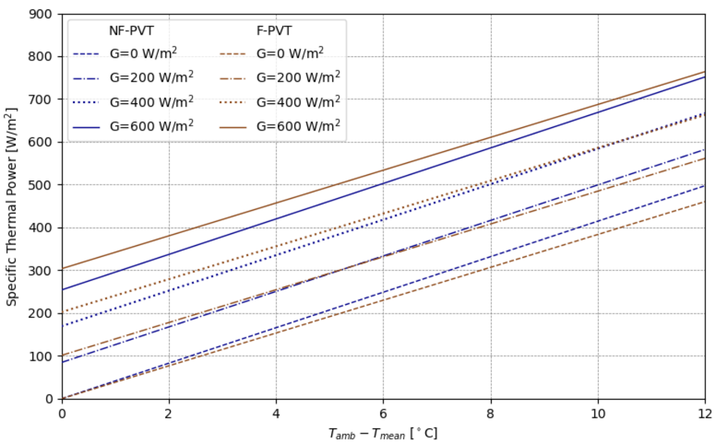

Fig. 6: Impact of increasing irradiance on the thermal performance of the non-finned (NF-PVT) and finned (F-PVT) PVT collector when using the baseline flow rate of 100 l/h per collector.

It can be seen from Figure 6 that at zero-irradiance the non-finned PVT collector has a higher specific thermal power than the finned collector. This is contrary to expectations but can be explained by a manufacturing defect on the non-finned PVT collector, resulting in a larger air gap between the PV panel and the absorber compared to that on the finned PVT collector. This will be discussed further in Section 5.

As with increasing irradiance, it was observed that increasing the wind speed improved thermal performance, see Figure 7. This is due to the greater airflow created around the PVTs, allowing for more efficient heat transfer. This can also be seen in the increasing U-values as the wind speed increases, see Table 4. Here it is also possible to see that the non-finned PVT collector appears to perform better thermally than the finned PVT collector. As above, this will be discussed in more detail below. It was found that as irradiance increases, the impact of increasing wind decreases. This shows that the thermal performance of the PVT is more sensitive to irradiance than wind speed. Finally, it was observed that the finned PVT was more sensitive to changes in wind speed, with an increase in wind speed resulting in greater improvements to the thermal performance and U-value of the finned PVT than the non-finned one. This was expected as the fins provide more surface area for the absorber to interact with the ambient air (Giovannetti et al., 2019).

Tab. 4: Impact of increasing wind speed on U-value of finned and non-finned PVT collector using a flow rate of 51 l/h per m^2.

Wind speed [m/s]	**Finned PVT** [W/(m^{2}K)]	**Non-finned PVT** [W/(m^{2}K)]
0.5	36.23	39.96
1.5	40.48	42.96
3	46.86	47.46

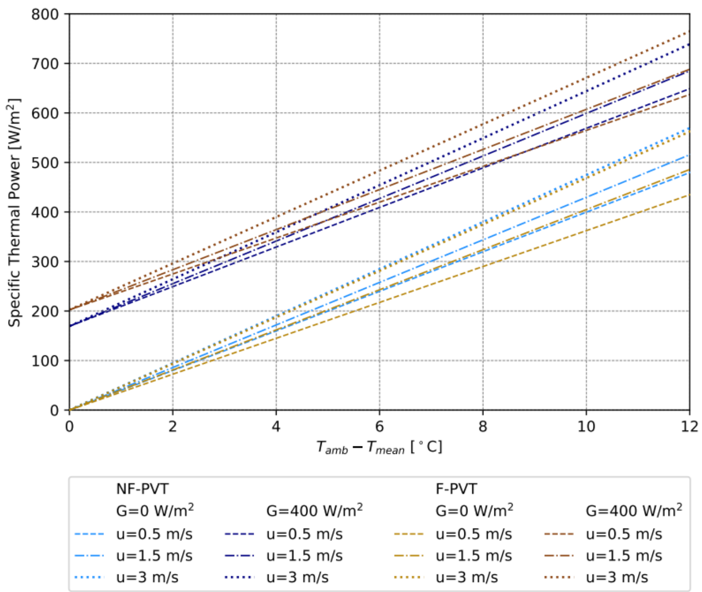

Fig. 7: Impact of increasing wind speed on the thermal performance of the non-finned (NF-PVT) and finned (F-PVT) PVT collector when using the baseline flow rate of 51 l/h per m^2 at two irradiance levels.

4.3. Flow Rate

When higher brine flow rates were used, it is possible to see how the thermal performance responded to the different ambient conditions described above.

As the mass flow rate of the brine was increased, the impact of increasing irradiance on the specific thermal power output of the PVT collectors was observed to decreased. This can be seen in Table 5. From this it is possible to see that the lowest flow rate is not fast enough to extract all the heat from the solar panel. However, the diminishing returns experienced at higher flow rates indicate the presence of an optimum flow rate for absorbing the solar thermal energy. It is also possible to see from Table 5 that the finned PVT collector displays higher improvements in specific thermal power than the non-finned PVT. This is due to a manufacturing defect resulting in better thermal contact between the PV panel and the absorber in the finned than the non-finned PVT collector. This will be discussed further in Section 5.

Tab. 5: Increase in the specific thermal power of both the finned and non-finned PVT collectors due to an increase in irradiance of 200 W/m^2.

Brine Flow Rate [l/h per m^2]	**Finned PVT** [W/m^2]	**Non-finned PVT** [W/m^2]
51	101	85
77	92	82
103	65	53

When looking at the impact of increasing wind speed on the different flow rates it was found that there is an optimal flow rate at which increasing wind speed significantly increases the specific thermal power. As seen in Table 6, for the PVT collectors tested, this flow rate was 77 l/h per m^2. This significant increase is due to the relative velocity of the wind and the brine being at the optimal speed for heat transfer. Through further testing it might be possible to derive a model for the optimal brine flow rate based on the predicted wind speed and direction. It is also possible to see from Table 6 that the finned PVT collector is more sensitive to increases in wind speed that the non-finned PVT collector, as mentioned before.

Tab. 6: Percentage increase in the specific thermal power of both the finned and non-finned PVT due to an increase in wind speed of 2.5 m/s at both zero irradiance and 400 W/m^2.

Brine Flow Rate [l/h per m^2]	**0 W/m^2**		**400 W/m^2**	
	Finned PVT	**Non-finned PVT**	**Finned PVT**	**Non-finned PVT**
51	+ 29 %	+ 19 %	+ 12 %	+ 9 %
77	+ 93 %	+ 73 %	+ 18 %	+ 12 %
103	+ 23 %	+ 10 %	+ 13 %	+ 7 %

Using the method described in Beltran et. al. (2024), it is possible to obtain the potential annual thermal energy output of each PVT collector, connected in series to a GSHP in a Nordic climate, at different flow rates. These can be seen in Table 7. The thermal performance coefficients used to calculate these annual thermal energies are given in Table 1. It is possible to see that under a typical meteorological year in Stockholm, the finned PVT collector produced more energy annually than the non-finned PVT collector. The amount by which the finned PVT collector thermally outperforms the non-finned one increases with increasing flow rate. This shows that a higher flow rate is more beneficial for a finned PVT collector than for a non-finned one.

Tab. 7: Potential annual thermal energy output of both the finned and non-finned PVT collector at the three tested flow rates.

Brine Flow Rate [l/h per m^2]	**Finned PVT** [kWh/m^2/yr]	**Non-finned PVT** [kWh/m^2/yr]	**Finned vs Non-finned**
51	2161	2070	+ 0.4 %
77	2685	2427	+ 11 %
103	2360	2033	+ 16 %

4.4. Roof Installations

To evaluate the impact of different roof installations, the potential annual thermal energy output (following the same method as above) of the different scenarios was compared. This can be seen in Table 8. As the different roof installation types are all evaluated at the baseline flow rate of 51 l/h per m^2, the potential annual thermal energy output is compared to the baseline flow rate case. For all three cases, the roof installation caused the

PVT to perform worse thermally than the baseline with no obstruction to the airflow around the absorber. Nonetheless, the finned PVT collector produced more heat energy per m^2 than the non-finned. This again shows that the additional surface area provided by the fins is beneficial to heat exchange with the ambient, as the restriction of the airflow does not impact the finned PVT collector as much as the non-finned PVT collector.

Tab. 8: Annual thermal energy of both the finned and non-finned PVT collector at the three tested roof distances.

Roof Installation Type	**Finned PVT** [kWh/m^2/yr]	**Finned PVT Comparison to baseline**	**Non-finned PVT** [kWh/m^2/yr]	**Non-finned Comparison to baseline**	**Finned vs Non-finned**
Side Panels	2016	- 5 %	1906	- 8 %	+ 6 %
Back Panels	1840	- 15 %	1723	- 18 %	+ 7 %
Side and Back Panels	1451	- 33 %	1528	- 26 %	- 5 %

In the third configuration of roof installations, consisting of both the side and back panels, the finned PVT gives a lower potential annual thermal energy output when compared to the non-finned, see Table 8. However, Table 9 shows that the thermal performance coefficient a_1, the heat transfer coefficient, of the two PVT panels is similar, withing statistical error. This shows that in the absence of wind, as with both the side and back panels the airflow around the absorber is severely restricted, the two PVT collectors behave the same in terms of heat transfer with the ambient. This is expected as the fins should help with extracting heat from the ambient air, and so when there is no movement of the air the fins will not impact the efficiency of the PVT collector. The a_3 thermal performance coefficient, the wind dependence of heat transfer coefficient, shows that the non-finned PVT is more sensitive to changes in wind speed, contrary to previous findings. This could be an artefact of the multivariable regression overestimating the impact of wind due to the recorded wind speed by the weather station not being equal to the wind speed experienced by the absorber.

Tab. 9: Thermal performance coefficients of the finned and non-finned PVT for the roof installation of both side and back panels.

Thermal performance coefficient	**Finned PVT**	**Non-finned PVT**
a_1	21.382	21.899
a_3	1.943	2.786
a_6	0.019	0.015
R^2	0.97	0.97

5. Discussion

When comparing the two PVT collectors in terms of their annual thermal energy, the finned PVT always outperforms the non-finned PVT collector, apart from the roof installation with both side and back panels. This can be seen in Tables 7 and 8 above. This shows that for the typical ambient conditions found in Stockholm, the finned PVT collector has the potential to generate more thermal energy output annually. However, as the additional cost of adding the fins is not known, it is imperative to conduct an economic analysis to determine whether the additional heat gained justifies the extra costs and well as the additional weight.

From testing different roof installations, it is possible to see that the fins improve heat exchange with the ambient, as expected from the result of Chhugani et. al. (2020). This is because when specific roof installations are added, and airflow around the absorber is restricted, the potential annual thermal energy output of the finned PVT collector decreases less with respect to the baseline than the potential annual thermal energy output of the non-finned PVT collector. This means that the finned PVT thermally outperforms the non-finned PVT collector under these conditions. Similarly, when wind speeds were increased, the finned PVT performed significantly better than the non-finned PVT collector. It was also observed that the specific thermal output of both collectors is very sensitive to wind speed, as previously found by Lammle and Munz (2022). To more accurately quantify the impact of wind, a longer testing period is needed. This additional data could enable the creation of a model that can provide the optimal flow rate for the predicted wind speed and direction.

As previous literature has found, it is extremely difficult to determine the optimal flow rate of an integrated PVT and GSHP system as there are many variables affecting the system's operation (Yan et. al., 2022). It has been widely agreed that increasing flow rate results in more heat being collected under constant ambient conditions. However, there are diminishing returns as flow rate increases with Abdul-Ganiyu et. al. (2021) finding that for a solar thermal collector in Ghana, flow rates above 227 l/h per m^2 do not result in additional heat gains. In the current study it was found the optimal flow rate was 77 l/h per m^2. This is much lower compared with Abdul-Ganiyu et. al.'s (2021) result, however this can be explained by the large difference in ambient temperature between the two locations.

When comparing the finned and non-finned PVT, this study found that the optimal flow rate is the same for both collectors. This is because of the large intervals used when testing different flow rates. However, as the two PVTs are affected differently by the ambient conditions, it is possible that the optimal flow rate for the two collectors is not the same. By testing a greater number of flow rates around the optimal flow rate of 77 l/h per m^2 it will be possible to determine the true optimum for each PVT collector as well as how rapidly changes in flow rate cause deviations from the maximum thermal performance. This will show if there is a range of optimal flow rates rather than a singular optimum. The data gathered could be used to incorporate the flow rate into the coefficient calculation, creating a model that considers flow rate as well as other ambient conditions such as irradiance and wind speed. This would help expand on Yan et. al. (2022) work. In addition to testing a greater number of flow rates, looking at the trade-offs between the larger specific thermal power gained by the larger flow rate and the increase in pumping power required could help determine a global optimum flow rate rather than a flow rate optimised for thermal performance of the PVT collector. In a previous study, Gomariz et. al. (2019) found that the lower cost of using 20 l/h per m^2 did not justify the loss in heat gains compared to the 80 l/h per m^2 flow rate for solar thermal collectors.

When comparing the two PVTs, some results contrary to what was expected from literature were found. These results were the generally higher a_1 thermal performance coefficient of the non-finned PVT collector, resulting in lower U-values for the finned PVT collector compared to the non-finned one, and the higher zero-loss efficiency of the finned PVT collector. This is the opposite to what was expected from the results of Beltran et. al. (2024) as well as Giovanetti et. al. (2019). Upon inspection of the PVTs it was determined that this was due to imperfect thermal contact between the PV panel and the absorber on the non-finned PVT. This resulted in less efficient thermal exchange between the PV panel and the absorber, lowering the zero-loss efficiency of the non-finned PVT collector compared to the finned PVT collector, and created an airgap between the PV panel and the absorber. This meant that there was more surface area exposed to ambient air for heat exchange, artificially increasing the a_1 thermal performance coefficient. This was exacerbated by the more exposed location of the non-finned PVT collector on the roof, allowing a greater airflow around the collector. Figure 8 provides thermal images of the two PVT collectors showing the identified imperfect thermal contact. While both PVT collectors experience this problem, the higher temperature of the "hot spot" on the non-finned PVT demonstrates worse thermal contact and so a larger airgap.

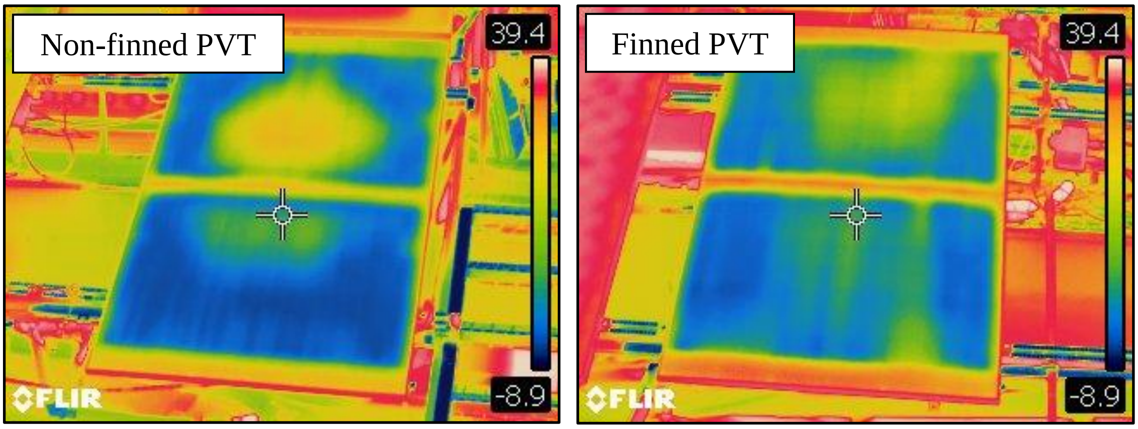

Fig. 8: Thermal images of the two PVT collectors (non-finned on the left and finned on the right) to show the imperfect thermal contact between the PV and the absorber, showing the larger airgap present in the non-finned PVT collector.

6. Conclusion

In conclusion, using the U-value, specific thermal power output and potential annual thermal energy output, the thermal performance of a finned and non-finned prototype PVT collector were compared. The PVTs were evaluated outdoors in Stockholm, simulating cold temperature operation for PVT integration with a GSHP system as a borehole regeneration mechanism. It was found that the finned PVT collector has an overall better thermal performance than the non-finned PVT collector. This can be seen by the finned PVT collector displaying potential annual thermal energy outputs 11% higher than that of the non-finned PVT collector at the optimal flow rate.

In general, higher levels of irradiance and wind speeds lead to improved values of specific thermal power output, with a 200 W/m^2 increase in irradiance resulting in increases in specific thermal power output of 92 W/m^2 for the finned PVT collector and 82 W/m^2 for the non-finned PVT collector. When considering irradiance, a higher flow rate is always desirable due to the higher specific thermal power output, however, the trade-off with increase pumping power needs to be determined. With increasing wind speeds, for optimal increase in performance, a balance between the wind speed and the brine flow rate must be found. In this study, the optimal flow rate was around 77 l/h per m^2. As mentioned above, each PVT collector was affected differently by the ambient conditions so to determine the optimal operating conditions the average ambient conditions need to be considered.

This study found that a higher flow rate appears to be more favourable for the finned PVT while the non-finned PVT performs thermally better at the lower flow rates. This can be seen by greater improvements in the finned PVT collector as flow rate increased compared to the non-finned one. However, to determine the true optimum, or if a range exists, smaller increments in flow rate need to be evaluated. When combined with the analysis of ambient conditions, a global optimal flow rate can be determined for the entire system.

The impact of restricting airflow around the absorber by adding different roof installations proved to decrease potential annual thermal energy output of both PVTs between 7% and 33%, with the non-finned thermally underperforming the most. This can be seen by the finned PVT collector's thermal performance coefficients resulting in a potential annual thermal energy output around 6% higher than the non-finned PVT collector. This further supports the found positive impact fins have on aiding heat transfer with the ambient. It can also be concluded than on a sloped roof, the addition of fins is beneficial as they allow for greater heat absorption. However, the fins will add weight to the PVT collector and so a full system analysis needs to be conducted to see if the additional heat gains justify the installation constraints.

Further work to this study includes a full techno-economic analysis to determine the financial feasibility of the addition of fins to the PVT absorber. This will show whether the additional heat absorbed justifies the additional cost. Secondly, the ambient conditions studied did not include cold climate weather patterns such as condensation, rain and frost. Therefore, to obtain a full picture of the operation of these two PVT collectors in cold climates further studies on these phenomena are needed. Lastly, as it was observed that the zero-loss efficiency and the a_1 thermal performance coefficient are sensitive to the thermal contact between the PV panel and the absorber. This led to results that are contrary to what has been previously found in literature. However, based on the trends observed, even with the manufacturing defect, the fins increase heat exchange with the ambient. To provide more certainty in the results, a further study with multiple panels could be conducted to help quantify the impacts of manufacturing deviations.

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