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Proof-of-Concept Testing of the Passive Cooling System (T-CLIP^{TM}) for Solar Thermal Applications at an Elevated Temperature

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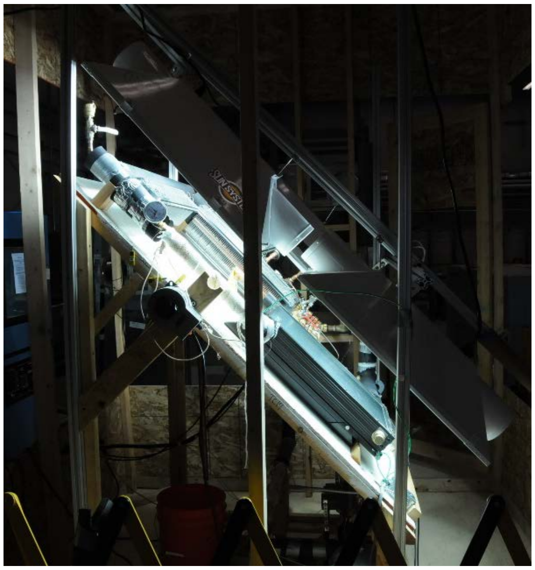
ABSTRACT

The Applied Engineering and Technology-1 group (AET-1) at Los Alamos National Laboratory (LANL) conducted the proof-of-concept tests of SolarSPOT LLC's solar thermal Temperature-Clipper, or T-CLIP^{TM} under controlled thermal conditions using a thermal conditioning unit (TCU) and a custom made environmental chamber. The passive T-CLIP^{TM} is a plumbing apparatus that attaches to a solar thermal collector to limit working fluid temperature and to prevent overheating, since overheating may lead to various accident scenarios. The goal of the current research was to evaluate the ability of the T-CLIP^{TM} to control the working fluid temperature by using its passive cooling mechanism (i.e. thermosiphon, or natural circulation) in a small-scale solar thermal system. The assembled environmental chamber that is thermally controlled with the TCU allows one to simulate the various possible weather conditions, which the solar system will encounter. The performance of the T-CLIP^{TM} was tested at two different target temperatures: 1) room temperature (70 °F) and 2) an elevated temperature (130 °F). The current test campaign demonstrated that the T-CLIP^{TM} was able to prevent overheating by thermosiphon induced cooling in a small-scale solar thermal system. This is an important safety feature in situations where the pump is turned off due to malfunction or power outages.



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1. Introduction

The purpose of this document is to describe the work scope, associated designs, and test data for the SolarSPOT LLC's solar thermal collector with a T-CLIP™. The present work is the extended effort from the last year's solar test conducted by AET-1, which was done without a thermal environmental chamber [1]. During the summer of 2015, LANL's AET-1 group conducted instrumented, heated flow, proof-of-concept tests of SolarSPOT LLC's solar thermal system T-CLIP™, under temperature-controlled environmental chamber conditions to evaluate the feasibility of the T-CLIP at elevated temperatures. The tests were conducted at the AET-1 laboratory space at Technical Area 35, building 128.

The T-CLIP™ is a plumbing appliance that attaches to a solar collector. The purpose of this appliance is to control fluid temperature in order to prevent the working fluid in the system from overheating at the normal operating condition (pump-on) as well as the abnormal operating condition (pump-off). Thus, the T-CLIP™ will increase the amount of useful renewable energy delivered by a solar thermal system, prevent damage to solar thermal systems in overheating situations, and reduce the cost of these solar thermal systems. During the test campaign over the summer the main goal for the current project was to build a thermal enclosure to test the T-CLIP™ under extreme weather conditions, regardless of whether the solar thermal system's pump was turned on or off.

The thermal enclosure was constructed with a wood frame structure. On the outer surface, two layers of construction grade foam board were attached for thermal insulating purposes. In order to control the temperature of the assembled enclosure, a thermal control unit (TCU) with supply and return lines was attached to the backside of the enclosure to maintain the desired temperatures in the chamber. All of the experimental test data such as, a transient temperature history at multiple locations in the loop, flow rate, system pressure, and the pressure difference at points of interest in the system, were recoded from the data acquisition system (DAQ) with the visual programming language LabVIEW (by National Instruments).

The goal of the current test was to demonstrate that the T-CLIP™ can prevent the working fluid from overheating regardless of whether the pump in the solar thermal loop was on or off at the various environmental temperature conditions. More interestingly, the feasibility of T-CLIP™ at the elevated temperature condition (130 °F could easily occur in some states such as Arizona or Florida during the summer) is the main demonstration point from the current test with support from the TCU.

In this test, the functionality of the T-CLIP™ at the pump off condition at different thermal environments is a key checkpoint. Two environmental chamber temperatures (70 °F and 130 °F) were used to test the T-CLIP functionality. The thermosiphon induced cooling mechanism (so called passive heat removal system) was evaluated by monitoring the operational parameters of temperature and differential pressure. The work is funded through the State of New Mexico's Small Business Assistance (NM-SBA) program supported by Los Alamos National Laboratory (LANL).

2. Background

The main purpose of a solar thermal collector is to collect heat by absorbing sunlight. Most solar thermal collectors utilizing antifreeze (propylene glycol) are typically used in residential and commercial buildings for water and space heating (See Figure 1). Overheating in the thermal fluid loop is a critical safety issue in the solar thermal collector design. Unlike other conventional heating systems (such as furnaces, boilers and water heaters) that can be turned off when desired temperatures are achieved, the solar heat source cannot be turned off and consequently the solar collectors and systems can overheat.

An example of this is a pump failure in an electrical power failure. With the sun providing energy to the system and the pump off, stagnant coolant in the solar collector can overheat, degrade, boil and turn to an acidic slurry that ruins the solar system. This safety concern prompts solar thermal system designers to undersize hot water systems to provide about 90% of the hot water needed in summer. Unfortunately, this means that the system will only provide about 40% to 50% of the hot water in winter when there are fewer hours of sunshine and the solar intensity is lower. In addition to the undersized design approach, a heat dump component (i.e. thermal storage or heat exchanger) is sometimes added in the solar system to mitigate the possible overheating situation by inherently releasing the excess heat from the system.

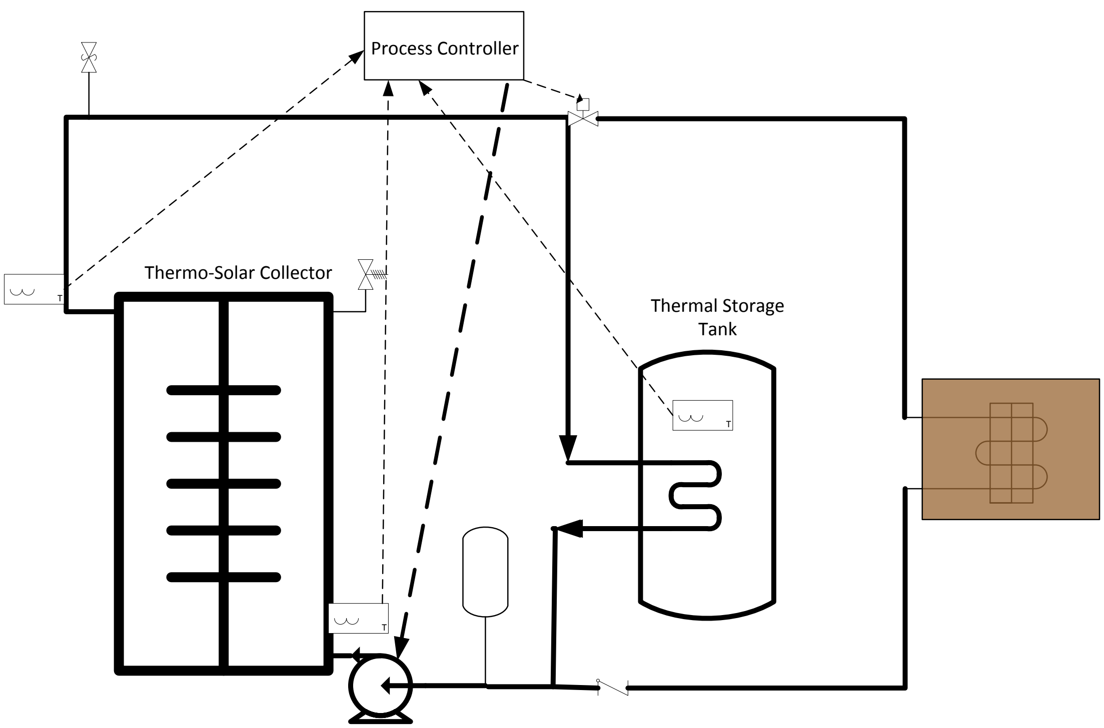


Figure 1. Schematic diagram of a conventional solar thermal design.

These off-normal conditions are known in engineering terms as a "loss of load" and a "loss of flow". First, a loss of load occurs whenever the heat destination such as a hot water tank is already at a specified temperature, thus not requiring any additional heat. However, if the sun is still shining, the solar thermal collector will continue to collect heat. This sometimes happens during low use times (for example summer vacations) when the hot water is not used.

Second, a loss of flow, also known as stagnation, typically occurs when the fluid pump stops but the sun is still shining. The most common reason for pump stoppage is an electrical power outage, but some control systems simply turn off the pump when the storage tank has reached the desired temperature. In the hot sun, stagnant fluid in the solar collector can boil and thus degrade the components. Therefore, to ensure safe and reliable operation, a viable solar thermal system requires an apparatus that can remove excess heat and protect against overheating regardless of whether the pump is on or off and regardless of whether electrical power is available or not.

SolarSPOT LLC is developing such a device, the T-CLIP™. With the T-CLIP™, the temperature of the fluid leaving the solar collector is clipped or throttled back to desired temperature limits. This limit may be set at the failure temperature of the components such as PEX plastic tubing, the degradation temperature of the fluid, the boiling point of the fluid, or other desired limit temperatures. The T-CLIP™ acts as a temperature "controller", analogous to a speed governor on an engine. It is comprised of a heat dump, a thermostatic mixing valve (TMX), a check valve and piping as shown in the schematic in Figure 2.

The T-CLIP™ provides two parallel flow paths for fluid leaving the solar collector outlet, a heat dump flow path and an insulated flow path. The two flow paths are rejoined into one at the thermostatic mixing valve where flow continues to the heat load. With the heat dump sized large enough, the thermostatic mixing valve can effectively limit the temperature of the flowing fluid leaving the T-CLIP™ when the system pump is on. Electricity is not required for the TMX to operate. The T-CLIP™ heat sink is also connected to the solar collector inlet through a check valve. When the solar system's pump is off, the check valve opens passively or can be opened with very little force. As the fluid in the solar collector continues to heat up in the sun and the fluid in the heat dump continues to cool down, the temperature differential between the solar collector side and the heat-dump side increases. When the fluid density difference between the two sides is large enough, natural circulation through the check valve could trigger passively and thus cool down the system (thermosiphon). Once the flow moves through the check valve, into the solar collector, into the heat dump, and back through the check valve, the fluid is no longer stagnant and the temperature limits are avoided.

When the T-CLIP™ is sized appropriately, the heat dump can limit the temperature of the flowing fluid by natural circulation and prevent damage to the system. A rough estimate for the total length of the finned tube heat dump (with a 1" copper pipe) needed to accomplish this task is the sum of the length and width of the solar collector. To cover the estimate and to allow for margin, the heat dump for the T-CLIP™ used in these tests was built to be variable with effective active linear lengths of 40, 60 and 80 inches. The size of the solar collector used in the tests is 24" high by 17" wide. The T-CLIP™ is intended primarily for polypropylene glycol based solar thermal systems, but could also be used for other types of heat sources in hydronic systems.

In this project, SolarSPOT applied for and received small business assistance (SBA) funded through the State of New Mexico and supported by Los Alamos National Laboratory. LANL provided technical capability that SolarSPOT did not have, namely a controlled environment for testing, artificial sunlight and the electrical power needed, sensors, data collection equipment and personnel to run the equipment. SolarSPOT's goal was to demonstrate that the T-CLIP™ works in extreme conditions so that it can claim that the T-CLIP™ will work at a wide range of weather conditions especially over the summer season.

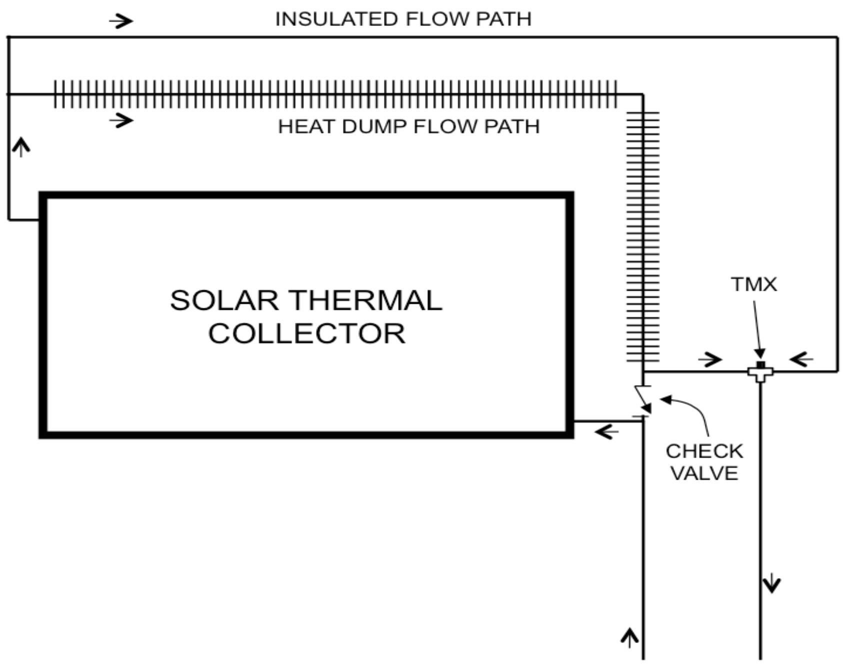


Figure 2. Schematic of the T-CLIP™ used in the present investigation, attached to a small-scale solar collector.

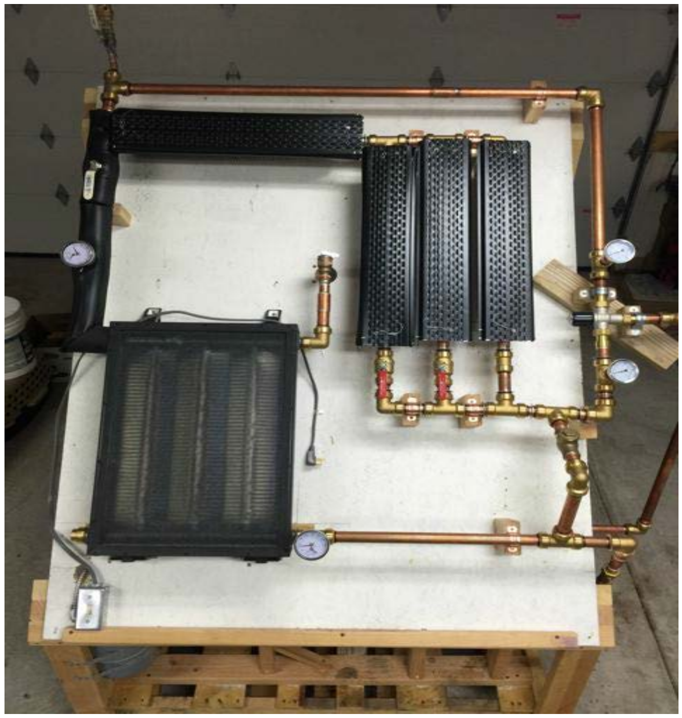
3. Test Objectives

In the current investigation, there were two principal objectives for the feasibility test on the T-CLIP™. The first objective was to test if the T-CLIP™ was able to limit the temperature of the system without pump operation, using the thermosiphon induced cooling feature (i.e. natural circulation) only. This first test was performed at room temperature (70 °F), which was a reference test. The second test was to demonstrate that at an elevated temperature (130 °F) the T-CLIP™ was able to limit the temperature of the system using natural circulation flow through its finned tube flow path and its swing check valve. This was one of the possible postulated extreme weather conditions the T-CLIP™ might encounter in operation. The desired temperature (130 °F) inside the environmental chamber was controlled by attaching a high capacity air based thermal control unit. The transient thermal fluid behavior in T-CLIP™ loop was evaluated by measuring the fluid's thermal properties (temperature, pressure and flow rate).

4. Experimental Setup

4.1 T-CLIP™ Test Device

SolarSPOT LLC designed and built the T-CLIP™ test stand pictured in Figure 3, and shown schematically in Fig. 4. The T-CLIP™ is the portion of the piping system that includes the finned tube flow path, the insulated flow path, the thermostatic mixing valve (TMX), the check valve, and associated piping as shown within the dashed line in Figure 4. The frame of the test stand is wood with a standard commercial 40"x48" wooden pallet as the base. The front of the test stand is about 45" high, and the back about 90". The miniature solar collector (24"x17"), four finned tube radiators (heat dumps, each active length measuring 20" long by 4¼" square) and associated 1" copper piping are mounted on oriented strand board, painted white, which is at a 45-degree angle, simulating a flush-mount, pitched-roof solar thermal collector installation. Each finned tube radiator is made of 24” long, 1-inch copper pipe with compression-fit square aluminum fins. The finned tube radiators are covered with slotted sheet metal to shield them from direct solar radiation. The pump, expansion tank and associated 1” pipes are plumbed underneath the oriented strand board.



(a)

(b)

Figure 3. A picture of the T-CLIP™ test stand from view before pipe insulation (a) and a view of the backside of the system showing components (pump, expansion tank and piping) underneath the oriented strand board (b).

After test stand delivery to Los Alamos National laboratory AET-1 engineers fitted the wooden structure with an aluminum frame and hangers for mounting sun lamp fixtures that provided the artificial sunlight (Sun System). Each Sunmaster lamp emitted 1 kilowatt in a 26½” by 32½” lamp enclosure, an average of 1.8 kw/m^2. The maximum (solar heat flux) encountered on the Earth’s surface is about 1 kW/m^2, thus we are considering 80% higher heat fluxes in this application. The lamp enclosures were kept parallel to the solar system with a 3” gap to the main board to minimize solar radiation leakage and to ensure high flux on the components. The solar collector and the four covered finned tube radiators were bathed in this high heat flux, artificial sunlight during testing (See Figure 5).

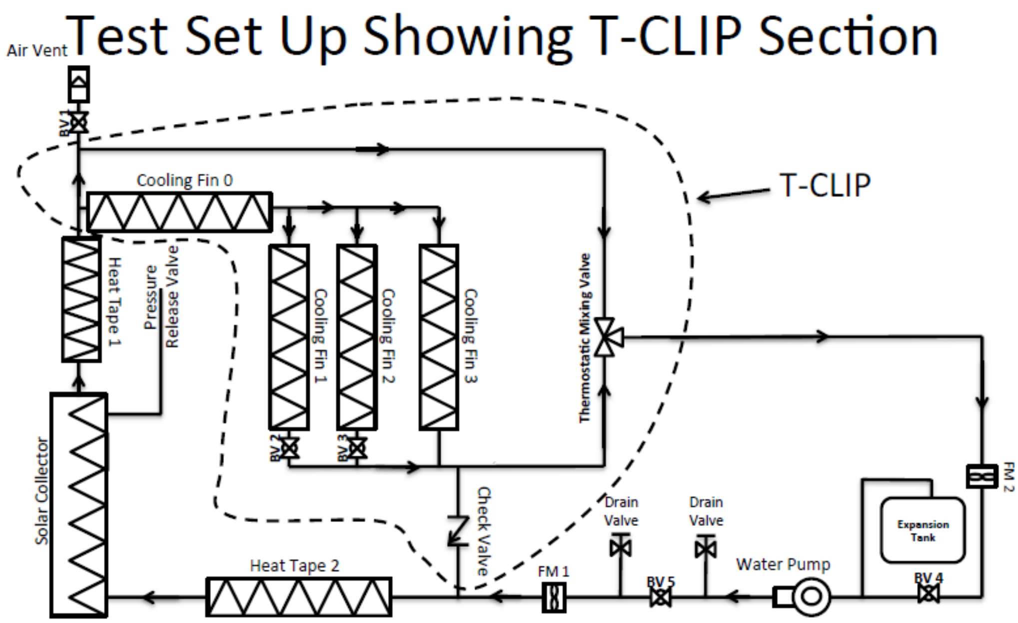


Figure 4. T-CLIP™ test stand plumbing schematic.

Figure 5. Artificial sunlight illumination on the T-CLIP™ test stand (Left side view and right side view).

4.2 Thermal Enclosure and Temperature Control Unit (TCU)

This section describes the associated design and construction process of the thermal enclosure for the test. The main goal of using a thermal enclosure was to create the temperature-controlled environment around the solar thermal collector and to evaluate the functionality of the T-CLIP^{TM} at different temperatures. To mimic the thermally stressing weather condition the team built an 8'x8'x10' wood enclosure around the solar thermal system. Two different types of foam board insulation were used. The first layer of foam board was a 1" thick by 4'x8' foam board with a reflective film on one side, and the second layer of insulation was a 2" thick by 4'x8' piece of foam board. It was desired to design the enclosure with minimal free space in order to increase the thermal response. A practical design was selected as a box-shaped 8'x8'x10' volume with one door, and two small windows as shown in Figure 6.

Figure 6. Enclosure frame with solar thermal system inside and two sunlamps hanging off of the aluminum support structure.

The physical and visual accessibility to the solar testing area through the enclosure was required for a variety of safety reasons. One door and two windows were constructed while the thermal enclosure was being designed and built. The door was a basic 89"x32" frame with a foam board for insulation. The windows was a basic 1'x2' frame with acrylic sheet. Overall, the thermal enclosure was completely insulated with thermally shielded foam board (see Figure 7). The TCU was connected to the thermal enclosure with appropriate large diameter insulating hoses with adapter plates as shown in Figure 8.

(a)

(b)

Figure 7. Pictures of the completed thermal enclosure for the solar test from a top view (a) and front view (b).

Figure 8. A picture of the TCU connected to the completed thermal enclosure during testing.

Prior to the actual testing, the energy balance between the enclosure system, the pump, the solar lamps and the TCU was calculated to evaluate if the heating and cooling capacity of the TCU was sufficient for the testing. The calculation indicated that the insulating effects of the enclosure provided sufficient heating for the tests and the TCU should be utilized only as a cooling system in order to throttle the heat for the testing. Thus, the TCU was used to cool the enclosure down to the test temperatures of 70 °F and 130 °F. The detailed calculation and assumptions on the energy balance are listed in Appendix B. The TCU is a Russell's Environmental Chamber (REC) with a Temperature/Humidity module designed to deliver air temperatures in a range from -68 to 177 °C (-90 to 350 °F). Humidity is controlled from 10 to 95% relative humidity up to 85 °C and a minimum dew point of 4 °C. Cooling is maintained via a cascade refrigeration system with a pair of 5 hp compressors. The high temperature stage has R-507 as a refrigerant while the low stage uses R-508B. The condenser is water-cooled; therefore the cooling capacity is largely dependent on the flow and temperature of the building chiller water. The chamber heats the air by placing an electrical resistance heater element in the air circulation.

4.3 Measurements

4.3.1 Temperature measurement and thermocouple calibration

In order to monitor the fluid temperature in the T-CLIP^{TM} test loop, 19 thermocouples were installed to measure the copper wall temperatures at key locations as the test progressed. The locations of the thermocouples and the naming convention is listed in Table 1 and shown graphically in Figure 9. The thermocouples were “type K” (chromel and alumel alloy) and commercially available. All thermocouples and the data acquisition (DAQ) system were calibrated using a thermocouple calibration system before the tests in order to ensure the fidelity of the thermocouple readings. The detailed procedure and the results of the thermocouple calibration are presented in the Appendix C. Since the thermocouples were attached to the outer surfaces of the pipes it was important to ensure the measuring locations were thermally insulated with standard pipe insulation. To prevent any damage due to strain in the thermocouple wiring, the female plug of thermocouple connector was attached to the 2”x4” wood frame of the solar test structure as shown in Figure 10.

Table 1. Thermocouple (TC) designations and locations.

TC#	Location
1	Solar collector inlet
2	Solar collector bypass outlet
3	Outlet of valve vertical finned tube 1
4	Outlet of valve vertical finned tube 2
5	Outlet of non-valve vertical finned tube 3
6	Inlet to thermostatic mixing valve from finned tube flow path
7	Inlet to thermostatic mixing valve from insulated piping from solar collector
8	Outlet from thermostatic mixing valve
9	Upper right stagnant outlet of solar collector near relief valve
10	Piping downstream of swing check valve
11	Solar collector outlet (after Heat Tape-17, before tee to horizontal finned tube)
12	Inlet of valve vertical finned tube 1
13	Inlet of valve vertical finned tube 2
14	Inlet of non-valve vertical finned tube 3

15	Piping before the Heat Tape-18 and -19
16	Piping between the expansion tank and the pump
17	Metal outer surface of the Heat Tape
18	Metal outer surface of the Heat Tape
19	Metal outer surface of the Heat Tape

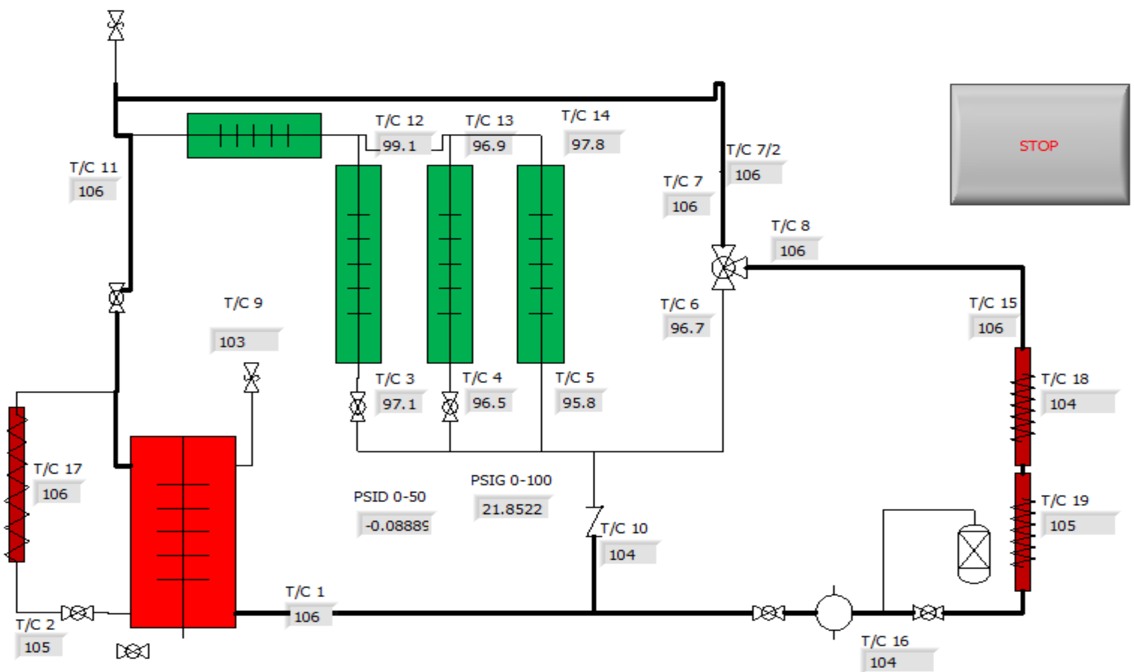


Figure 9. A schematic diagram of the solar test loop showing the locations of the thermocouples.

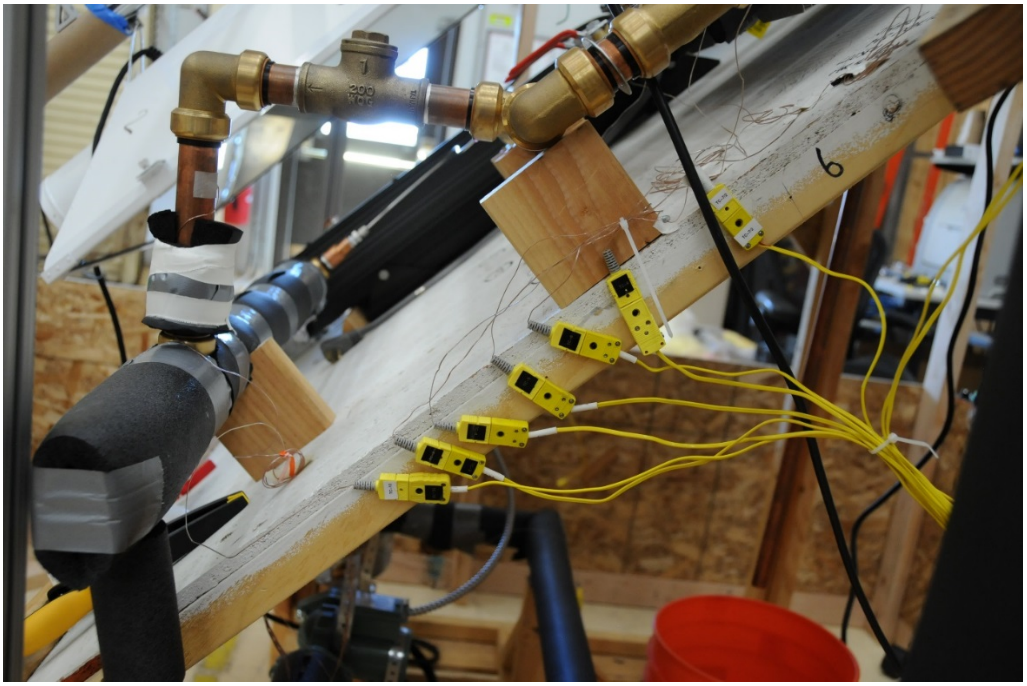
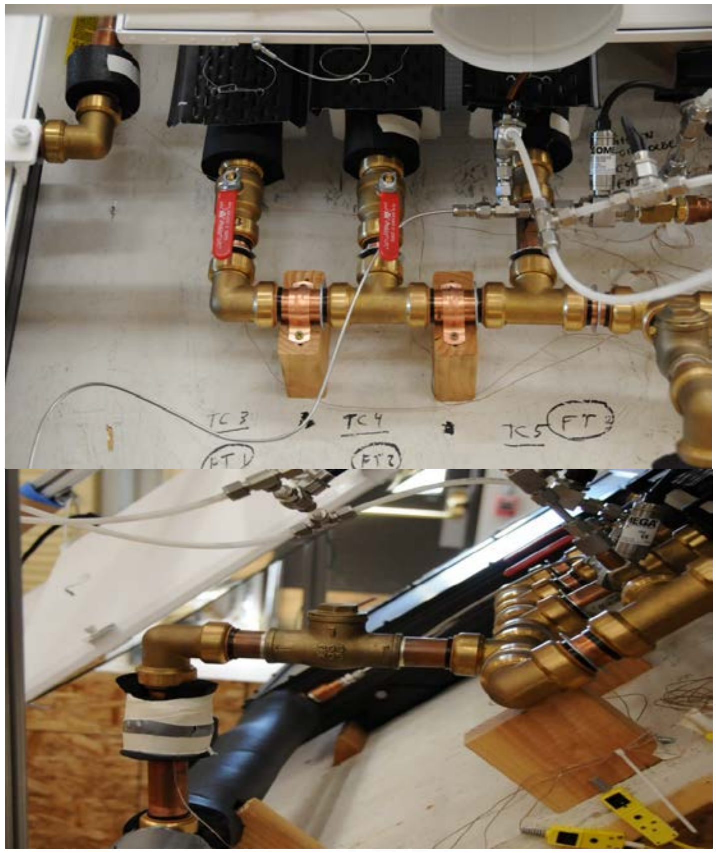


Figure 10. An image of mounted thermocouples and the insulated piping in the test apparatus.

4.3.2 Differential pressure across the check valve

In order to monitor the pressure in the system, two types of pressure transducers were installed upstream and downstream from the check valve. These were used to measure the pressure at these locations and evaluate the pressure drop across the check valve at key times during the tests. System pressure was measured downstream of the thermostatic mixing valve and upstream of the check valve with a pressure transducer (Omega model PX209, 0-100 psig with 0 to 5 DC output) and the pressure drop across the check valve was measured with a differential pressure transducer (Omega model PX409, 0-50 psi) as shown in Figure 11. The main purpose of those pressure transducers was to evaluate the pressure perturbation while the check valve was open due to triggering of the thermosiphon. The uncertainty of the pressure transducers is 1% of the full maximum reading based on the specification sheets given from the manufacturer. It is worthwhile to note that monitoring the pressure difference over the check valve is a challenging task. The pressure perturbation that occurs due to the check valve functioning due to thermosiphon activation is small or non-detectable in some tests. The system pressure was approximately 25 psig over the test period, which is a desirable system pressure for this application.



(a)

(b)

Figure 11. A picture of the pressure transducers (a) and the check valve orientation from the side view (b).

4.3.3 Flow rate measurement with ultrasonic flow meter

Since the goal of the current experimental test is to understand the thermal fluid behavior while the thermosiphon is working, it was desired to measure the flow rate in the T-CLIP^{TM}. When the thermosiphon is triggered (i.e. natural circulation condition) the flow rate in the system is small (less than 0.1 gallons per minute (gpm)). The experimenters tried to measure the flow rate in the system using a non-intrusive ultrasonic flow meter, which did not disturb or restrict the flow condition. The ultrasonic flow meter required approximately 10 diameters of straight pipe length upstream and downstream of the measurement location. The ultrasonic sensors were attached to the pipe upstream of the solar collector region as shown in Figure 12. The ultrasonic flow meter used in the tests was a SITRANS FUP101-Portable, and the minimum detectable flow velocity was 0.3 m/s, which is equivalent to 0.1 gpm [2]. Unfortunately, the analytic solution of the steady state natural circulation flow rate is approximately 0.01 gpm or less (see the Appendix A). During the tests, the flow rate reading from the ultrasonic flow meter after the pump was turned off was not readable since the measurement is below the minimum detection level. The cost of a new low flow meter was not budgeted in the scoping statement and the researchers knew this was a risk at the start of the project. The flow rate reading from the ultrasonic meter at the normal operating condition (pump-on) was obtained without any issues.

Figure 12. A picture of the ultrasonic sensors (left), and the portable ultrasonic flow meter readout device (right).

In this test the researchers attempted to characterize the thermo-fluid behavior in the system by measuring various thermal system properties (flow rate, pressure drop across the check valve, temperatures) and it turned out that the temperature monitoring was most reliable diagnostic tool to understand the natural circulation flow in the system.

4.3.4 Data Acquisition system

The National Instruments DAQ system allowed the researchers to view and archive the senor response using the LabVIEW (by National Instruments) DAQ software. With the help of the LabVIEW event log function, the researchers manually recorded the flow rate reading from the ultrasonic flow meter as the test progressed, as well as the each experimental event (i.e. pump on/off, and the heat tape power level while the test progressed. Since the current test was conducted under the high environmental temperature condition (130 °F) all of the DAQ system electronics and signal conditioners were staged outside of the thermal chamber as shown in Figure 13.

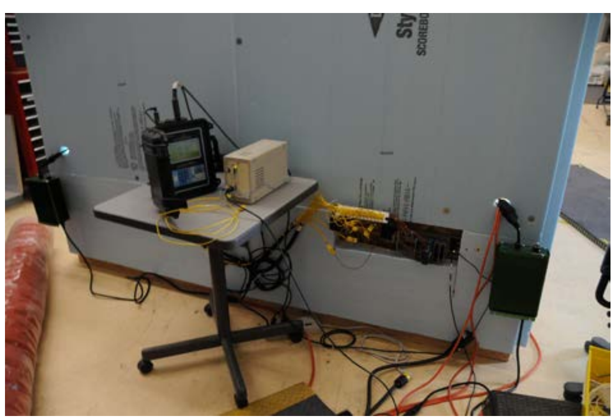


Figure 13. A picture of the DAQ system installation attached to the backside of the thermal chamber.

5. Experimental test case

5.1 Pump off test with the thermal enclosure at room temperature (70 °F)

The purpose of this test was to evaluate if the thermosiphon induced cooling occurs during the pump off condition in the T-CLIP^{TM} solar loop while the environmental chamber temperature is maintained at room temperature (70 °F). The steps of this test procedure are summarized below while the timeline is presented in Table 2.

1) Maintain the environmental chamber temperature at 70 °F using the TCU
2) Heat up the thermal fluid in the loop using supplemental heat tape and radiant heat from the solar lamps while the pump is on
3) Shut down the pump and isolate the T-CLIP^{TM} loop to induce the thermosiphon test
4) Turn off the all of heat tapes and leave the solar lamp on
5) Monitor the transient thermal behavior in the T-CLIP^{TM} by evaluating the temperature profile in the system
6) Evaluate the temperature at the check valve location (TC-10) and determine if it is rapidly deceasing due to the thermosiphon induced cooling.

Table 2. Detailed test procedure at the room temperature condition.

Time	Action taken into the experiment
T=0 sec	LabVIEW recording was started to begin the test. The maximum flow was 3 gpm. The valves at locations before and after the pump were opened, the valve on the outlet of the solar collector was opened half way, the bypass valve was opened, and the heat sink valves were opened
T=2 min	The sun lamp over the solar collector, also known as lamp 2 was powered at 100%
T=5 min	The lamp 2 and 3 were turned up to 100%
T=10 min	All three heat tapes were set at 50%
T=15 min	All three heat tapes were set at 80%
T=20 min	All three heat tapes were set at 90%
T=30 min	The flow rate was manually lowered to 1 gpm
T=50 min	Start of thermosiphon test - Pump-off, all heat tapes turned off, T-CLIP^{TM} was isolated by closing valves, and the solar lamps were left on - Monitored the transient temperature trend over the T-CLIP^{TM}

At the beginning of the test the overall temperature in the solar loop started ramping up very quickly with excessive energy dump from the heat tapes. The thermostatic mixing valve was in the fully out position which is set to approximately 180° F. Once the pump was turned off, the temperatures started to cool down. The temperature difference (delta T) between the heat source component (i.e. solar collector) and the heat sink components (i.e. heated pipes) started to become much larger due to the lamp still adding thermal energy into the solar collector and the thermal energy being dumped from the heat sink. Once the delta T became large enough, thermal mixing took place when the check valve opened.

Thermosiphon induced mixing is due to the temperature gradient in the hot side and cold the side of the T-CLIP^{TM}. The proof for this sudden mix is based on the TC10 signal, which is located right after the check valve (see Figure 14). When the density difference becomes high enough all of the cooler liquid that has been sitting in the cooling fins is able to flow out of the check valve causing the thermocouple to read a much lower temperature. Besides the temperature monitoring at the check valve location, the differential pressure over the check valve was monitored to determine if the check valve opened or not during the moment the thermosiphon triggered. Figure 15 demonstrated that the differential pressure is perturbed at the moment the TC10 temperature was rapidly dropping, which is a good indicator that the check valve opened and the thermal mixing was triggered in the T-CLIP^{TM}.

Next the researchers wanted to observe if the system had the ability to maintain temperature to avoid overheating. The way this was accomplished was by creating a steady state scenario by turning on the sidearm heat tape. With the help of a variable autotransformer they were able to adjust the voltage coming into the heat tape. They first set the transformer to add 30% voltage to the heat tape and observed the temperature signals to insure the temperatures reached equilibrium. This was followed by a subsequent test where the transformer was increased to 60% and the temperatures were monitored as the system reached a new equilibrium (Figure 16). Reaching the second equilibrium state took much longer due to the increased amount of energy the system now had to dispose of to avoid overheating.

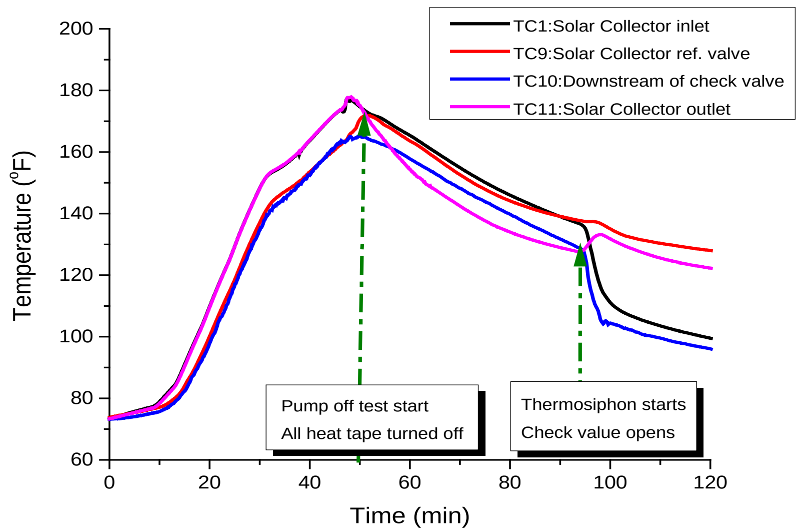


Figure 14. Temperature history with the pump on and off (note the onset of thermosiphoning at around the 94 minute test time).

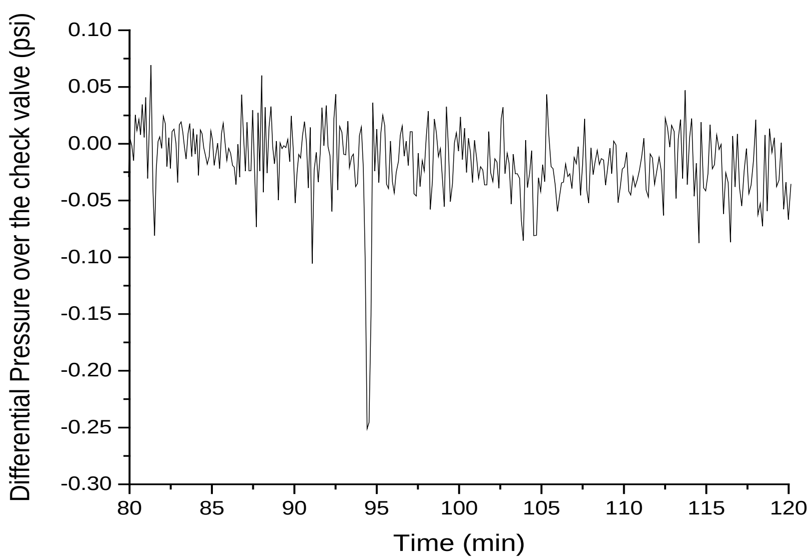


Figure 15. Differential pressure at the check valve location over the time.

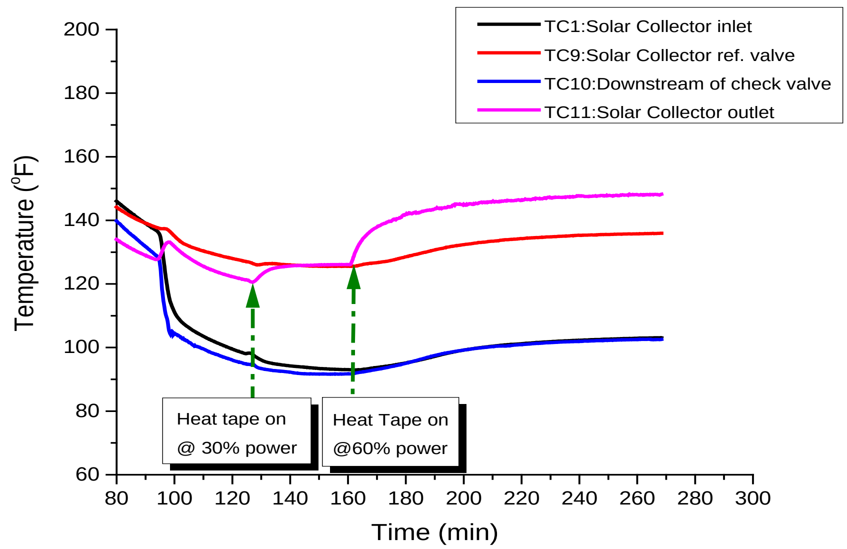


Figure 16. Temperature history after the heat tape turned on at 30% and 60% power.

5.2 Pump-off test with the thermal enclosure at 130 °F

The purpose of this test was to determine if the thermosiphon induced cooling is working in the T-CLIP™ at the elevated temperature of 130 °F. The procedure steps of the current test are summarized below while the timeline is presented in Table 3.

1) Maintain the environmental chamber temperature at 130 °F using the TCU
2) Heat up the thermal fluid in the loop using the heat tapes and radiant heat from the solar lamps while pump is on
3) Shut down the pump and isolate the T-CLIP™ loop for the thermosiphon test
4) Leave the solar lamps on at full power
5) Turn off the all of heat tapes except for the Heat tape-17 which will produce an additional heat source into the T-CLIP to mimic more realistic extreme weather conditions
6) Monitor the transient thermal behavior in the T-CLIP™ by evaluating the temperature profile in the system
7) Evaluate if the temperature at the check valve location (TC-10) is rapidly deceasing due to the thermosiphon induced cooling
8) To ensure the thermosiphon induced flow (natural circulation flow) in the T-CLIP™ loop, stagnate the two vertical heat pipe route by closing the corresponding check valves and monitor the temperature history behavior over the stagnated heat pipe route (TC3 and TC4) and flowing heat pipe route (TC5)

Table 3. Detail Test procedure at the elevated temperature (130 °F) condition.

Time	Action taken into the experiment
T=0	LabVIEW recording was started to begin the test. The maximum flow was 3 gpm. The valves locations before and after the pump were opened, the valve on the outlet of the solar collector was opened half way, the bypass valve was opened, and the heat sink valves were opened as well. The thermal control unit is set to 130 °F
T=5 mins	The flow rate was fixed to 1 gpm
T=25 mins	All three heat tapes were set to 80%
T=30 mins	The environmental chamber temperature was maintained as 130 °F
T=60 mins	The sidearm heat tape (HT-17) was lowered to 30% and the other two heat tapes (HT-18, HT-19) were turned off
T=80 mins	Start of thermosiphon test - Pump-off, all heat tapes turned off, T-CLIP™ was isolated by closing valves, and the solar lamps were left on - Monitored the transient temperature trend over the T-CLIP™

Similar to the previous room temperature test, the temperatures rose quickly, but once the heat tapes were turned off, immediately the temperatures lowered simultaneously. This happened even when the environmental chamber temperature was maintained at 130 °F (See Figure 20). Note that the environmental chamber temperature was maintained to the desired temperature of 130 °F even though additional heat sources were being applied into the T-CLIP™ system through the heat tape (HT-17) power ramping up from 30% to 50%, 70%, and 80%. Note that the trace for TC-17 is not the fluid temperature: it is the temperature trace for the outer surface of the copper pipe under the heat tape. Fluid inside the copper pipe at TC-17 did not boil.

As the heat source temperature was increasing, the delta T between the heat source and heat dump was increasing and at 135 minutes (Figure 17) the temperature of TC10 (located downstream of the check valve) rapidly dropped. This was a good indicator of the cool fluid from the heat dump moving the fluid and opening the check valve. This let the cool fluid flow through the T-CLIP™. Note that the trace for TC-11 is not the fluid temperature: it is the temperature trace for the outer surface of the copper pipe very close to the heat tape which dominates the recording. Fluid inside the copper pipe at TC-11, the exit of the solar collector, did not boil.

Another indication of the thermosiphon phenomena in the T-CLIP™ is shown in Figure 18 by a more detailed inspection of the temperatures at TC1, TC9 and TC10. As the check valve opened due to the density difference on the T-CLIP™, the cool fluid transported from the TC10 location downstream of the check valve to the TC1 location (Solar collector inlet) and finally to TC9 (solar collector relief valve).

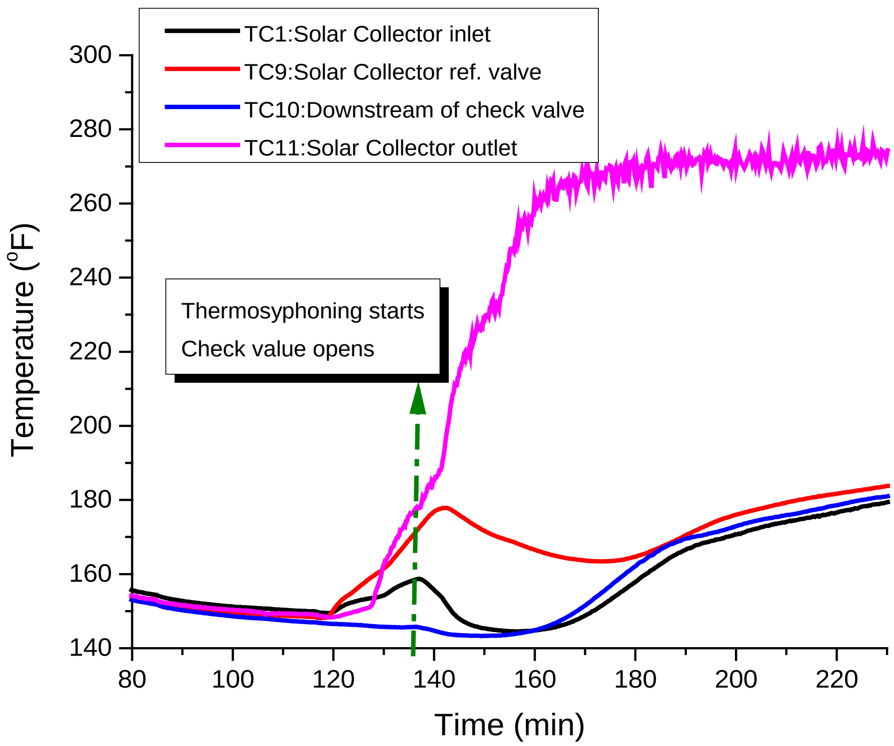
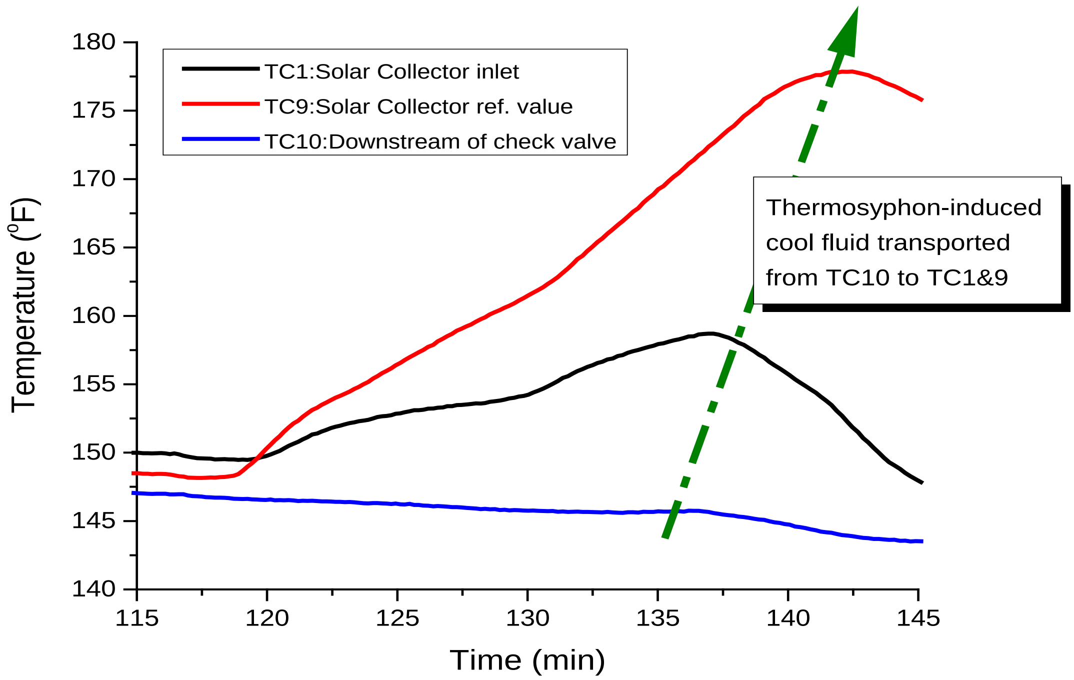


Figure 17. Temperature history after the pump was turned off and the thermosiphoning behavior was noted at TC10 and TC9.



(a)

(b)

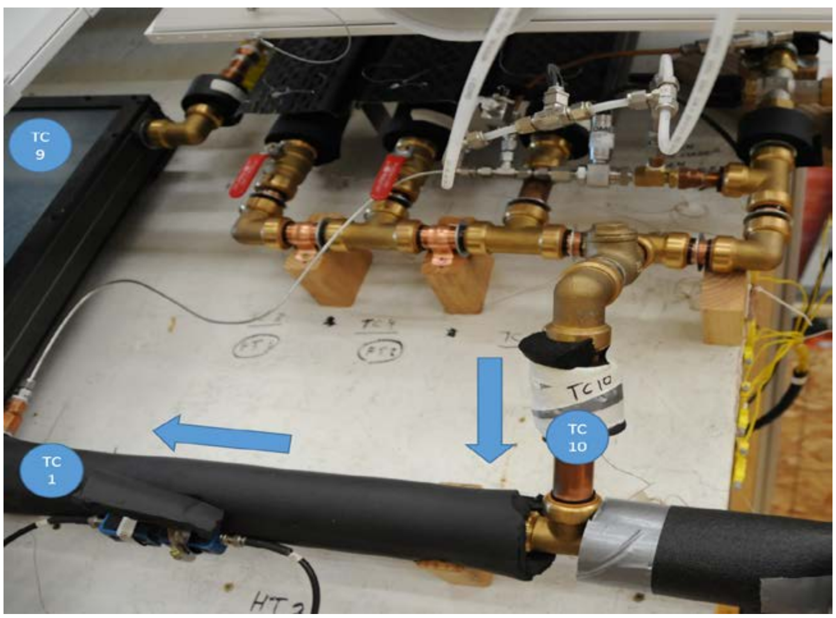


Figure 18. Close look at the temperature history at TC1, 9 and 10 (a) with a photo (b).

After the onset of the thermosiphon induce temperature cooling in the T-CLIP^{TM} the researchers wanted to ensure the thermosiphon induced thermal fluid was continuously flowing in the loop. A flow path perturbation was introduced by closing two of the vertical heated pipe routes (the HP-1 and HP-2 paths were closed and the HP-3 path was left open as it was shown in Figure 9 and Table

1). When the downstream location of the vertical heat pipe temperature was stabilized (around 230 min shown in the Figure 19), it was observed that the temperature at the TC-5 location (downstream of the vertical heat pipe) started increasing due to the large amount of heated fluid transported from the solar collection while the other routes were stagnated. At the same time, TC-3 and TC-4 were decreasing via the heat dump without any additional heated fluid transferred convectively. This test was also good indicator that the thermosiphon flow was working over the T-CLIP™ during the elevated temperature (130 °F) condition. In this test, it was demonstrated that the thermosiphon induced temperature control over the T-CLIP™ worked at the harsh environment (elevated ambient temperature and the additional heat source from the heat tape). Note, that the test was conducted under a controlled and steady environment, with a limited amount of time. True long term environmental conditions and degradation in the system can affect the operation of the T-CLIP™ and its passive cooling feature.

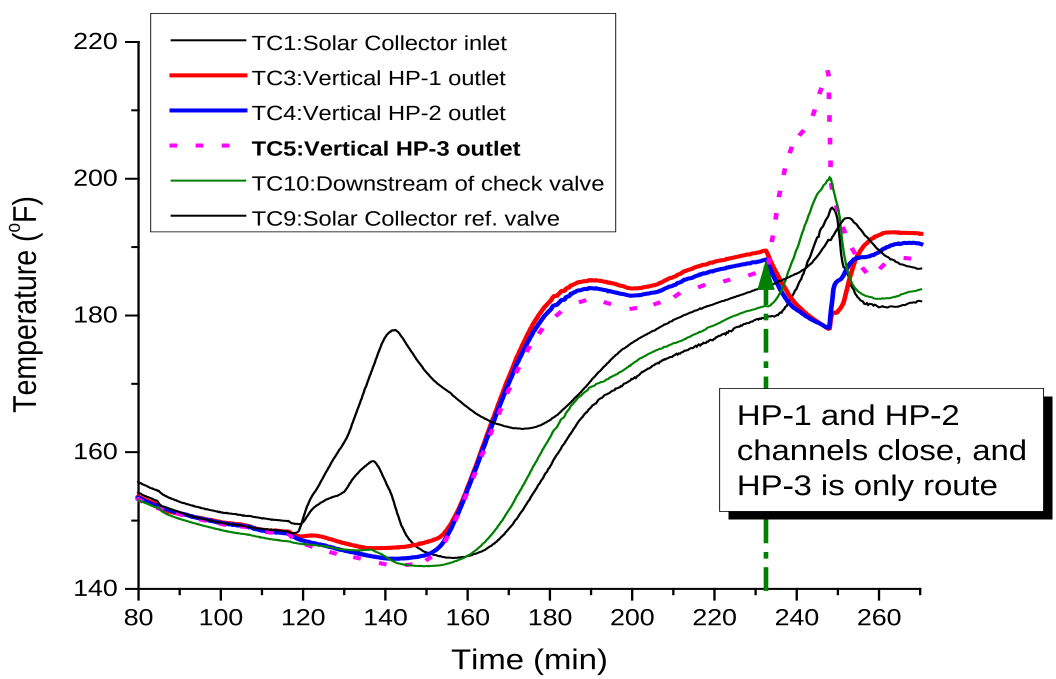


Figure 19. Temperature history of the TC-3, 4 and 5 (heat dump sections).

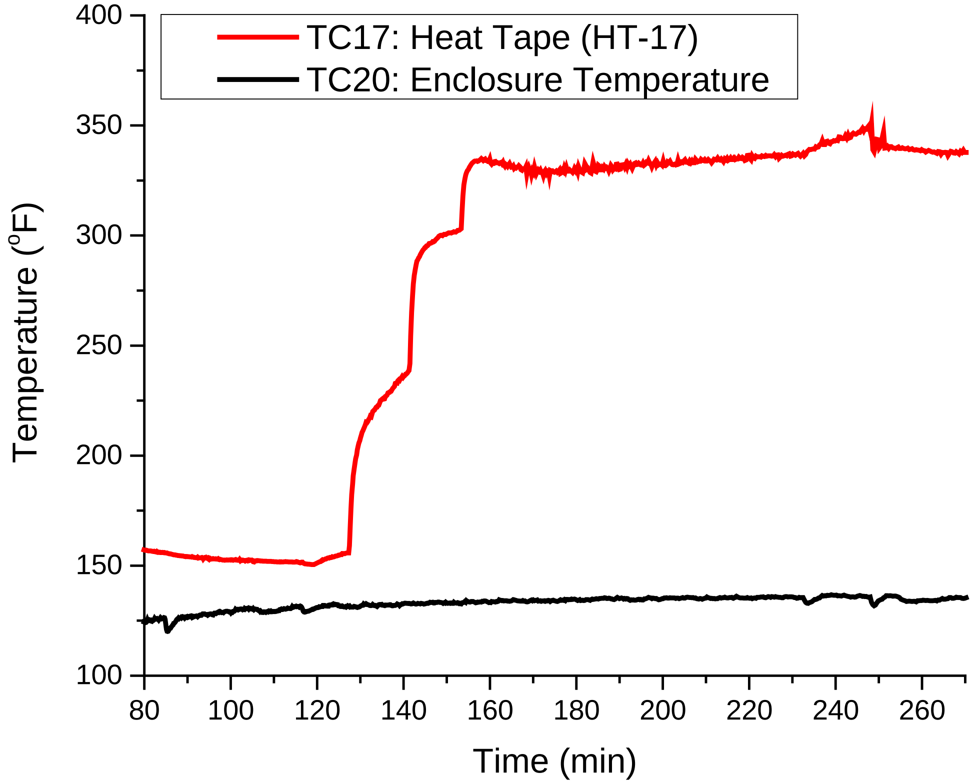


Figure 20. Temperature history of the TC17 (heat tape region).

6. Conclusion and Future Work

The current test campaign demonstrated the capability of the thermosiphon (i.e. natural circulation) induced cooling in the T-CLIP^{TM} at room temperature (70 °F) and elevated temperature (130 °F) with the pump off condition. The work performed can be summarized as follows:

1. A temperature controlled environmental enclosure for the solar test was built to evaluate the feasibility of the T-CLIP^{TM} at various temperatures.
2. The effort to monitor the temperature, pressure, and flow rate over the system was made to have a better understanding of the convective heat transfer in the T-CLIP^{TM}. At the pump off condition in which the thermosiphon triggered, the direct observations of the system behavior were basically made from the temperature and pressure only.
3. At the pump off condition, the flow rate at the thermosiphon was assumed to be too low for existing measurement devices in the test area. There were no reliable flow rate data obtained due to the measurement detection limit of the ultrasonic flow meter. In addition, the analytic solution of the flow rate at the simplified natural circulation loop was calculated by using dimensionless analysis. This calculation indicated that the possible flow rate at the thermosiphon (0.01 GPM) is way below than the current ultrasonic flow meter detection level (0.1 GPM) in the test area.
4. At room temperature, the thermosiphon induced cooling was observed by monitoring the temperature history over the locations of interest. The opening of the check valve was detected by the pressure drop change at the moment the thermosiphon triggered from the temperature history.
5. At the elevated temperature test, the temperature history also indicated that there was a clear thermosiphon induced cooling triggered while in the pump off condition, and the transport of the cooled fluid from the thermosiphon was observed from a close look at the related flow path in the T-CLIP loop (TC10 → TC1 → TC →9). To ensure the presence of the thermosiphon induced flow in the T-CLIP^{TM} the flow paths at the vertical heat pipes -1, and -2 were closed and flow was diverted to heat pipe -3. The result again indicated that the T-CLIP^{TM} operated while the environmental temperature is maintained to 130 °F.

Further work to improve the test project can be addressed as follows:

1. The thermal collector design can be improved and optimized for higher efficiency of the solar collector system. For example, numerical analysis on the collector design using the finite element method is a good approach to make a better design on the collector and explore ways to improve system efficiency.
2. The heat dump system can be improved by employing the heat pipes at different orientations and locations.
3. The functionality of the check valve can be improved by the angled orientation or an improved valve design.
4. A piping system with more economical material and better thermal performance is also suggested.

7. Acknowledgements

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We would like to express the co-author's individual contributions on the project:

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- Gabrielle Vigil, a summer student from the University of New Mexico, for designing and planning on the thermal enclosure for the T-CLIP^{TM} test, and demonstrating detailed note taking on the test procedure and data collection
- Martin Perraglio, a summer student from the University of New Mexico, for preparing various measurement devices for the high-fidelity data acquisition process and showing a great attitude to learn about the physics of the natural circulation phenomena in the T-CLIP^{TM} test
- Cory Farley for the time he helped on the thermal enclosure set up and testing
- Jose I. Tafoya for his quick and professional support on the thermocouples and pressure transducer installation on the test loop
- Adam L. Martinez for quick support on the thermal enclosure building and his professional oversight on the experiment setup and testing.

8. References

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3."Scaling laws for single-phase natural circulation loops", P.K. Vijayan, H. Austregesio, Nuclear Engineering and Design 152, 1994, pp 331-347

Appendix A- An analytic solution of steady-state natural circulation (NC) flow rate using dimensionless analysis for the rectangular NC loop

Natural circulation is being increasingly employed in many innovative designs of thermal systems (i.e. Nuclear power plants, solar thermal systems). The basic advantage of natural circulation systems is the enhanced safety due to its passive nature. Therefore, natural circulation plays an important role in the long term cooling of the thermal system during accident scenarios such as (a) loss of coolant or (b) pump failure or (c) power outage. Consider the following simple representation of a thermal system operating under steady state natural circulation. In general, the actual thermal system will be much more complex with various geometry conditions. However, the flow rate calculation of the steady state natural circulation with the simple system configuration gives a rough idea of the flow rate in the system. In many cases, the flow regime of the natural circulation in the system falls into the laminar flow, it has been a challenging task to evaluate the flow rate in the system without using non-intrusive flow meter. The analysis presented below is based on the one-dimensional approach as shown in Figure 21. The following simplifying assumption are made:

(1) The coolant is a single phase liquid, the fluid is assumed to be incompressible
(2) The Boussinesq approximation is valid, i.e. fluid properties can be considered to be constant in the governing equations, except for the density in the buoyancy term, which is assumed to vary linearly with temperature as $\rho = \rho_0\{1 - \beta(T - T_0)\}$
(3) The flow path is composed of constant area flow segments, (i.e. no expansion and contraction considered)
(4) The thermal system is closed loop with heat source (i.e. solar input, reactor) and heat (i.e. heat exchanger), and the heat loss from the system is negligible.
(5) Viscous heating and axial conduction effects are also negligible

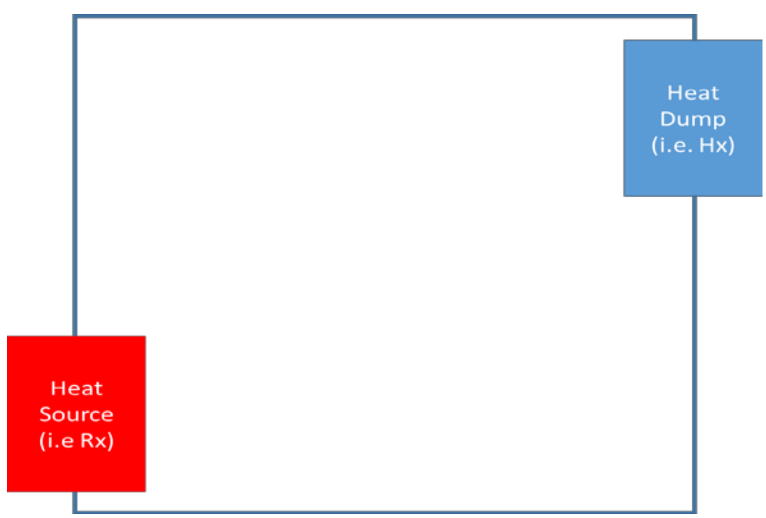

Figure 21. Simple representation of a natural circulation loop.

With the mass conservation assumption, the momentum equation over the loop become a function of time only, and is independent of the space coordinate. The integrated momentum equation can be written as

$$\frac{L}{A}\frac{dW}{dt} = g\beta\rho_0 \oint T dz - f\frac{L}{D}\frac{W^2}{2\rho_0 A^2} \quad \text{Eq.1}$$

In this analysis, it is assumed that the form losses are negligible compared with the wall friction losses since the pipe diameter is fixed over the whole system including the heat source component and heat dump component. In general friction factor f can be expressed as

$$f = \frac{p}{Re^b} \quad \text{Eq.2}$$

$$f = \frac{64}{Re} \rightarrow laminar\ flow, f = \frac{0.316}{Re^{0.25}} \rightarrow turbulent\ flow \quad \text{Eq.3}$$

Where the constants p and b take different values for laminar and turbulent flow, for example, p=64 and b=1 for laminar flow, while p and b are respectively 0.316 and 0.25 for turbulent flow based on Blasius equation. Since we are interested in the laminar flow natural circulation condition, the fiction factor is selected as f=64/Re for the rest of analysis.

Based on the scaling laws for single-phase natural circulation loop proposed by Vijayan, 1994 [3], the momentum equation above can be then non-dimensionalized using the following substitutions:

$$\omega = \frac{W}{W_{ss}}, Z = \frac{z}{H}, \theta = \frac{T - T_s}{(\Delta T_h)_{ss}}, \tau = \frac{tW_{ss}}{V\rho_0} \quad \text{Eq.4}$$

With these substitutions, the Equation 1 can be rewritten with non-dimensionalized parameter as shown in Equation 5.

$$\frac{d\omega}{d\tau} = \frac{Gr_m}{{Re_{ss}}^3}\oint \theta dz - \frac{64}{Re_{ss}}\frac{L}{D}\frac{\omega}{2} \quad \text{Eq.5}$$

The non-dimensional groups in Equation 5 can be expressed as

$$Gr_m = \frac{D^3\rho^2\beta g Q H}{\mu^3 A C_p}\ or\ \frac{D^3\beta g \Delta T}{v^2}, \quad Re_{ss} = \frac{DW_{ss}}{A\mu} \quad \text{Eq.6}$$

Where, D=inside pipe diameter,

ρ=fluid density,

β=thermal expansion coefficient,

g=gravity,

Q=heat power,

H=the difference between each thermal center (the thermal center for heat source and the thermal center for heat dump),

ΔT=the temperature difference between the heat source and the heat dump

μ=fluid dynamic viscosity

v=fluid kinematic viscosity

A=cross-section area

Cp=specific heat

W_{ss}=mass flow rate at steady state

For the steady state condition, $\frac{d\omega}{d\tau} = 0$ and, by definition $\omega = \frac{W}{W_{ss}} = 1$ can be defined, in addition the integrated steady state temperature distribution for the rectangular closed natural circulation loops can be assumed as follows

$$\oint \theta_{ss}(Z)dZ = 1 \qquad \text{Eq.7}$$

Using this definition and result (Eq.7), the following equation for the flow rate under steady state condition can be obtained with the assumption that the flow in the natural circulation loop is laminar flow.

$$Re_{ss} = 0.1768\left[Gr_m \frac{D}{L}\right]^{0.5} \qquad \text{Eq.8}$$

In the present analysis, the simplified natural circulation loop presented in Figure 21 has L/D of 60 approximately, which is closed the solar loop pipe configuration. The Grashof number Gr is calculated based on the temperature difference between the thermal center of heat source (i.e. the representative temperature of the solar collector component), and the thermal center of the heat dump (i.e. the representative temperature of the heat exchanger component). The fluid thermal properties are selected from the water properties from the NIST database [3]. Note that the actual working fluid in the experiment is propylene glycol which has quite similar thermal properties with water with high melting temperature.

The non-dimensionless groups is calculated as

$$Gr_m = \frac{D^3\beta g\Delta T}{v^2} = \frac{0.025m^3\ X\ 0.000214K^{-1}\ X\ 9.8\frac{m}{s^2}\ X\ 283K}{\frac{10^{-5}m^2}{s} X \frac{10^{-5}m^2}{s}} = \sim 92730 \qquad \text{Eq.9}$$

Using the scaling laws (Eq.8), the Reynolds number at the steady state condition of the simplified natural circulation loop in the present analysis can be obtained as

$$Re_{ss} = 0.1768\left[Gr_m \frac{D}{L}\right]^{0.5} = \sim 6.9 \qquad \text{Eq.10}$$

Given the result from the Equation 10 with the pipe diameter of 1 inch and the working fluid properties, the flow rate at the steady state natural circulation condition is approximately calculated to 0.01gmp. Since the present analysis uses a simplified loop configuration than the actual solar test configuration, where more realistic friction losses are expected from the complex flow channel, the predicted flow rate from this analysis (0.01gmp) could be considered as a very conservative approximation. Most likely the actual flow rate at the solar test would be less than 0.01gmp which is unfortunately beyond of the ultrasonic flow meter measurement limitation. Although this analysis cannot be directly validated with experimental measurement, the calculation is still worthwhile to have a rough estimate of the flow rate in the steady state natural circulation in the solar test.

Appendix B- Energy balance calculation for the integrated solar system

During the design stage of the thermal enclosure, we calculated the energy balance of the system at steady state with practical engineering assumptions. Figure 22 summarizes the brief calculation of the energy balance between solar test and temperature control unit. The assumptions are as follows:

1. The energy balance is calculated based on the steady state condition only
2. The calculated energy in (i.e. either cooling or heating) from the temperature control unit (TCU) should be less than TCU's thermal capacity for the operating safety concern
3. The sum of the energy in from the TCU and the heat generation from the solar lamps is equal to the energy loss from the thermal enclosure of the solar collector test.

The energy loss from the thermal enclosure is calculated using the overall heat transfer coefficient approach for a wall. The heat transfer coefficient of the outer wall and the inner wall are assumed to be 5W/m^2-K (i.e. a value for the radiant heat transfer coefficient toward to the room temperature environment) and 50W/m^2-K (i.e. a value for the force convective heat transfer coefficient inside of the enclosure). The thermal resistance value for the insulator is R-10 (i.e. 10m^2-K/W). The temperature different between the enclosure and room temperature is assumed to be 60K. The energy loss over the enclosure is estimated approximately 210W. With a maximum number of solar lamp installed (e.g. using 4 solar lamp (4000W)) the energy produced from the TCU should be a negative 3790W. This implies that the TCU has to be operated as a cooling unit which can be well covered with the cooling capability of TCU (i.e. 10KW). This type of energy balance calculation at the beginning of the thermal enclosure design gives a good insight on the selection of insulator material and the requirement of temperature control unit capacity.

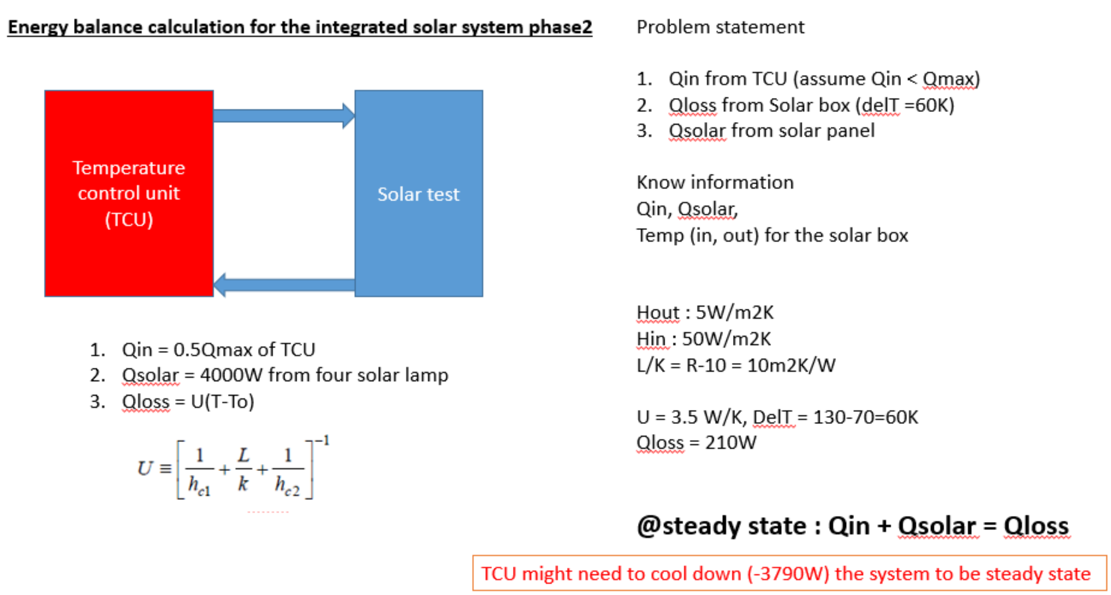

Figure 22. Energy balance calculation for the thermal control unit capability.

Appendix C- Thermocouple Calibration

The purpose for the calibration testing on the thermocouples is to ensure that the thermocouples and each component involved give the right measurement. The thermocouple that apply to the T-CLIP project are "K-type" which has the material Chromel (made 90% Nickel and 10% chromium) and Alumel (made of 95% nickel, 2% manganese, 2% aluminum and 1% silicon). K-type thermocouples can handle a temperature range of -270 °C to 1,260 °C. The highest temperature we are exposing in the current test is approximately 400 degrees °F (~204°C).

The thermocouple calibration is performed by checking the resistance for each thermocouple with a thermocouple calibrator. The calibrator has a port for thermocouples which makes it easy to check a thermocouple relative to the others in the system; we can also send a signal to the DAQ system to ensure the program is reading the right signal. By sending a signal to the DAQ that also insures that the wire is right material and the plugs are wired in properly. All of thermocouples read the same value that the calibrator indicates, within 1°C (See Table 4). The data below shows the accuracy of the thermocouples in relation to each other and also the signal that we are sending out to the DAQ system. The calibration process and the tabulated data below indicate that all thermocouples are wired properly and are showing the expected, repeatable, temperature values recorded by our DAQ system. All thermocouples were attached the surface of the pipe using adhesive. At the current test condition (below 400°F) a self-adhesive style is sufficient to measure the temperature profile. In the current test we configured the copper piping system with the appropriate insulating material. It is assumed that the temperature discrepancy between the thermocouple reading at the pipe surface and the actual fluid temperature is not significant.

Table 4. Temperatures reading from thermocouples (TC-1-TC-17) and set point value from thermocouple calibrator.

Set Point by calibrator	0 °C	50 °C	100 °C	200 ° C
TC-1	-0.29	49.88	99.75	199.77
TC-2	-0.25	49.88	99.81	199.83
TC-3	-0.26	49.79	99.76	199.75
TC-4	-0.23	49.81	99.74	199.74
TC-5	-0.21	49.86	99.78	199.76
TC-6	-0.18	49.83	99.75	199.73
TC-7	-0.28	49.75	99.76	199.73
TC-8	-0.23	49.82	99.66	199.79
TC-9	-0.39	49.75	99.67	199.65
TC-10	-0.27	49.76	99.78	199.75
TC-11	-0.23	49.81	99.77	199.82
TC-12	-0.24	49.86	99.69	199.59
TC-13	-0.27	49.71	99.58	199.72
TC-14	-0.28	49.78	99.69	199.74
TC-15	-0.18	49.91	99.85	199.81
TC-16	-0.31	49.82	99.71	199.65
TC-17	-0.09	49.91	99.85	199.85