Development and Indoor Testing of a High-Performance PV/Thermal Panel with Integral Stagnation Control

Lucio Mesquita[1], Steve Harrison[2], Roy Indranil[2], and Ben Stinson[2]

[1] Natural Resources Canada, CanmetENERGY-Ottawa, Ottawa (Canada)

[2] QSBR Innovations Inc., Kingston (Canada)

Abstract

Photovoltaic-thermal (PVT) collectors, as devices that can provide both electricity and heat, have the potential to achieve lower installation costs and higher total energy production for the same roof or ground area than separate photovoltaic (PV) and solar thermal (ST) systems. High-performance PVT collectors can enhance the economics of PVT systems by producing heat that can be used directly for domestic hot water systems, space heating and industrial process applications. The increased maximum temperature in high-performance PVT collectors carries an inherent risk of absorber overheating under stagnation conditions. Many PV panels' damage mechanisms are related to higher temperatures, and some of them can lead to catastrophic failures. This work presents outdoor and indoor test results for PVT collectors equipped with an anti-stagnation mechanism, evaluating maximum absorber temperature under stagnation conditions. A glazed PVT collector prototype was built by adapting a commercially available PVT collector with an anti-stagnation device. The prototype was subsequently modified to incorporate low-emissivity glass top glazing. The testing conducted has shown the effectiveness of an air-venting channel on the back of the absorber in reducing the maximum stagnation temperature of the PVT collector, even when oriented in a relatively challenging landscape orientation. Finally, the use of a solar simulator for stagnation temperature measurement has been shown to produce results similar to those measured outdoors and offers the advantage of obtaining steady-state repeatable conditions

Keywords: *photovoltaics, solar thermal, PV/Thermal, PVT, stagnation, overheating, Canada*

1. Introduction

Increasing the use of non-emitting, renewable energy sources is an essential element of greenhouse gases (GHG) emissions reduction initiatives. In Canada, energy use in housing, buildings, and communities accounts for about a quarter of the country energy consumption (NRCan, 2019) and 17% of its GHG emissions (ECCC, 2022). Residential space heating (SH) consumed 885 PJ of energy in 2016, 47% of which was supplied by natural gas (26% by electricity) (NRCan, 2016). Domestic hot water (DHW) represented an annual load of 284 PJ of which 68% was supplied by natural gas. Photovoltaic-thermal (PVT) collectors, as devices that can provide both electricity and heat, offer interesting opportunities to support GHG emissions reductions. They have the potential to achieve lower installation costs and higher total energy production per m^2 of occupied roof space than separate photovoltaic (PV) and solar thermal (ST) systems, as shown by Lämmle et al. (2017).

As with solar thermal collectors, a PVT collector can have either a gas or a liquid as the heat transfer fluid. The collectors can also be glazed or unglazed, and non-concentrating or concentrating. Until now, most PVT collectors available in the market are liquid, unglazed and non-concentrating (De Keiser et al., 2017). This is in part because unglazed collectors have a small impact on the module's electricity production and require minimal or no changes to the standard PV panel frame. However, unglazed PVT collectors have limited potential to generate heat at temperatures that can be used directly for domestic water heating, space heating and industrial processes. Therefore, in recent years, there has been a greater effort in the development of high-temperature PVT (HT-PVT) collectors. High performance at elevated temperature levels is mostly achieved by reducing convective thermal losses, as with the vacuum insulated model developed by UK-based Naked Energy (Mellor et al, 2018) and/or by reducing the radiative thermal losses, as presented by Lämmle et al. (2016).

doi:10.18086/eurosun.2022.12.13 Available at http://proceedings.ises.org

2. Overheating Protection in Solar Thermal Collectors

Overheating protection has been developed for solar thermal collectors to prevent damage to the heat transfer fluid and/or to the absorber. Harrison and Cruickshank (2012) reviewed different technologies used for stagnation control in solar thermal systems. The authors divided the stagnation control approaches into system, array and collector levels. They also pointed out the main advantage of anti-stagnation technologies that are integral to the collector design: by addressing stagnation at the source, this approach maintains lower collector temperatures during stagnation, therefore eliminating negative effects of excessive temperatures, e.g., thermal stresses, over-pressures, and material and heat transfer fluid degradation.

Harrison et al. (2004a) proposed an innovative integral stagnation control. The approach uses a passive venting channel located below the absorber (Fig. 1). The bottom (or back) of the channel is insulated to reduce heat loss during normal operation. Flow through the channel is induced by buoyancy-driven natural convection, initiated by a valve assembly designed to open at a predetermined temperature. An automatic valve controls airflow through the channel, effectively reducing the maximum absorber temperature under stagnation conditions.

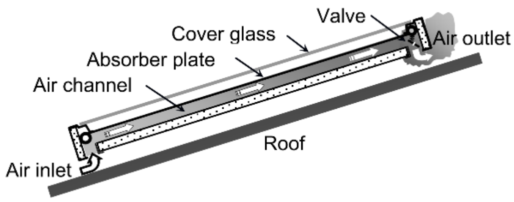

Fig. 1: Conceptual design of a solar collector with integral stagnation temperature control

The increased performance in high-temperature PVT collectors carries an inherent risk of absorber overheating. Many PV cells and their encapsulation have damage mechanisms that increase with operational temperatures, and some of them can lead to catastrophic failures, depending on the maximum temperature reached by the absorber. The collector designer has essentially two choices: to develop new PVT collectors based on new materials that can withstand the stagnation temperatures (Matuska et al., 2015) or to control stagnation maximum temperature.

3. Prototype Design

In the present work, a HT-PVT collector prototype was designed and built with the same integral stagnation control presented by Harrison et al. (2004b). The prototype was built by adapting a commercially available PVT collector, Solimpeks model Powertherm, with the anti-stagnation device. Table 1 presents the relevant specifications for the PowerTherm collector.

Tab. 1: Commercial collector specifications, from Eurofin (2011) and Solimpeks (2019).

Overall Dimensions (mm)	870 x 1640 x 105
Gross Area (m²)	1.427
Aperture Area (m²)	1.420* (1.268)
Absorber Area (m²)	1.400* (1.214)
Absorber Material	copper
Absorber Thickness (mm)	0.12
Number of Risers	14
Risers OD (mm)	8
Headers OD (mm)	22
Glazing Material	low iron tempered glass
Glazing thickness (mm)	4
PV Cell Material	Si, Mono-Crystalline
Nominal PV Power (W)	180
Module Efficiency (standard conditions) (%)	12.90
Temperature coefficient of Pmax (%/°C)	-0.45

***See discussion regarding measured dimensions below.**

It is relevant to note that our measurements indicate significantly different aperture and absorber dimensions than what was reported by Eurofin (2011) and Solimpeks (2019). During this investigation, an aperture area of 1.268 m^2 and an absorber area of 1.214 m^2 was measured.

For the prototype, a 44 mm air channel and 25 mm thick polyisocyanurate (PIR) insulation board replaced the original collector's 50 mm glass wool back insulation. The 25 mm PIR insulation has approximately the same conductive thermal heat transfer coefficient as that of the 50 mm glass wool (0.93 W/m^{2}K for PIR vs 0.89 W/m^{2}K for glass wool). Temperature sensors were added to the back of the absorber and positioned as shown on Fig. 2. Both the back of the absorber and the front of the polyisocyanurate board were painted black to enhance the radiative heat transfer between the two surfaces. Air channel openings of 30 mm were installed along the full extension of the top and bottom of the collector (i.e., for the landscape orientation). Those openings were closed with foam insulation and sealed with aluminium tape during the "closed" tests, and then opened to evaluate the impact of the air channel airflow on maximum stagnation temperatures (see Fig. 3). A commercial version of such solution would have automatically operated valves/dampers as described by Harrison et al. (2004a).

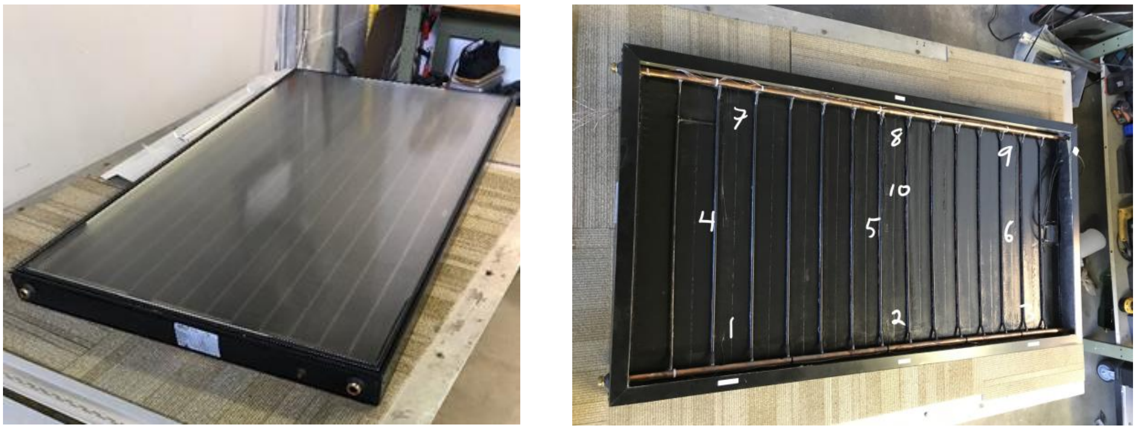

Fig. 2: Original commercial PVT collector (left) and collector being modified (right). Numbers denote the position of temperature sensors that were attached to the back of the absorber.

Fig. 3: Photo showing the 30 mm air channel openings installed along the full extension of the top and bottom of the collector (left, open channels), (right, channels sealed).

After the outdoor and initial indoor tests, the collector was modified once again. A low-iron glass with a low emissivity coating replaced the original top glazing. This glass, manufactured by Pilkington under the trade name Advantage Low-e, has, according to the manufacturer, an infrared emissivity of 0.1428.

4. Stagnation Testing

4.1 Outdoor Testing

Due to COVID-19 restrictions, the initial testing in 2020 of the prototype with the original glazing was done outdoors. The tests were conducted at NRCan's National Solar Test Facility (NSTF), in Mississauga, Ontario

(43.6°N Latitude). Although the vented air channel had been successfully used in solar thermal collectors before (Harrison et al., 2004), questions remained regarding the cooling capacity of the channel for a "landscape" configuration such as in this prototype, as there is a reduced buoyancy to drive the airflow in such configuration, as compared to a "portrait" configuration. The panel was mounted at 30° tilt, facing south. Daily irradiance, wind speed, panel and ambient temperatures were recorded with the air-vent open and closed. Figure 4 shows the prototype mounted for testing. Measured stagnation temperatures on the absorber and insulation surfaces and in the air-stream (at the center of the back of the panel) are shown on Figs. 5a and 5b for two similar days and with the vent channel closed and open. Results are summarized in Table 2. The stagnation temperature was measured by sensor 10, which is positioned at the centre of the absorber width (along the direction of the headers), and at 2/3 of the absorber height (along the direction of the risers). Under stagnation, absorber temperatures reached 124°C with the vent closed, as opposed to 95°C when the vent was open.

Tab. 2: Summary of outdoor stagnation test results for Aug 20 (channel closed) and Aug 23 (channel open).

Period 1PM to 2:30PM	Avg. Solar Rad. (W/m^2)	Avg. Amb. Temp. (°C)	Avg. Wind Speed (m/s)	Peak Absorber Temp. (°C)
Vent Closed Aug 20	1106	27	1.50	124
Vent Open Aug 23	1108	32	1.55	95

Fig. 4: Prototype undergoing outdoor stagnation testing (left), and open vent in rear of collector (right).

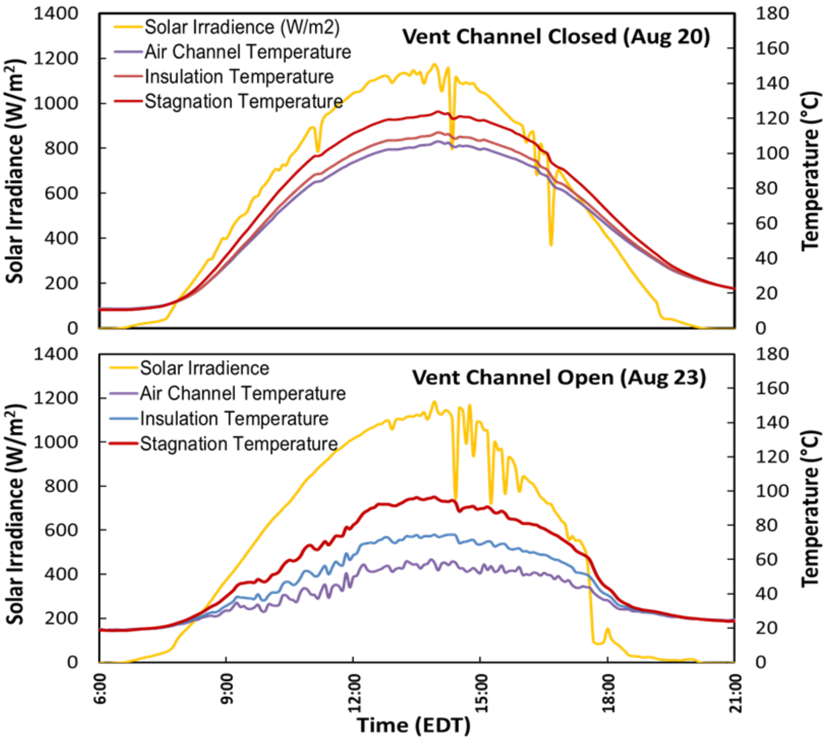

Fig. 5: Test results for prototype undergoing outdoor stagnation testing, a) top – air vent closed, b) bottom- air vent open.

4.2 Indoor Testing

Once most COVID-19 restrictions were lifted, the collector prototype was tested indoors under controlled conditions using the environmental chamber and solar simulator at the National Solar Test Facility, Fig. 6. The simulator uses a 200 kW VORTEK single-source arc-argon lamp. The prototype was mounted at 60° tilt and all tests were performed at a wind speed of 0.65 m/s. Twelve different conditions were tested, as shown in Table 3.

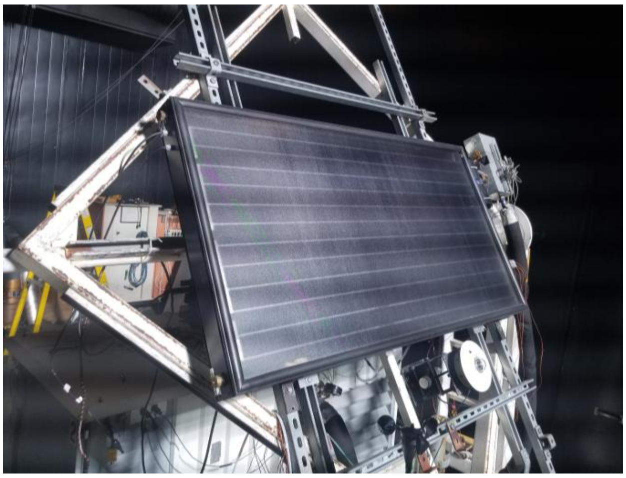

Fig. 6: Collector mounted for indoor stagnation testing using the solar simulator.

The highest stagnation temperature was achieved with the collector operating under open circuit, at irradiation level of 1000 W/m^2, closed vent and low-e glazing. In this case, the stagnation temperature reached 143.9 °C. As with the outdoor tests, opening the air vent provided significant relief regarding the stagnation temperature. For the conditions mentioned above, opening the vent reduced the stagnation temperature from 143.9 °C to 82.1°C. By reducing the heat losses, the use of low-e glazing leads to significant increases in stagnation temperatures. Under the same conditions of cases 1 and 3, the stagnation temperature for the collector with low-e glazing was 23.3°C than the collector with the original glass. However, in the case of operation with the air vent open, the collector with low-e glazing presented a stagnation temperature lower than the collector with the original glass. The explanation for this is the fact that, with the air vent open, the heat losses are dominated by convective processes and, at the same time, less irradiation reaches the absorber due to the lower solar transmittance of the low-e glass. The test results are also grouped according to their test configuration and plotted in Figs. 7 to 10 for comparison.

Tab. 3: Test cases for the indoor stagnation tests.

Case#	Nominal Irradiation (W/m2)	Vent	PV Operation	Top Glazing	T_{STAG} (°C)	Avg Irrad (W/m²)	Avg Tamb (°C)
1	1000	Closed	OC	Low-e	143.9	1041	31.2
2	1000	Closed	MPP	Low-e	133.8	1044	31.6
3	1000	Closed	OC	Original	120.6	1059	31.4
4	1000	Closed	MPP	Original	111.2	1061	31.6
5	800	Closed	OC	Original	102.7	799	31.4
6	800	Closed	MPP	Original	94.1	799	31.3
7	600	Closed	OC	Original	88.3	603	31.1
8	1000	Open	MPP	Original	86.7	1060	31.4
9	1000	Open	OC	Low-e	82.1	1043	31.7
10	1000	Open	MPP	Original	79.7	1057	31.7
11	800	Open	OC	Original	75.4	798	31.5
12	600	Open	OC	Original	66	599	31.2
OC= open circuit, MPP= maximum power point, Tstag is the maximum temperature at sensor 10							

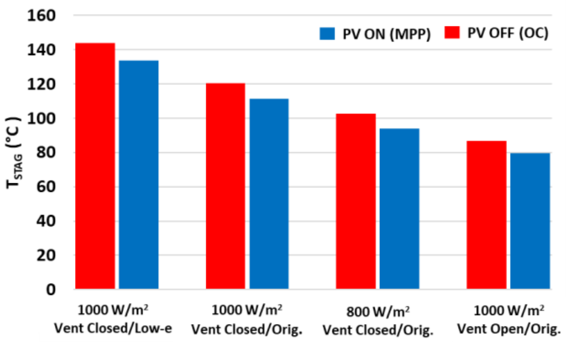

Fig. 7: Stagnation temperatures for cases with PV operating in open circuit (OC) and maximum power point (MPP).

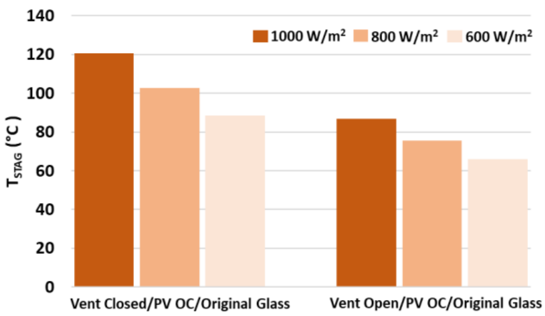

Fig. 8: Stagnation temperatures for cases with varying irradiation levels.

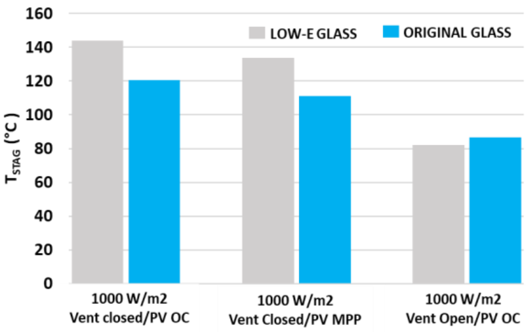

Fig. 9: Stagnation temperatures for cases with the original and low-e glazings.

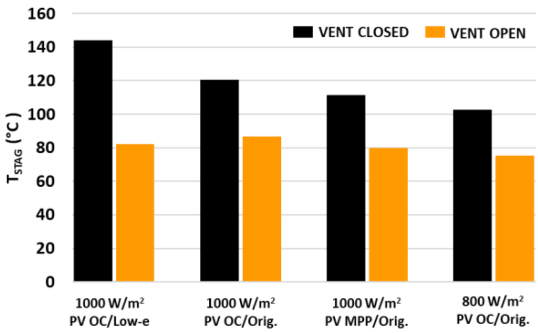

Fig. 10: Stagnation temperatures for cases with air vent channel closed and open.

5. Conclusions and Future Work

As anticipated, the results confirm that when PV output is reduced, stagnation temperatures further increased. The testing conducted has shown the effectiveness of the air channel in reducing the maximum stagnation temperature of the PVT collector, even when oriented in a relatively challenging landscape orientation.

The results also show that the addition of a Low-E coating to the interior of an exterior glazing in a PVT collector significantly increases stagnation temperature to potentially damaging levels. For the Low-E glazing used, the solar transmittance was not as high as the transmittance of the "solar" glass used in the unmodified collector. If further improvements in the solar transmittance of Low-E coated glass are made, stagnation temperatures would be significantly increased, requiring the redesign of PVT collectors, or the inclusion of active stagnation control to deal with times when the thermal and PV loads are reduced.

Finally, the use of a solar simulator for stagnation temperature measurement has been shown to produce results similar to those measured outdoors and offers the advantage of obtaining steady-state repeatable conditions. It is important to note the solar simulator facility used for this study consists of a single-source lamp equipped with water cooled mirror elements that reduce excessive thermal irradiance, while also providing a highly collimated beam that closely matches natural sunlight.

Future work will include additional testing of the prototypes to fully characterize their thermal and PV efficiency under different operational conditions.

6. Acknowledgments

The authors would like to thank Khaled Ayyad (Element Materials) for his technical support and his contribution to many discussions on the topics studied in this paper. Funding for this project was provided by NRCan's Program of Energy Research and Development (PERD).

7. References

De Keiser, C., Bottse, J. and De Jong, M., 2017, PVT Benchmark – an overview of PVT modules on the European market and the barriers and opportunities for the Dutch market, SEAC/TNO, Eindhoven, Netherlands.

ECCC, 2022. 2030 Emissions Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy. Environment and Climate Change Canada. Gatineau, Quebec.

Eurofins – Modulo Uno S.P.A, 2011, Test report M1.11.NRG.0319/43724, Torino, Italy.

Harrison, S. and Cruickshank, C., 2012, A review of strategies for the control of high temperature stagnation in solar collectors and systems. Energy Procedia, 30, pp.793-804, https://doi.org/10.1016/j.egypro.2012.11.090

Harrison, S.J., Lin, Q., Mesquita, L.C.; Valletta, D.A., 2004a, Method and apparatus for solar collector with integral stagnation temperature control - WO 2004070289 A1. Patent.

Harrison, S.J., Lin, Q., Mesquita, L.C.S., 2004b, Integral Stagnation Temperature Control for Solar Collectors. SESCI 2004 Conference, University of Waterloo, Ontario, Canada August 21st–25th, 2004.

Lämmle, M., Kroyer, T., Fortuin, S., Wiese, M. and Hermann, M., 2016, Development and modelling of highly efficient PVT collectors with low-emissivity coatings. Solar Energy, 130, pp.161-173, https://doi.org/10.1016/j.solener.2016.02.007.

Lämmle, M., Oliva, A., Hermann, M., Kramer, K. and Kramer, W., 2017, PVT collector technologies in solar thermal systems: a systematic assessment of electrical and thermal yields with the novel characteristic temperature approach, Solar Energy, 155, pp. 867-879, https://doi.org/10.1016/j.solener.2017.07.015.

Matuska, T., Sourek, B., Jirka, V., and Pokorny, N., 2015, Glazed PVT Collector with Polysiloxane Encapsulation of PV, Cells: Performance and Economic Analysis, International Journal of Photoenergy, Volume 2015, Article ID 718316., https://doi.org/10.1155/2015/718316.

Mellor, A., Alonso Alvarez, D., Guarracino, I., Ramos, A., Riverola Lacasta, A., Ferre Llin, L., Murrell, A., Paul, D., Chemisana, D., Markides, C. and Ekins-Daukes, N., 2018, Roadmap for the next-generation of hybrid photovoltaic-thermal solar energy collectors. Solar Energy, 174, pp.386-398, https://doi.org/10.1016/j.solener.2018.09.004.

NRCan, 2016, Table 7: Space Heating Secondary Energy Use and GHG Emission by Energy Source, NRCan Energy Use Statistics Residential Sector, Natural Resources Canada, Ottawa, Ontario.

NRCan, 2019, Canada's Secondary Energy Use (Final Demand) by Sector, End Use, and Subsector, National Energy Use Database, Natural Resources Canada, Ottawa, Ontario.

Solimpeks, 2019. General Catalogue - 022019/1. Available at https://solimpeks.com.tr/wp-content/uploads/dokumanlar/kataloglar/Solimpeks_EN.pdf, Accessed 07/09/2022.

Zondag, H.A., 2008, Flat-plate PV-Thermal collectors and systems: a review. Renew. Sustain. Energy Rev., 12, pp. 891-959, https://doi.org/10.1016/j.rser.2005.12.012.