Study of the Impact of Automatic Backflush on Direct SDHW Thermosyphon Systems

Ben Stinson[1], Stephen J. Harrison[2], Joseph Breton[1], Anh Kiet Nguyen[1]

[1]QSBR Innovations Inc. Kingston (Canada)

[2]Queen's University, Dept. of Mechanical and Materials Engineering. Kingston (Canada)

Abstract

Thermosyphon solar water heaters are often deployed in regions where freezing ambient conditions do not occur, allowing potable water from the storage tank to be directly circulated through the solar collectors. In many regions "hard water" conditions exist where dissolved minerals can deposit on hot surfaces within the solar collector's flow tubes, restricting the flow of water and resulting in increasing collector temperatures. A recent development aims to alleviate this condition by introducing a novel flow configuration and valving system that reverses the flow of cold "mains" water through the solar collectors each time hot water is drawn from the system. This configuration was pioneered at Queen's University and developed further by QSBR Innovations Inc. This valve and flow configuration flushes the collector, and the regular introduction of cooler "mains" water significantly reduces the potential of hardwater scaling in the solar collectors. This study investigates the effect of this flow reversal on the energy delivered to the end user through a side-by-side comparison of two thermosyphon solar systems; one with the backflush feature and one without.

Testing was conducted during the summer/fall of 2023 and then again during the summer of 2024 using two identical solar thermal collectors and tanks. Flow and temperature measurements were taken at regular intervals and used to compare the performance of the two systems. The results indicate that reversing the flow of mains water through the solar collector at regular intervals does not have a significant effect on the energy delivered to the operator or the temperatures in the storage tank. These laboratory results need to be verified in the field; however, the initial data is very promising.

Keywords: thermosyphon, backflush, valve, SDHW

10.18086/eurosun.2024.07.17 Available at http://proceedings.ises.org

1 Introduction

Thermosyphon solar water heaters have existed for over a century as an inexpensive and simple method to heat domestic water and other process fluids (Ragheb, 2014; Jamar et al., 2016). These systems typically consist of solar thermal collectors that circulate water from elevated thermal storage during charging. A feature of thermosyphon systems is the low parasitic energy consumption, as buoyancy forces in heated solar collectors cause the circulation of water, to and from an elevated thermal storage. Most of these systems are deployed in regions where freezing ambient conditions do not occur, allowing potable water from the storage tank to be directly circulated through the solar collectors. In many regions, however, “hard water” conditions exist where dissolved minerals in the water supply can deposit on hot surfaces within the solar collector’s flow tubes, restricting the flow of water and resulting in increasing collector temperatures (Arunachala et al., 2009; Kedar, 2014). If this condition is allowed to continue, flow through the solar collectors will be restricted such that solar collectors stagnate, potentially damaging the system components and causing systems to over-temperature.

A recent development aims to mitigate this condition by introducing a novel flow configuration and valving system that reverses the flow of cold “mains” water through the solar collectors each time hot water is drawn from the system. This configuration was pioneered at Queen’s University and developed further by QSBR Innovations Inc. and allows a thermosyphon system to function normally in heating mode but reverses the flow direction within the collector when there is a draw of hot water, Fig. 1. This flushes the system, and the regular introduction of cooler “mains” water significantly reduces the potential of hardwater scaling in the solar collectors. This approach was previously applied to backflushing plate style heat exchanger (Harrison, 2005). This study investigates the effect of flow reversal in thermosyphon solar systems on the energy delivered to the end user, through a side-by-side comparison of two thermosyphon solar systems; one with the backflush feature and one without.

2 Methodology

Two identical direct thermosyphon systems were set up in June 2023, one with the flow reversal (automatic backflush or ABF) feature and the other without, as a baseline system, Fig. 2. Programmed hot water draws at various flow rates, e.g., 0.0067-liter s^{-1} (4 liters min^{-1}), 0.1-liter s^{-1} (6 liters min^{-1}) and 0.167-liter s^{-1} (10 liters min^{-1}), were made on the systems at regular intervals. The systems were controlled with a National Instrument Data Acquisition system to draw water from the thermosyphon tanks using a United States Department of Energy specified draw schedule, adapted for 2 people of 120 liters per day (U.S. DOE) (Tab. 1).

Tab. 1: U.S Department of Energy small draw profile in liters (U.S. DOE).

Draw Schedule												
Time (h:mm)	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Draw Volume (liter)	0	0	0	0	0	1.82	10.91	12.73	10.91	7.28	7.28	5.46
Draw Schedule												
Time (h:mm)	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Draw Volume (liter)	5.46	3.64	1.82	3.64	5.46	5.46	7.28	9.09	7.28	5.46	5.46	3.64

Each system was supplied by mains water and included a 110-liter horizontally mounted tank, insulated with 5 cm of foam insulation, located above the collector. The mains water temperature was not controlled but was measured and recorded at multiple locations. During a draw the DA system sample rate was once every 0.5 seconds. Each tank contained a temperature probe, with 8 type T-thermocouples, to measure temperatures vertically at 5 cm intervals. This allowed measurement of the degree of stratification and the impact of backflushing on stratification within the tank. No diffusers or baffles were used on the inlet water pipes to aid stratification.

The system also included an Eppley PSP pyranometer located between the collectors, and type T-thermocouples to measure the inlet, outlet, and ambient temperature conditions. Flow measurements were taken using 2 Yokogawa AXF multi-directional magnetic flow meters with an accuracy of 0.35% of rate. One was located on the mains water inlet supplying both systems and the other was located on the cold side of the thermosyphon loop of the system equipped with the backflushing valve, allowing for accurate measurements of the thermosyphon flow rate and backflushing flow rate. There was no flow meter installed on the baseline thermosyphon loop. For comparison of the buoyance driven flow rate, the backflushing valve was removed from the system with no other modification to the piping configuration, Fig. 6.

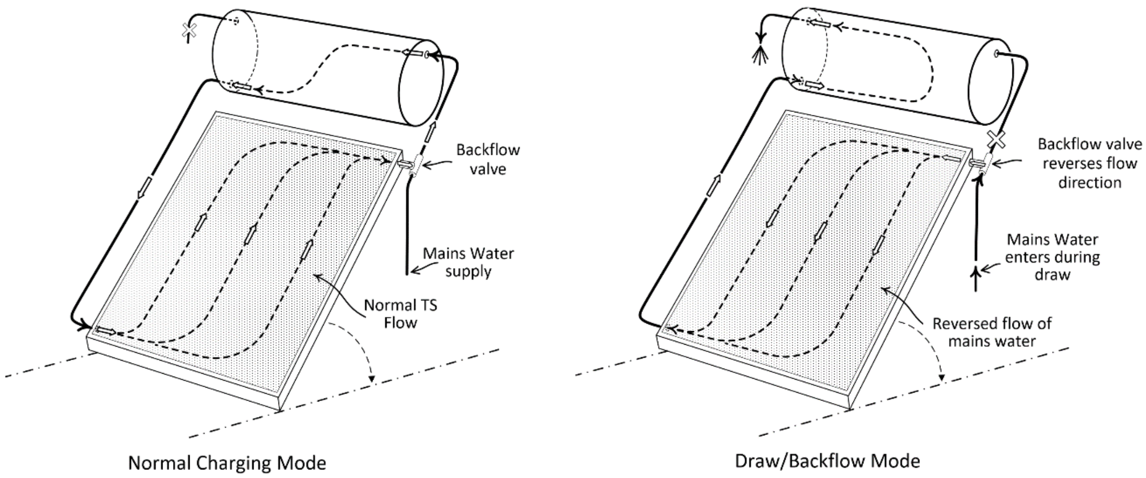

Fig. 1: Illustration of backflush operation during charge and discharge operation. (QSBRI)

Check valves on the inlet to each system were installed and a 10-minute delay was set between the hot water withdrawal from each system to prevent mixing and to allow each system to receive full mains pressure and flow. Each draw consisted of three parts: (1) a pre-draw that flushed the exterior mains line, thus cooling the water and ensuring similar inlet water temperatures for both systems; (2) a draw from the backflush system and (3) an identical draw from the baseline system. A Supervisory Control and Data Acquisition (SCADA) system was set up in LABVIEW™ to gather data, view current conditions, and change system operating parameters as required. This setup allows a high degree of versatility, and users can change the automatic draw schedule on an hourly basis.

Infrared (IR) pictures and videos were taken using a Flir T640 IR camera to illustrate the flow reversal in the collector and the re-establishment of the buoyancy driven flow rate. The collector used for these pictures and video was an identical model to the ones used in the experiment but was modified to allow for thermal imaging to capture the desired results. The modifications included removing the glazing and painting the absorber surface with black paint so that an IR image could be captured with an emissivity of 0.9, Fig. 7. The images were captured in June 2023, between 11:30 am – 1:00 pm on a clear day with an ambient temperature of 25°C and an average solar irradiance of 1000 W/m^2.

The systems were set up in June of 2023 and operated until late October. It was then drained for the winter and restarted in May 2024. The draw flow rate of 0.1-liter s^{-1} (6 liters min^{-1}) was set during the time of July – October 2023, 0.0067-liter s^{-1} (4 liters min^{-1}) was set from May – June 2024, and 0.167-liter s^{-1} (10 liters min^{-1}) was set from June – July 2024 to cover both the low and high flow rate range. The energy performance results are from the 2023 testing period using 0.1-liter s^{-1} (6 liters min^{-1}) and the impact of higher flow rates were taken from the 2024 testing period using 0.167-liter s^{-1} (10 liters min^{-1}).

Fig. 2: Installation of identical thermosyphon domestic hot water heaters installed for testing.

The following was the equation used to calculate the energy performance of each system. The results were then compared to identify if the backflushing action impacted the system energy performance. The energy delivered was calculated by integrating all energy values obtained at a scan interval of 0.5 seconds, as described in eq.1.

$$Q = \int \dot{Q}.dt = \int \dot{m}.c_w.(T_{delivered} - T_{mains\ in}).dt \qquad \text{(eq. 1)}$$

where: Q: is the energy delivered (kJ) over the draw period

$\dot{Q}$ is the power delivered (kW) over the draw period

$\dot{m}$ is the mass flow rate of water (kg s^{-1}), calculated from water volumetric flow rate ($\dot{V}$) and density

$T_{delivered}$ is the water temperature at the outlet (°C)

$T_{mains\ in}$ is the water temperature at the inlet (°C)

c_w is the specific heat capacity of water (kJ kg^{-1} K^{-1})

t is the time interval between each reading (i.e. scan rate). In this DA system, t = 0.5s

The density and specific heat capacity of water are calculated based on the water average temperature. (($T_{delivered}$ +$T_{mains\ in}$) / 2).

It should be noted that the incoming water is directly sourced from the building's main water supply, with no additional processing applied. Thus, the incoming water temperature varied based on the mains temperature and was neither controlled nor maintained at a specific, constant temperature level for this experiment. An example of a daily temperature profile is illustrated below in Fig. 3.

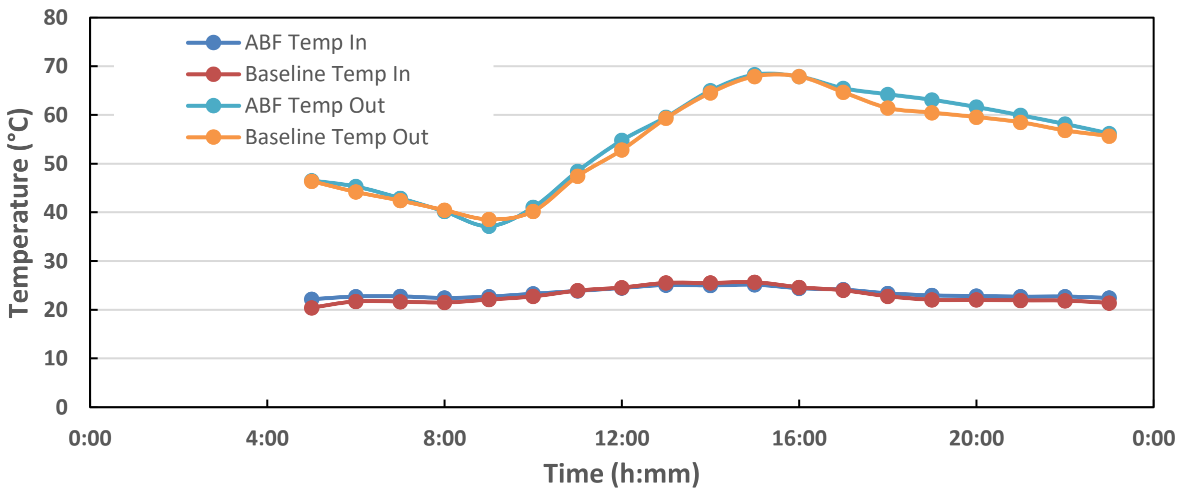

Fig. 3: Example of a daily water temperature profile (Kingston, Canada, 2023/10/03)

The accuracy of the temperature and flow rate measurements is shown below in Tab. 2. By using uncertainty analysis (Moffat, 1985), the calculated energy number has the relative uncertainty of $\pm\mathbf{4.8\%}$.

Tab. 2: Measurement accuracy of instruments.

Instrument	Purpose (Measurement)	Accuracy (±)
Yokogawa AXF025C	Volumetric Flow Rate of the Draw	0.35% of rate
Yokogawa AXF015C	Volumetric Flow Rate of the Thermosyphon Flow	0.35% of rate
Type T Thermocouple	Water Temperature	1℃ or 0.75% whichever is greater

3 Results

Over a 21-day testing period, the results showed a 0.12% increase in the energy output from the system equipped with the backflush feature when compared to the baseline thermosyphon system, Fig. 4, which is less than the 4.8% measurement errors mentioned above. The results of this test indicate that the automatic backflush valve configuration had no apparent impact on the delivered energy when subjected to daily hot water draws consistent with normal usage patterns. A review of delivery hot water temperatures and stratification temperatures in the hot water tanks indicated insignificant differences between the system equipped with the backflush feature and the baseline system.

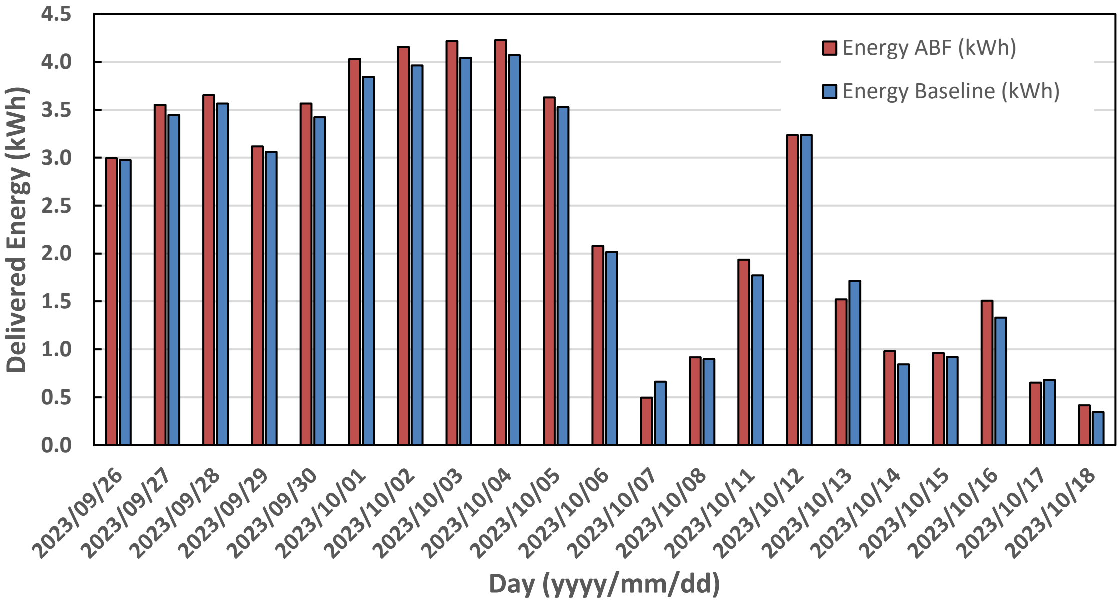

Fig. 4: Comparison of daily energy delivered by the ABF and baseline thermosyphon systems over a 21-day period.

It was also observed that the backflush operation had no significant impact on the buoyancy-driven, thermosyphon flow rate as compared to the baseline, Fig. 5 & 6. This was compared and the system had no issue restarting its buoyancy-driven flow after a backflush, as seen in the IR pictures Fig. 7, of a 1-minute backflush at 0.26-liter s^{-1} (16 liters min^{-1}). The pictures in Fig. 7 from top left to bottom right illustrate the flow reversal through the collector as a function of temperature. Starting in the top left, the collector under full sun (clear sunny day, at 11:30 am, with approximately 1000 W m^{-2}) and normal thermosyphon operation. Picture two of Fig. 7 shows the start of a draw and the flow reversal of cool mains water into the top of the collector. Pictures 3 & 4 of Fig. 7 show the temperature drop throughout the entire collector caused by a draw and corresponding backflush. Pictures 5 & 6 of Fig. 7 demonstrate the collector resuming its buoyancy driven thermosyphon flow in 1-2 minutes under optimal solar irradiance conditions.

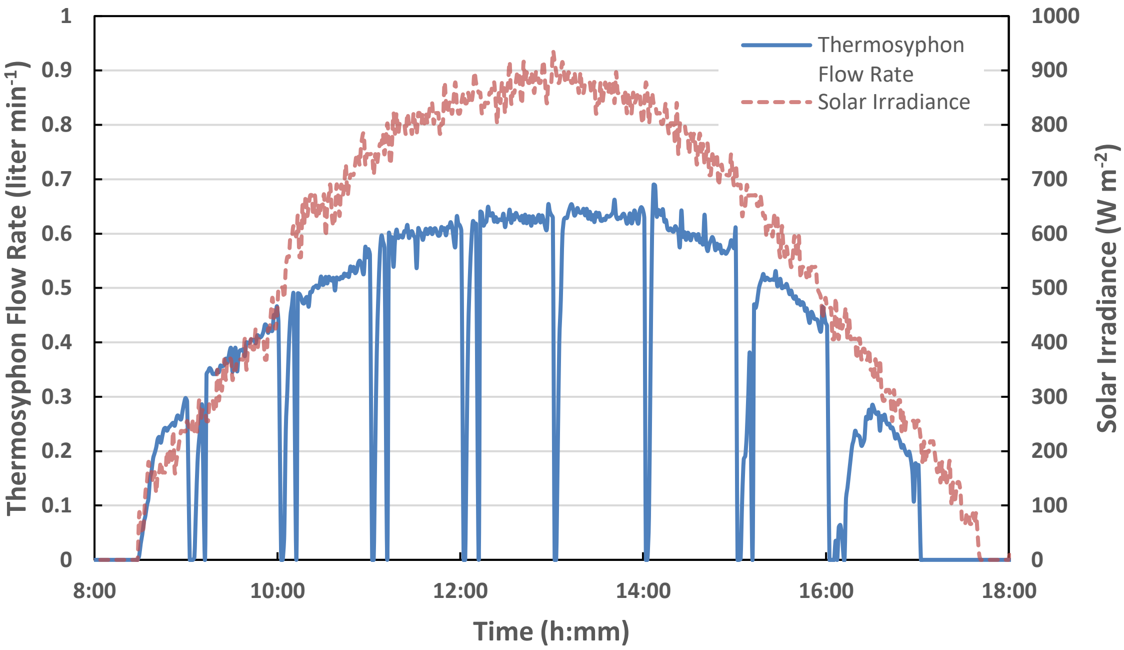

Fig. 5: Thermosyphon flow rate (liter min^{-1}) & solar irradiance (W m^{-2}) vs. time (sunny clear sky). Automatic Backflush valve installed and draw profile during operation. (Kingston, Canada, 2023/10/03)

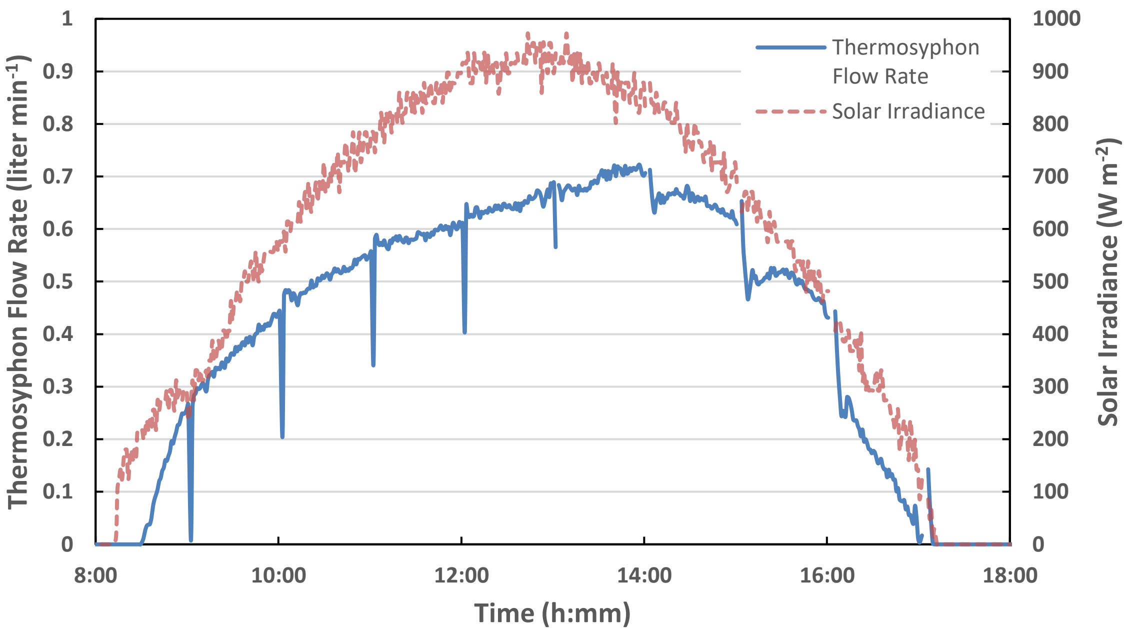

Fig. 6: Thermosyphon flow rate (liter min^{-1}) and solar irradiance (W m^{-2}) vs. time (clear sunny day) without Automatic Backflush valve installed and draw profile during operation. (Kingston, Canada, 2023/10/23)

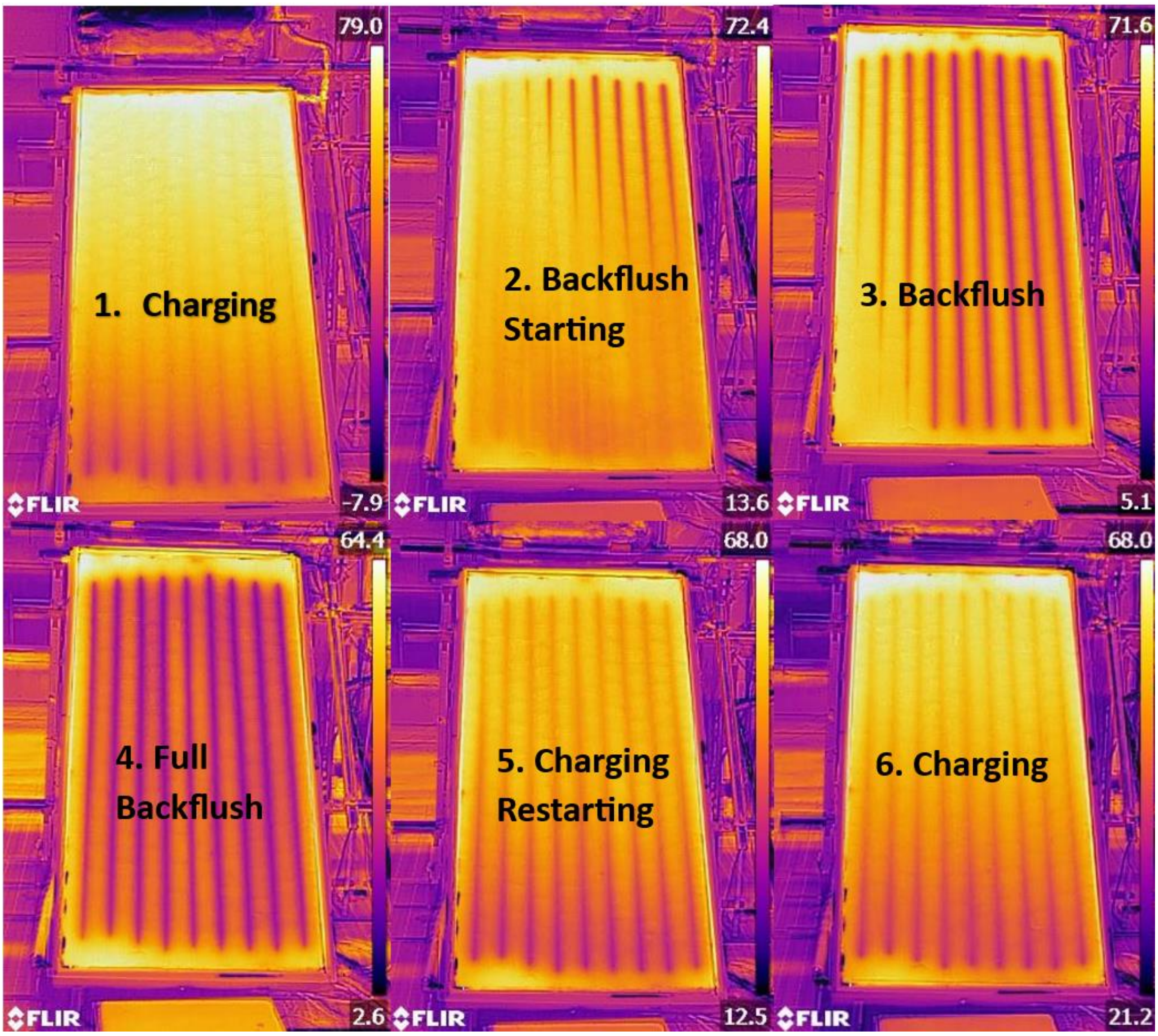

Fig. 7: Backflush through a solar thermal collector with an IR camera. The draw was conducted at 0.26-liter s^{-1} (16 liters min^{-1}) for one minute. The total time of the test was 4 minutes.

Stratification in the tank was also a key indicator of the energy performance, and thus, the temperatures in the tanks were compared. Tests were conducted at 2 flow rates: 0.1 liters s^{-1} (6 liters min^{-1}), Fig. 8 & 9, and 0.166-liters s^{-1} (10 liters min^{-1}), Fig. 10 & 11. The results indicated that backflushing had virtually no impact on the stratification in the tank at 0.1 liters s^{-1} (6 liters min^{-1}). At 0.166 liters s^{-1} (10 liters min^{-1}), there is minimal impact, but with a less than 1% difference in energy delivered in a 24-hour period. The thermosyphon flow rates are added to Fig. 8 to show how the spikes in the tank temperature profile match with the spikes in the thermosyphon flow rate profile, which represent hourly draws/backflushes.

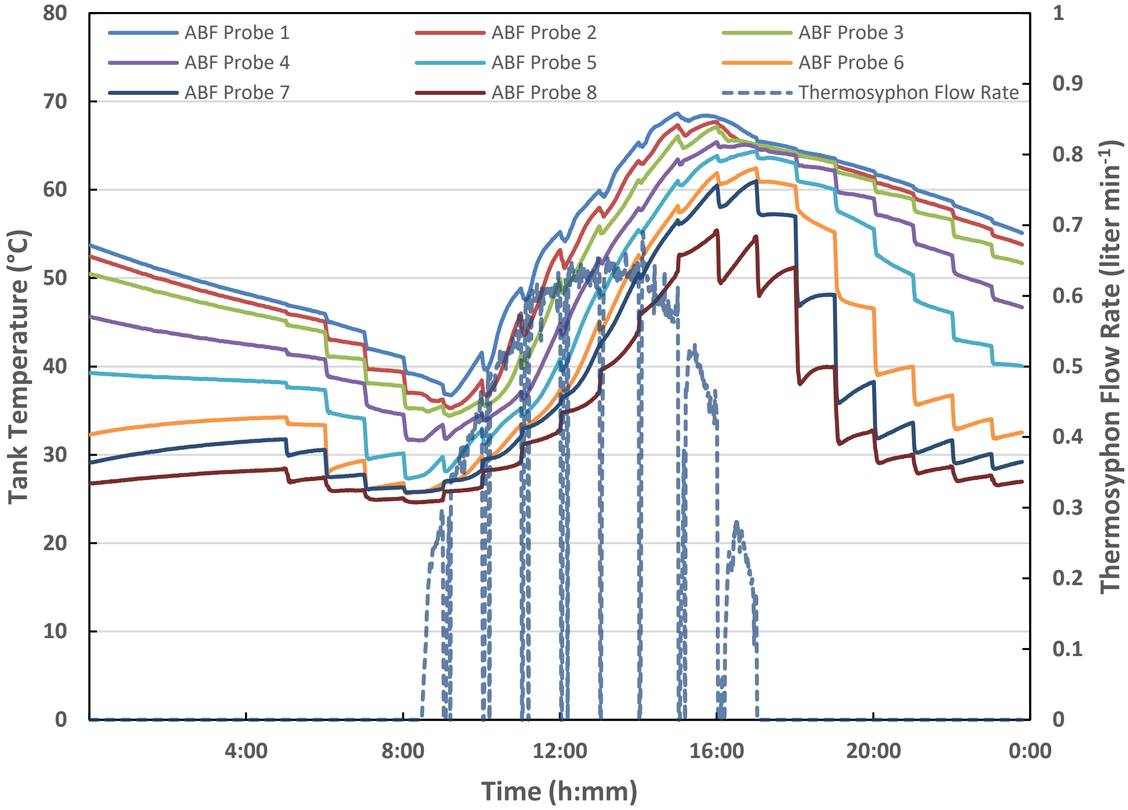

Fig. 8: Tank temperatures (°C) in the backflush system with thermosyphon flow rates shown on the right under high solar irradiance conditions with a draw flow rate of 0.1 liters s^{-1} (6 liters min^{-1}). The spikes represent hourly draws/backflushes as per DOE. Draw profile. (Kingston, Canada, 2023/10/03)

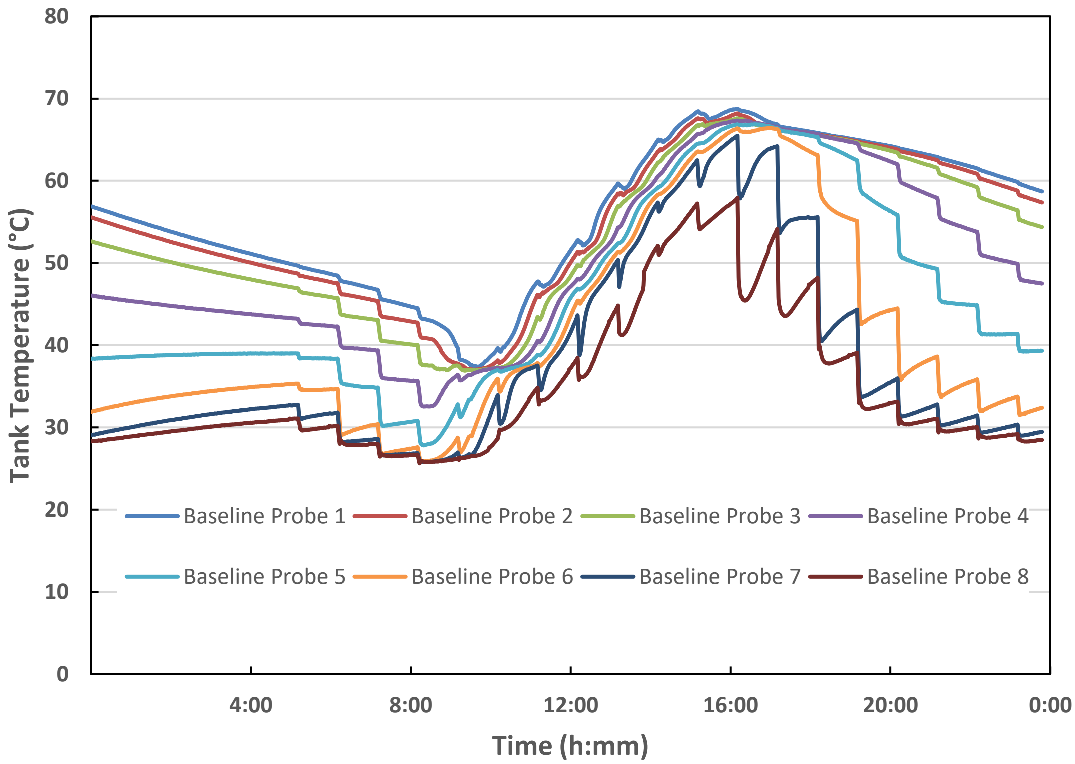

Fig. 9: Baseline thermosyphon tank temperatures (°C) vs. Time under high solar irradiance with a flow rate of 0.1 liters s^{-1} (6 liters min^{-1}). (Kingston, Canada, 2023/10/03)

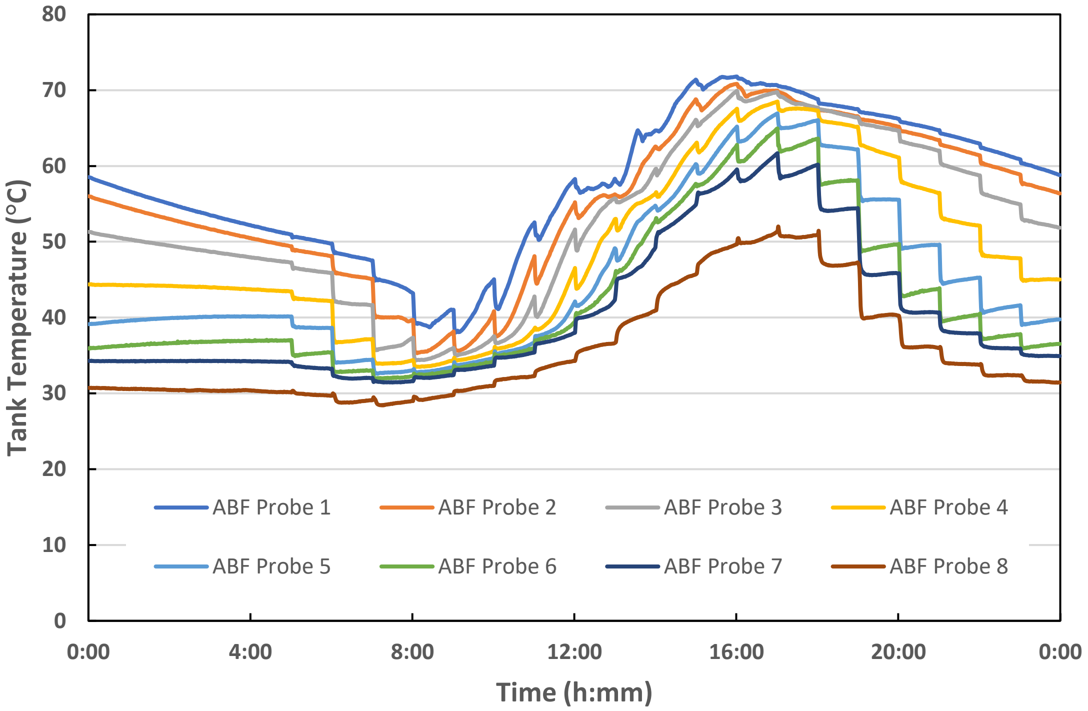

Fig. 10: ABF thermosyphon tank temperatures (°C) vs. Time under high solar irradiance, and the impact of backflush on tank stratification at 0.166 liters s^{-1} (10 liters min^{-1}) draw. (Kingston, Canada, 2024/07/08)

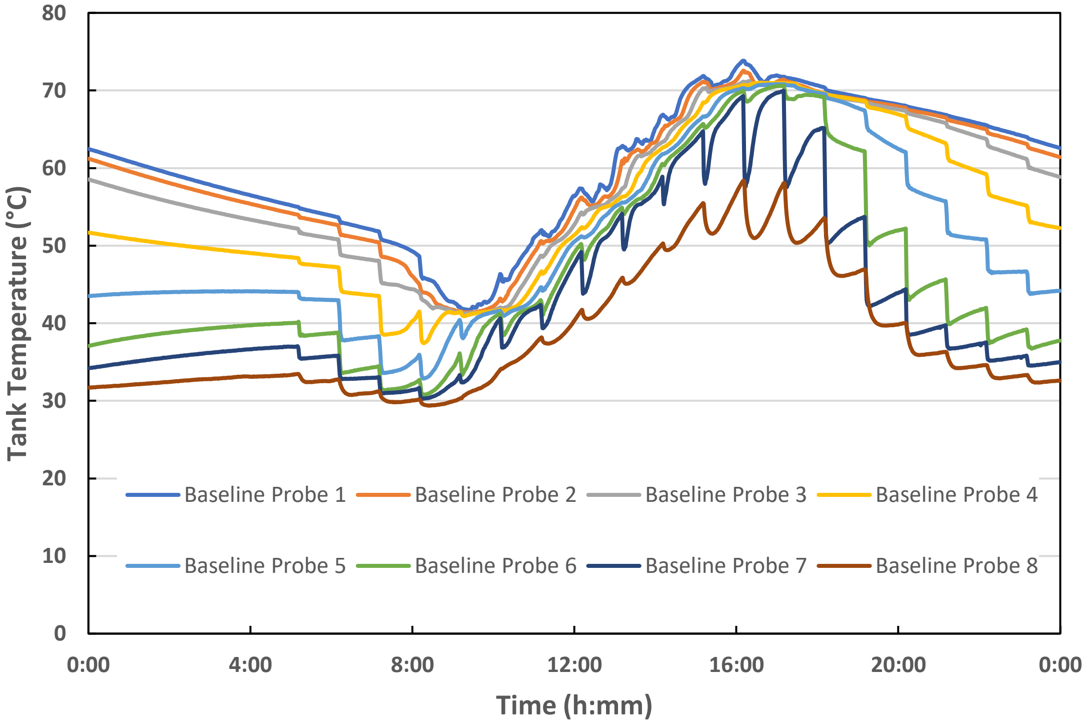

Fig. 11: Baseline thermosyphon tank temperatures (°C) vs. Time under high solar irradiance with a flow rate of 0.166 liters s^{-1} (10 liters min^{-1}). (Kingston, Canada, 2024/07/08)

4 Discussion

This study investigated the impact of backflushing on the energy performance of direct solar thermosyphon systems to prevent scale and fouling inside the solar collector. Analysis of the energy delivered (Fig. 4), the thermosyphon flow rate (Fig. 5 & 6), and tank stratification and flow rate (Fig. 8 to 11) has been performed to assess the effect of the backflushing so solar thermal collector. The results show a negligible impact on the energy performance of the overall system, including maintaining tank stratification and restarting of the buoyancy driven flow.

Hardwater scaling in solar thermal collectors has been known to cause a reduction in system performance due to reduced heat transfer and flow rates, and potential system failure when not addressed (Arunachala et al., 2009; Kedar, 2014). Backflushing heat exchangers prevent the build-up of scale has been shown to be an effective for heat exchangers (Harrison, 2005; Al Nasser et al., 2016), yet little was known on the system impact of backflushing solar thermal collectors.

This study was carried out under controlled laboratory conditions. While every effort was made to simulate typical draw patterns, further testing in ‘real world’ conditions or ‘field studies’ should be undertaken to fully understand the impact of backflushing the solar thermal collector, when a draw of hot water occurs. In addition, work is currently underway to analyze and compare the energy delivered by the thermosyphon system with the backflush feature against the baseline system at higher flow rates. Despite the limitations, this initial study has yielded positive results for maintaining the performance of solar thermosyphon systems, in that no significant impact was observed on the energy output from a system using automatic backflush.

5 Conclusion

While backflushing has been shown to prevent the formation of scale in heat exchangers, no work to the author’s knowledge has been conducted on backflushing of solar thermal collectors and its impact on system performance. This is a key topic for future research, given the need of more renewable energy technologies, like solar thermal, and the simplicity and availability of direct thermosyphon systems. These systems are expected to perform reliably for several decades and, in regions with moderate to hard water, scaling will negatively impact the system’s performance over time. Backflushing these systems will help to maintain their rated energy performance.

The results of this study indicate that backflushing a solar thermal collector has little to no effect on the energy performance of a direct thermosyphon solar thermal system. Analysis of the temperatures, flow rates and flow volumes indicate that reversing the flow of water through the solar thermal collector during a draw of hot water from the storage tank has no impact on the energy production of the system compared to an identical system without a flow reversal function. Further testing under real world conditions to validate the findings and a field trial with different sized systems and anticipated draw volumes should be considered in the future to help validate these findings.

6 Acknowledgments

The authors wish to acknowledge the support of QSBR Innovations and Neoperl GmbH. in this study.

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