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Observations of the Efficiency of a Passive Thermosiphon

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Abstract

Variations with different geometrical parameters of a passive thermosiphon, a device that contains no moving parts, were investigated experimentally to determine their impact on the collector efficiency. The thermosiphon, comprising a collector, reservoir, and interconnecting tubing, was instrumented with thermistors and flow meters to calculate the thermal efficiency of the collector. The location of the inlet and outlet of the collector, the orientation of the reservoir from vertical to horizontal, and the height between the outlet of the collector and the inlet of the reservoir (i.e., the hot leg height), were varied along with concomitant changes in flow behaviors to show the effect on collector efficiency. The thermal efficiency increased when the inlet and outlet on the collector were diagonally opposed, which resulted in more uniform flow throughout the collector, a finding based on thermal imaging. The efficiency also increased when quasi-steady flow was observed for the horizontal reservoir orientation as compared to oscillatory flow observed with the vertical reservoir orientation. Variations in the hot leg height did not have a large impact on the collector efficiency as long as the flow remained steady.

Keywords: Thermosiphon, Interconnecting Tubing, Efficiency

1. Introduction

A thermosiphon converts solar radiation into usable thermal energy. A positive difference between passive thermosiphon systems and many other solar energy systems is that a thermosiphon does not require any electrical power input or moving parts, which minimizes maintenance costs.

The general principle of operation of a passive thermosiphon is that flow is established by buoyancy differences between the fluid in the hot and cold legs. Fluid flows up the hot leg from the collector to the top of the reservoir and down the cold leg from the bottom of the reservoir to the collector. The height of the hot and cold legs as well as the difference in the density of the fluid between the two legs defines the driving force for flow. The flow may be steady, quasi-steady, or oscillatory, depending on the ability of the fluid to absorb sufficient heat within the collector for a given hot leg height and density difference.

As energy is added to the solar collector, a temperature difference across the inlet and outlet of the collector occurs. Because the system is initially at uniform conditions, there is no density difference between the hot and cold leg. The water begins flowing at a low flow rate once energy is added to the collector and, because the flow rate is low, there is a large increase in the temperature of the fluid within the collector. The hot fluid flowing slowly out of the collector rises through the hot leg while simultaneously mixing with the cooler fluid contained initially within the hot leg. This causes a small difference in the temperature and, therefore, density between the hot and cold legs and creates a small flow throughout the thermosiphon. As the fluid warms up in the hot leg, the flow is initially slow enough for the fluid passing through the collector to absorb sufficient heat to remain hot. However, as the hot leg fluid warms up, the flow rate increases. The flow within the thermosiphon will eventually reach a critical flow that depends on the temperature of the fluid in the hot leg and the height of the hot leg. Flow will be steady if the fluid flowing through the collector can absorb sufficient heat to maintain the temperature and, therefore, the density difference that drives the flow for a given hot leg height. If not, the flow rate is faster than the rate at which thermal energy is being added to the collector and the system can't maintain the density difference in the hot leg that has been initially established. The momentum that has been built up due to the large driving force flushes the hot water out of the collector resulting in the temperature difference across the collector to drop and returns the fluid to a rate slow enough for another oscillation to begin.

The application of thermosiphon systems has been in practice for many years, for example, in the year 1994 Greece was installing around 120,000 m^2/year of collector area [1]. Since then, research has been completed that analyzes the effect of vertical versus horizontal reservoirs, however, it focuses on the effect the geometrical differences have on freeze damage at night [2]. Previous research has also shown that horizontal passive thermosiphon systems with heat exchangers can reach solar collector efficiencies of up to 58% for quasi-steady state flow regimes [3]. While this research mentions that the thermosiphon system experiences quasi steady flow, it does not bring into question the effect that different flow behaviors would have on the efficiency of the solar collector. A relatively new area of thermosiphon research has been a numerical methods approach to modeling systems like the work of Andres and Lopez [4]. In order to validate these models, it must be compared to empirical data obtained from physical systems. This work could contribute to data for current and future models to be compared against.

The current research examines geometrical features of a thermosiphon that influence the flow behavior. The goal of the research is to determine the impact that various geometrical parameters have on the efficiency of the thermosiphon collector and identify ways to improve its efficiency.

2. Experimental Method

Figure 2 shows the arrangement of the vertical thermosiphon system that was used to perform some of the tests reported in this paper.

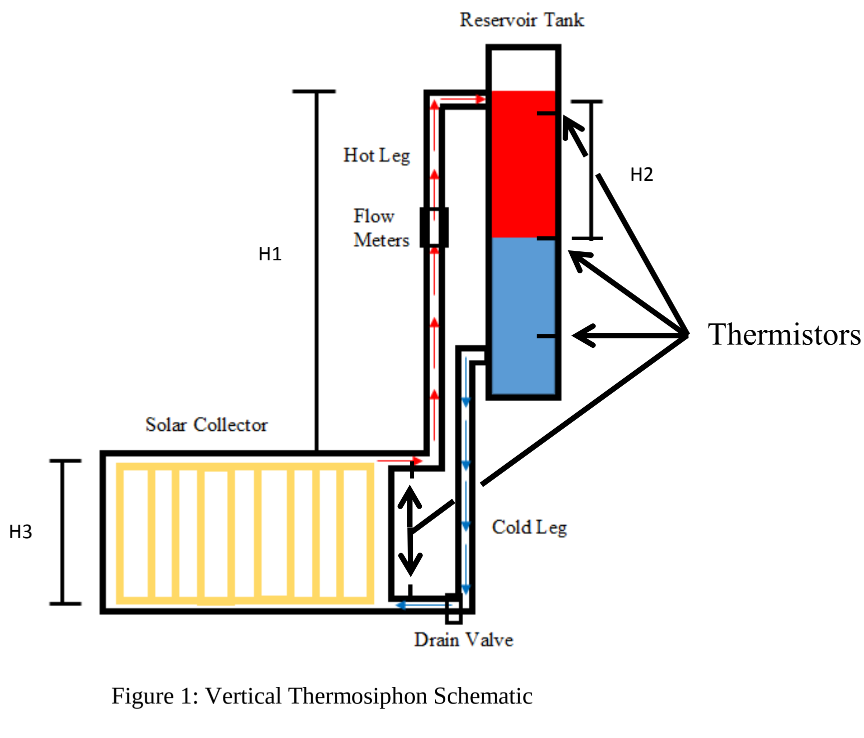

Figure 1: Vertical Thermosiphon Schematic

It consists of five major components. The first is the solar collector, which is made of uniformly spaced, vertical, parallel copper pipes. The next parts are the hot and cold legs which are located at the outlet and inlet of the solar collector, respectively, and are made of flexible plastic tubing. The fourth part is the reservoir tank, and the fifth part is the working fluid. Water was used as a working fluid for the research completed here. The thermosiphon system was instrumented with a flow meter and five thermistors, located throughout the system. In Figure **1**, H1 is the "hot leg height" which is the height between the outlet of the solar collector and inlet of the reservoir. H2 is the height of the hot water in the reservoir. H3 is the height of the solar collector pipes. The height defined by H1+H3-H2 is important because it is proportional to the driving force in the system.

Figure 2 shows the setup of the horizontal thermosiphon system that was also used to perform tests reported in this paper.

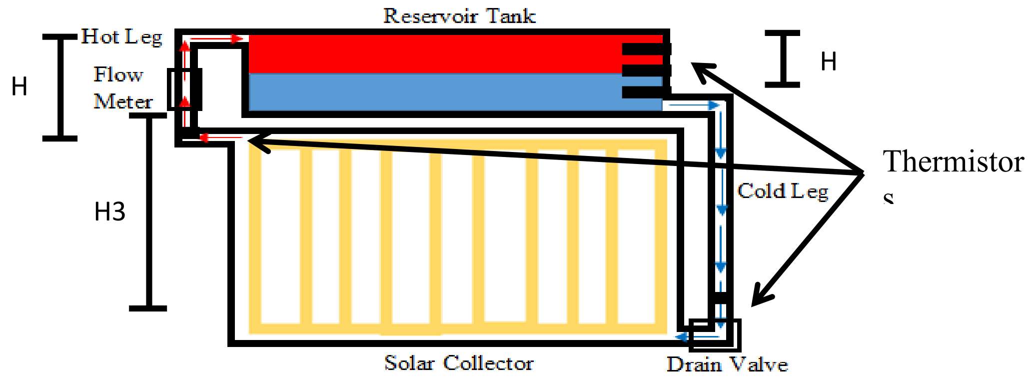

Figure 2: Horizontal Thermosiphon Schematic

The major components of the system are the same. Notice, however, that the length of H1, the hot leg height, has dramatically decreased compared to the vertical reservoir arrangement. Also, the contact area between the hot and cold fluid of the reservoir has greatly increased. With the vertical system, the reservoir contact area is a characteristic of the diameter of the reservoir. For the horizontal system, the reservoir contact area is a characteristic of the length of the reservoir. Because of the increased contact area, H2 varies less with time during the course of a test. The height associated with the driving force, H1+H3-H2, does not vary as much with time compared to the vertical reservoir allowing for steadier system parameters.

Another important feature to note is that the inlet and outlet were changed from being on the same side (Figure 1) to being diagonal from each other. The change was made because it created uniform heating conditions inside the solar collector. With the inlet and outlet diagonally opposed, the flow path was the same regardless of the vertical pipe within the collector that the water flows through.

Because it was desired to have repeatable testing conditions across multiple tests, electric heating was substituted for solar radiation. The heating strips were wrapped around the copper piping inside the solar collector. Voltages to the heating strips were controlled by variable transformers (variacs), which allowed for adjustable power input. Electric heating input was selected to be consistent with outdoor solar heating input. This system was also placed outdoors for several tests to ensure results produced in the lab were consistent with outside conditions. For outdoor testing, the heating strips and variacs were removed from the system and a plate of glass was placed on the front of the solar collector.

The solar collector piping was made of copper and sweat fitted together with male nipples attached at the inlet and outlet. The horizontal tubing in the collector was 1inch in diameter and 24 inches long. The six vertical tubes were ½ inch in diameter and 25 inches long. The total vertical length of the collector was 35 inches due to 5 inch lengths of ¾ inch connecting copper tubes on either side of the smaller vertical tubes.

The horizontal reservoir was constructed from 8 inch diameter hard PVC tubing with end caps that were drilled and tapped to allow for the male nipples. The horizontal reservoir was 46 inches long. The vertical reservoir was made of 6 inch diameter PVC tubing and was 56.5 inches long. Insulation was applied to all sides of the solar collector and reservoir to minimize heat loss to the environment. The tank was wrapped in three layers of Reach Barrier Reflective Air Insulation while the outside of the solar collector was wrapped with 7 to 10 layers. The inside of the solar collector was lined with fiberglass blanket insulation to further increase insulation. The tubing between the solar collector and tank consisted of clear ¾ inch OD PVC flexible tubing.

The resistive thermistors at the inlet and outlet of the solar collector were used to monitor the temperature for efficiency calculations. Also, three temperature measurements were taken using 4.5 inch long sheathed thermistors to measure the vertical stratification within the reservoir. For the horizontal reservoir, the thermistors were placed on the end cap of the outlet side of the tank. One thermistor was placed near the center of the end cap and the other two were placed 2 inches above and below the thermistor at the center. When the vertical reservoir was used, thermistors were located vertically along the length of the reservoir. The thermistors were placed 10 inches, 26 inches, and 44 inches below the center of the inlet to the tank. The outlet of the tank was centered 56 inches below the center of the inlet. Through calibration, the thermistor uncertainty was calculated to be ±0.2ºC. The flow meter was placed in series between the solar collector and tank to record flow rates. To begin the testing, the team originally used Kobold variable area rotameter flowmeters (Model KSM-3001) and later switched to a Spire meter 280W-D ultrasonic flowmeter. The Kobold flowmeter has an uncertainty that was calculated to be ±0.011 gpm and the Spire meter's uncertainty was found to be ±0.005 gpm. The two meters have different operating principles associated with them and the effects of the two will be discussed in the results.

A standard test was conducted in the following manner; first the system was filled with fluid from the lowest point to avoid trapping gas in any pockets. The system was filled completely and the tank reservoir was vented at the top to ensure atmospheric pressure in the system while testing. Next the system was run without recording data to heat the fluid in the tank to liberate dissolved gases in the water, which were then released from the thermosiphon. Usually, the collector was gently rocked during this stage to assist in working any gas bubbles through the system. The previous step was only required after the initial filling of the thermosiphon system with new water. Once dissolved gases had been removed, subsequent tests could be run without going through this process. After this, the system was allowed to cool completely before testing began. After cooling, input power was supplied to the collector and the instrumentation was turned on at the same time the power was supplied. Once a test was concluded, power to the system was removed and the instrumentation turned off. The data was then processed by a Microsoft Excel template that was created to calculate the collector efficiency for the tests.

3. Analytical Method

The efficiency of the collector was calculated to compare efficiencies among various tests. This was done by performing a thermodynamic efficiency analysis of the collector. The control boundary and energy crossing the boundary is shown in Figure 3.

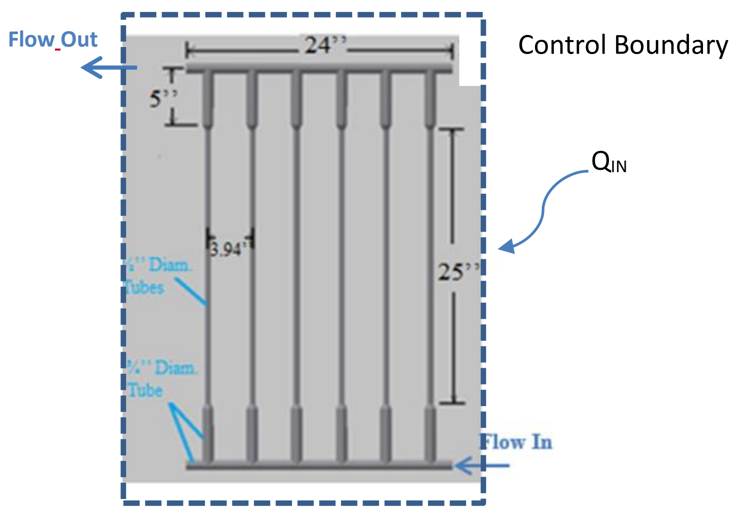

Figure 3: Control Boundary of Solar Collector

This resulted in Eq. (1).

$$\eta_i = \frac{Q'_{out}}{Q'_{in}} = \frac{\rho V' c(T_{out} - T_{in})}{\frac{V^2}{R}} \qquad \text{Eq. (1)}$$

Eq. (1) represents the formula to calculate the thermal efficiency of the collector for indoor testing. Q' represents the heat rate into and out of the system as designated by the subscript. On the far right side, the numerator stands for the thermal energy being removed from the collector by the working fluid while the denominator represents the total electrical energy supplied to the collector. ρ represents the density of the fluid, which was assumed to be constant during the course of testing. V' is the volumetric flowrate of the fluid passing through the system as measured by the flowmeters. $(T_{out} - T_{in})$ is the difference in the temperature between the outlet and inlet of the collector. In Eq. (1), V is the voltage of the variacs and R is the resistance of each heating strip.

The efficiency calculations were performed after the initial transient period of each test. Furthermore, in the case where periodic oscillatory flow was observed, the analysis was taken over a multiple of whole periods. This was to ensure a consistent and repeatable result between tests. To analyze the results, a numerical method solution was adopted and trapezoidal approximation was used to estimate the results of the discrete data collected during testing. Data intervals for the flow rate were once every 15 seconds and once every second for the temperatures and pyranometer, which was used to measure solar insolation during outdoor testing. All other variables were constant over the course of testing. A typical uncertainty for the reported efficiencies is about 6% of the reported value.

4. Results

Four tests were performed to determine how variations in the geometrical parameters of the thermosiphon impacted the efficiency of the collector. In each case, only one parameter was varied between tests to isolate the effects of the change. A summary of the tests and efficiency results are provided in Table 1.

Table 1 Summary of experimental tests.

Test Description	Flow Behavior	Collector Efficiency
Test 1-benchmark test, vertical reservoir, collector inlet and outlet were on the same side, obstruction-type flow meter was used	Periodic	57.8%
Test 2-same configuration as Test 1 except the collector inlet and outlet were diagonally opposed instead of on the same side	Periodic	77.8%
Test 3-same configuration as Test 2 except the reservoir was horizontal instead of vertical	Quasi-steady	84.4%
Test 4A-same configuration as Test 3 except an open bore ultrasonic flow meter was used instead of an obstruction-type rotameter flow meter	Steady	71.2%
Test 4B-same test and configuration as Test 4A except the hot leg height was decreased	Steady	70.1%

Test 1 was conducted using the experimental setup shown in Fig. 1. Important features to note of this test are that the inlet and outlet were on the same side of the collector, a vertical reservoir was used, the Kobold variable area rotameter flow meters were used, and the power input into the system was 1440 W. After the initial transient period, periodic oscillatory flow was observed. One characteristic of the periodic flow was that there were relatively long periods when there was essentially no flow while the fluid had a relatively high temperature. This allowed heat loss from the collector when little heat was being convected through the collector and into the reservoir, which may have contributed to the decrease in the overall efficiency. The thermal efficiency of the collector was calculated to be 57.8%.

For Test 2, the location of the collector outlet was switched to the opposite side of the inlet so that the inlet and outlet were diagonally opposed, as shown in Figure 4. Except for this change, all other test parameters were kept the same as Test 1, which used the arrangement shown in Fig. 1. The purpose of this test was to show the effect of flow uniformity within the collector on the efficiency.

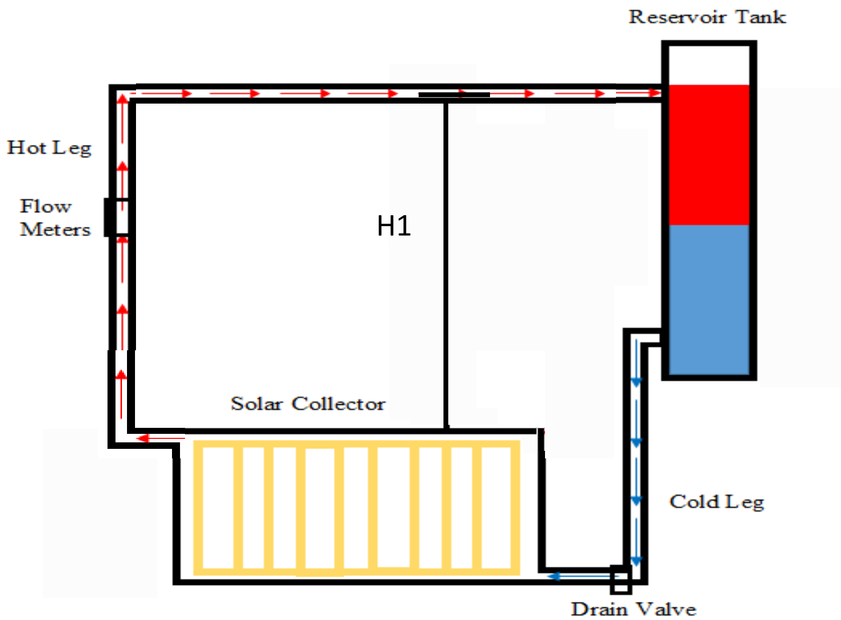

Figure 4: Diagram of Switched Outlet

An infrared camera was used to show the degree of uniformity of flow within the collector between the inlet and outlet arrangements show in Fig. 1 (inlet and outlet on the same side) and Fig. 4 (inlet and outlet diagonally opposed). The results of the infrared camera are shown in Fig. 5 for the arrangement with the inlet and outlet on the same side of the collector (left image) and the inlet and outlet diagonally opposed (right image). In both images, it is expected that the fluid will increase in temperature from the bottom of the collector to the top as the fluid rises due to buoyancy and absorbs heat. This will yield an image that shows the cooler temperature (purple color) at the bottom to the hotter temperature (orange color) at the top. However, any variation in color from left to right indicates a non-uniform temperature and flow distribution within the collector. The results from the infrared camera showed that, when the connections were on the same side, the fluid temperature was not uniform and was hottest near the connections. When the inlet and outlet were diagonally opposed, the temperature was uniform horizontally at any height across the collector. This was because the fluid had the same resistance to flow regardless of the path taken for the collector with diagonally opposed inlet and outlet.

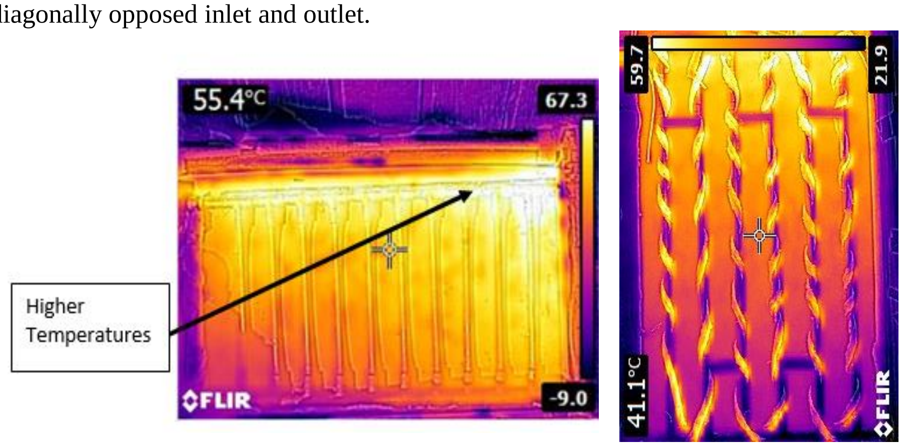

Figure 5: Infrared Display of Solar Collector

As with Test 1, the results of this test showed periodic oscillatory flow after an initial transitory period. However, there was a large improvement in the thermal efficiency of the collector, increasing from 57.8% to 77.8%. This improvement in efficiency can be solely attributed to the uniformity of flow within the collector as the only change between the two tests was the location of the outlet.

Test 3 was conducted with the reservoir in a horizontal orientation, as shown in Figure 2. The only difference between this test and Test 2 was the orientation of the reservoir, which changed the hot leg height. In Fig. 4, the height H1 was 72 inches between the outlet of the collector and the inlet of the tank compared to a height of 25.5 inches in Test 3. All other test parameters were kept the same.

The temperature difference in Test 3 was nearly steady while the flow exhibited some aperiodic behavior, yet the fluctuations in the flow were nearly an order of magnitude less than those observed in the previous two tests. The most obvious difference between the results of this test and the two previous tests were in the flow behavior. In the previous two tests, the flow behavior was oscillatory with well-defined periods. However, this test exhibited a more quasi-steady flow behavior. The decreased height of the hot leg due to the horizontal orientation of the reservoir promoted a more steady flow. The efficiency of the collector also increased from 77.8% in Test 2 to 84.4% in Test 3. This increase in efficiency can only be attributed to the change in the flow behavior since the only difference between the two tests was the orientation of the reservoir and concomitant reduction in the hot leg height.

It was desired to reduce the hot leg height even further because it was believed that a shorter hot leg height would produce steady flow. It was not possible to further reduce the hot leg height using the Kobold rotameter-type flow meter because the rotameter had to have a vertical orientation and, due to its length, the shortest distance for H1 was 25.5 inches. The Spire ultrasonic-type flow meter was chosen because the height, H1, could be reduced to 7.5 inches.

Using the Spire ultrasonic-type flow meter, a variable hot leg height test was conducted with the arrangement shown in Fig. 2. The horizontal reservoir was moved during the test from a height of H1 equal to 25.5 inches (Test 4A) to 7.5 inches (Test 4B). At the beginning of the test, H1 was equal to 25.5 inches and all parameters were the same as the previous test, except for the Spire ultrasonic-type flow meter. During the middle of the test, the horizontal reservoir was lowered to set H1 equal to 7.5 inches.

After the initial transient period, common to all tests, the flow was steady at both heights for H1. It was somewhat anticipated that this might happen for the lower value of H1 equal to 7.5 inches. However, it was a little surprising for the value of H1 equal to 25.5 inches as the previous test with the rotameter-type meter showed quasi-steady behavior. However when H1 equaled 25.5 inches, the current test and Test 3 were identical, except for the different flow meters. The difference in flow behaviors can likely be attributed to the resistance to flow between the Spire ultrasonic-type flow meter, an open bore meter, and the Kobold rotameter-type meter, an obstruction type flow meter having a bob rise through a conical tube. The collector efficiency varied between Tests 3 and 4A with H1 equal to 25.5 inches from 71.2% for the Spire meter to 84.4% for the Kobold meter, which showed the effect of overall hydraulic flow resistance on the thermosiphon performance.

When comparing results within the same test (Test 4A and 4B) at different heights for H1, the collector efficiencies were similar. There was a slight improvement in the efficiency as the height of H1 increased from 7.5 inches to 25.5 inches from 70.1% to 71.2%, respectively. However, these results showed that, at least within the range tested, the height of the hot leg did not have a large impact on the thermal efficiency of the collector as long as the flow was steady.

5. Discussion And Conclusions

A number of geometrical parameters were tested to explore the impact that flow behavior had on the thermal efficiency of the collector: the location of the inlet and outlet of the collector, the orientation of the reservoir, and the height of the hot leg.

The efficiency of the collector was improved from 57% to 77 % when the inlet and outlet of the collector were diagonally opposed as compared to when the inlet and outlet were on the same side of the collector. The diagonally opposed configuration had the same hydraulic loss for any tube and would encourage uniform flow through the collector, which was verified through thermal imaging.

The efficiency of the collector improved from 77% to 84% as the orientation of the reservoir changed from vertical to horizontal, which resulted in the flow changing from periodic oscillatory flow to quasi-steady flow. It is anticipated that the times of low flow within the period in an oscillation allows for heat loss from the collector when little heat is convected from the collector by the fluid, which would lower the efficiency.

The efficiency of the collector was not influenced greatly by changes in the height of the hot leg within the range tested, as long as the flow remained steady. The efficiency varied from 70% to 71 % as the height of the hot leg was varied from 7.5 inches to 25.5 inches.

Two flow meters operating under different physical principles were tested under otherwise identical conditions with measureable differences in the efficiency. One meter employed an ultrasonic method with a straight bore while the other was a rotameter-type flow meter with a bob obstructing the flow resulting in different hydraulic loss values for the meters. The efficiency of the collector increased from 71% to 84% when the rotameter-type flow meter was used compared to the ultrasonic-type flow meter. The effect of overall hydraulic loss of the thermosiphon on the efficiency was not investigated but determining if there is an optimal hydraulic loss to maximize the efficiency could be a potential area for future research.

6. Works Cited

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