AC 2012-3019: SOLAR WATER HEATING SYSTEM EXPERIMENTAL APPARATUS

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Solar Water Heating System Experimental Apparatus

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Abstract

This paper describes the design and development of an experimental apparatus for demonstrating solar water heating. This solar heating experimental apparatus was designed to meet several requirements: 1) the system is to operate using the thermosiphon concept, in which flow through the system is created by density differences in the fluid; 2) to increase the solar energy absorbed by the water and improve the educational value of the project, the solar collector must have the ability to rotate in order to maintain a position perpendicular to the sun's rays; 3) the experimental apparatus must be mobile. A prototype of a solar water heating system was constructed and tested. The solar collector rotated as the sun position/angle was changing, indicating the functionality of the control system that was design to achieve this task. Experimental measurements indicate that the water in the tank was heated by the solar energy being absorbed by the solar collector. Moreover, the water temperature measurements at different heights in the storage tank show the thermosiphon effect has been attained. Solar water heating utilizing thermosiphon is attractive because it eliminates the need for a circulating pump.

Introduction

Acquiring new instructional laboratory apparatus is a challenge due to typical budgetary limitations. In addition, the apparatus designed by companies specializing in education equipment may not exactly reflect the educational objective intended by the faculty. These obstacles had forced us to seek and search different venues to acquire experimental laboratory apparatus for demonstrating heat transfer principles. We concluded that such an apparatus can be designed, developed and constructed "in house" within a manageable budget. This can be successfully accomplished by taking advantage of the capstone senior design project and ASHRAE Undergraduate Senior Project Grant Program. The purpose of this ASHRAE's program is to fund equipment for undergraduate engineering senior projects on ASHRAE-related topics.

Solar water heaters can operate in any climate[1,2,3,4] . The performance of these heaters varies depending on how much solar energy is available at that locality, and more importantly on how cold the water coming into the system is. The colder the incoming water, the more efficiently the solar water heating system operates. A large number of studies have examined the performance of solar water heating system; see for example[5,6,7,8,9,10] and the references cited therein. Very recently, Jaisankar et al.[11] reported a comprehensive review on solar water heaters. They reported that the efficiency of solar thermal conversion is about 70% when compared to solar electrical direct conversion system which has an efficiency of only 17%. Owing to its ease of operation and simple maintenance, solar water heating systems play an important role in domestic as well as industrial sector.

Solar water heaters can be either active or passive. The active solar water heating system uses a pump to circulate the heated water through the system. On the other hand, passive solar water heating system move the heated water through the system without pumps. This type of system does not have electric components to break, which makes it more reliable and easier to maintain than active systems.

A thermosiphon solar water heater relies on warm water rising, a phenomenon known as natural convection, to circulate water through the solar collector and to the storage water tank. Temperature in the storage water tank is a function of the buoyancy-induced flow of heated water in from the water heater. In this type of installation, the storage water tank must be above the solar collector. As water in the solar collector heats up, it becomes lighter and rises naturally into the storage tank above. Meanwhile, cooler water in the tank flows down pipes to the bottom of the solar collector, causing circulation throughout the system. The water storage tank is attached to the top of the solar collector so that thermosiphon effect can take place.

Thermosiphon effect for solar hot water heating has employed with solar collectors as the principal heating component. These solar heating systems use either direct heating by the collector itself as reported by Huang and Shieh[12] and Morison and Braun[13] or indirectly via a heat exchanger (Parent et al.[14]). In these cases, the thermosiphon induced flow is a result of the incident solar radiation but is also affected by the hot water removal pattern. Recently, Kishor et al.[15] used fuzzy model system to predict the outlet water temperature of a thermosiphon solar water heating system.

This paper describes the design and development of an experimental apparatus for demonstrating solar water heating. This solar heating experimental was designed to meet several requirements: 1) the system is to operate using the thermosiphon concept, in which flow through the system is created by density differences in the fluid; 2) to increase the heat added to the water and improve the educational value of the project, the solar collector must have the ability to rotate in order to maintain a position perpendicular to the sun's rays; 3) the experimental apparatus must be mobile.

Design and Building Process

The design process that was employed in this research project is the one outlined by Bejan et al.[16] and Jaluria[17]. The first essential and basic feature of this process is the formulation of the problem statement. The formulation of the design problem statement involves determining the requirements of the system, the given parameters, the design variables, any limitations or constraints, and any additional considerations arising from safety, financial, environmental, or other concerns. The following is a summary of these guidelines:

- The solar water heating system must not require pumps. It should utilize thermosiphon effects.
- Solar collector controls – The control system is used to achieve the optimal sun exposure of the solar collector. The system is based on the fact that maximum sun exposure is achieved when sunlight hits the solar collector at a 90° angle. A mechanical system will

be designed to rotate and control the angle of exposure of the solar collector to achieve optimal exposure. This mechanical system will be designed such that a rotational motion device instigates the solar collector motion through an input from an electronic device. The electronic device (i.e. microcontroller or PLC) instigates the motion based on information obtained about the position of the solar collector relative to the sun.

- All components of the system must be visible and must be instrumented with thermocouples and flow rate meters. This is essential because, as mentioned above, the finished product would serve as an instructional laboratory apparatus for demonstrating solar water heating and thermosiphon concept.
- The material should endure flow and temperature variations and should be resistant to corrosion.
- The heating system components such as tubes and fittings must be standardized to lower the cost.
- Mobility – The system will be used for demonstration purposes and will require direct sunlight. Therefore, the system must be mobile, allowing for placement in sunlight. The system must also be designed so that it can be stored when not in use.

After the problem statement was formulated, several conceptual designs were considered and evaluated. Each design concept was evaluated by the following criteria: Effectiveness, Cost, Safety, and Size. The solar water heating system experimental apparatus that was designed and constructed is shown in Fig. 1.

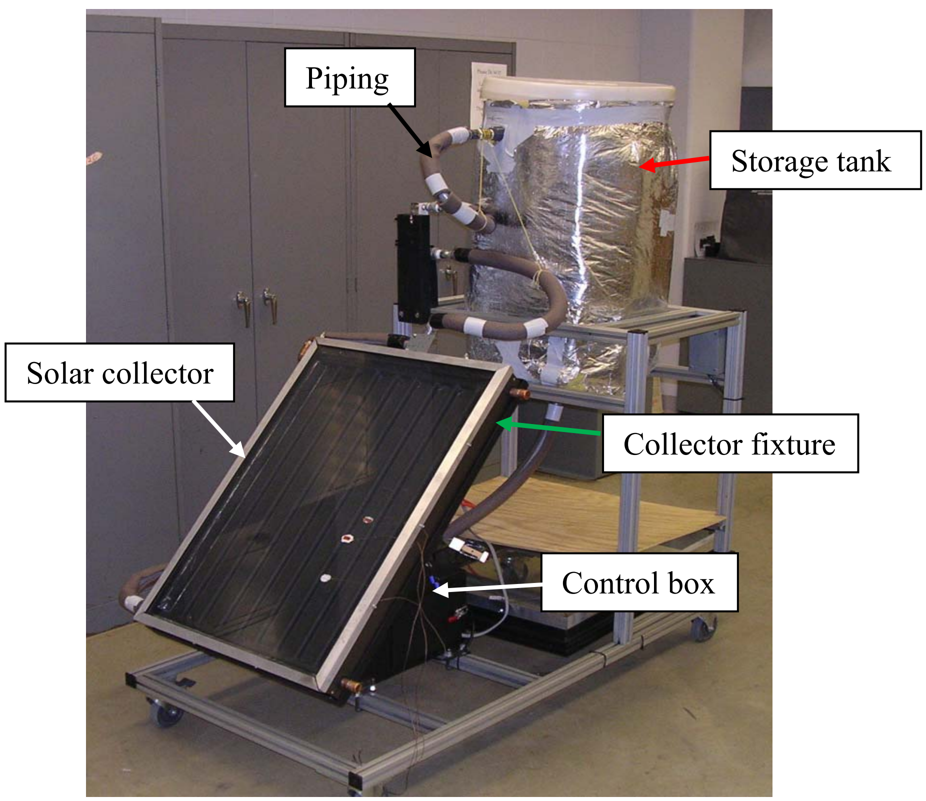

Fig. 1: Solar water heating experimental apparatus

Solar Collector

The solar collector was designed conceptually to have vertical runs of parallel pipe. The main restriction for the design of the solar collector was the size of the collector this was due to the fact that it must remain portable and safe. Therefore, a custom size of 2 ft wide by 3 ft long was specified, producing an overall area of 6 ft^2. The 2 ft width and 3 ft height allows for sufficient clearance in most doorways and would allow for safe transportation from storage to a testing environment. Along with the solar collector frame, other components such as the piping, absorber, and glass needed to be determined.

Since the width of the collector was set to be 2 feet, and typical solar collector piping is ½" copper, the number of pipes was determined to be seven. The piping was constructed of ½" nominal copper pipes that run lengthwise through the collector. The absorber was based on typical solar collector standards and was constructed of fiberglass. Like the absorber, the glass material was chosen based on industry standards. All of the solar collector components that would be exposed to the sun must be painted black in order to attract more sunlight. The glass cover over the absorber was constructed of low-iron, tempered glass.

Storage Tank

The tank that was selected from the design evaluation required that it must be of a vertical configuration. The tank also should be designed such that the water can enter and exit the tank, and allow for the thermosiphon effect to take place. The tank also must be designed taking into account proper safety precautions.

The tank size that was purchased was 40 gallons. The inlet and outlet fittings for the tank were ¾" threaded (male and female). The tank is 18 inches inner diameter and 34 inches in length, giving the required vertical configuration that is required to achieve the thermosiphon effect. To reduce the amount of heat lost by the water in the storage tank, standard insulation used for a water heater was purchased to go on the outside of the tank. The insulation also provides a burn barrier to users if they would touch the outside of the tank when the water was hot.

Inlet/Outlet Piping

A piping system was designed to allow for water to flow to and from the solar collector and the storage tank. The storage tank had ¾" male and female threaded inlet and outlet fittings. The solar collector was constructed with sections of ¾" copper piping outside of the frame for the connecting piping. Therefore, it was determine that ¾" piping or tubing will be used to allow water to flow to and from the tank and solar collector. To allow for proper rotation of the solar collector sections flexible tubing (standard, braided vinyl tubing) was used to connect the solar collector and the storage tank.

Thermocouples

The requirements of the thermocouples are that they must be located in positions that will show the system's ability to heat water utilizing the thermosiphon effect. The operating range for the thermocouples will be between 40-200°F. Five type-T thermocouples will be used. In order to show that the thermosiphon effect is taking place, thermocouples were placed at various elevations in the storage tank. Figure 2 shows a pipe with holes drilled through it such that rods could be placed through each of the holes; the thermocouples could then be wrapped around the rods and run through the pipe and outside of the tank was constructed. A cap was set into the bottom to keep the thermocouples from direct contact with the water. However, this caused the pipe to float and the top thermocouple would not be submersed in water at all times. Therefore, a hole was drilled through the bottom of the cap to allow water to flow inside and cause the pipe to sink. This design was sufficient and allowed for the water temperature measurements to be taken inside of the tank.

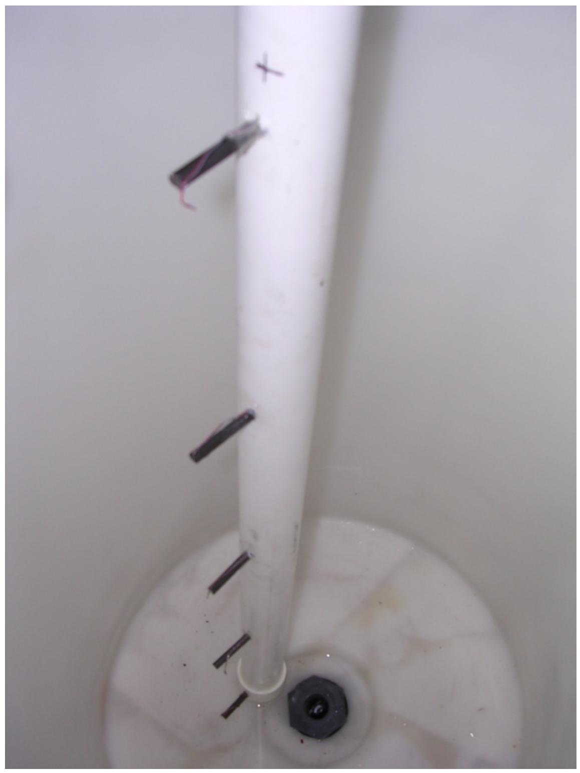

Fig. 2: Thermocouples location in the storage tank

Control System

The main component of the control system is the motor that is used to rotate the solar collector. The motor is a 12 V DC gear reduced motor with a 24 V DC brake. The motor is reversible, but only if the leads are switched. To allow for the motor to be reversed while utilizing the programmable logic controller (PLC), a relay circuit was developed. This circuit, which required two Contact Relays to be connected to the motor, allowed the leads to be switched, resulting in motor reversibility. This circuit is shown in Fig. 3. In the figure, CR1 designates control relay 1, and CR2 control relay 2. The motor rotates at approximately 7.5

rotations per minute and is gear-reduced at 620:1. The brake allows for quick stopping, eliminating the inertia often seen in such motors. Power must be supplied to the brake to run the motor; in the event of a power loss, the brake automatically engages.

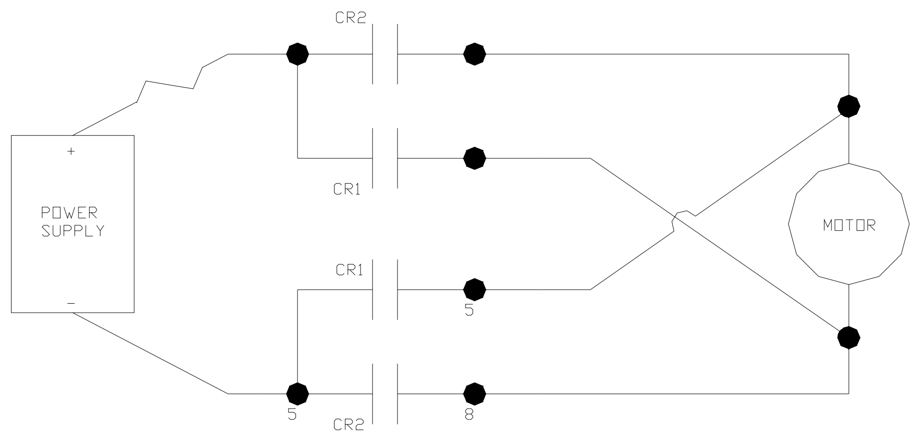

Fig. 3: Control circuit

Also added to the system were two switches, enhancing the available control of the system. As mentioned, motion of the motor was going to be instigated by sensors. But this does not allow for motion of the motor in dimly lit areas, such as a lab or workshop. During construction and testing, motor rotation was desired that the sensor setup did not allow for. To overcome this, a "Jog" or "Manual Rotation" switch was added. This switch, shown in Fig. 4, is a three-position spring-return switch. In the neutral position, the motor sits idle. If the switch is toggled to the left, the motor rotates in a counter-clockwise direction. If the switch is toggled to the right, the motor rotates in a clockwise direction. This is a great convenience.

The addition of the "Manual Rotation" switch meant that the motor was capable of running in two modes: the automatic mode in which rotation was based on sensor input, and a manual mode in which rotation was based on user input. To distinguish between these modes, a second switch was added, an "Auto / Manual" switch. This switch lets the user decide which mode suits their needs.

The final addition to the control system is the use of limit switches. These limit switches are mounted to the motor housing, and are simply used to prevent the motor from rotating more than the desired 180 degrees. This is a safety feature in that if the collector were to rotate further, piping would likely be wrenched out of its connections, causing a mess.

The brain of the control system is the PLC. It is an Allen-Bradley Micrologix 1500, capable of handling twelve inputs and twelve outputs. Many cards can be added, increasing the capability of the PLC; due to the sensors used, an Analog card was added to the base PLC. The base inputs only allow ON/OFF inputs; the analog card allows for the use of analog inputs, which give outputs proportional to the inputs.

Fig. 4a: Manual collector rotation

Fig. 4b: Automatic Mode

The analog inputs used in this case were silicon semi-conducting solar cells. These solar cells produce electricity when exposed to sunlight. Under full sunlight, the solar cells used produce 5.5 volts. One solar cell was placed on each side of the solar collector and set an angle of approximately 35 degrees, though this angle can vary. Each sensor sends a value to the PLC, which are compared. Motor rotation is based on the difference in these sensor readings. During testing, the solar cells often received too much light, directly from the sun, and indirect reflections. Therefore, the sensors were entirely covered, save a hole with a 5/16" diameter. This minimized the amount of light on the sensors, and improved functionality greatly.

<u>Collector Fixture/Control Box</u>

The collector fixture shown in Fig. 5 is used to hold the solar collector as it rotates. Since the solar collector could not be fixed directly to the motor, a means of transferring the motors rotation to the solar collector had to be determined. This means was the collector fixture. The collector fixture was dimensioned based on the size of the solar collector, and the mating dimensions of the motor. 90° steel sections were formed into a fence that the solar collector would be able to set inside. A cross-beam was welded to the fence horizontally, to allow for a vertical piece to be connected to the solar collector fence which will in turn mate with the motor allowing for rotation. A screw is connected to the horizontal cross-beam to allow for the solar collector to be positioned at various angles. The vertical post running from the horizontal cross-beam to the motor mate was designed with a height such that the solar collector would be able to rotate freely without being obstructed by the control box or by the cart. The fixture was able to mate with the motor by creating a disc that would sit on top of the motor with four holes drilled through that were positioned based on the screw holes in the motor. Bolts were then used to secure the solar collector fixture to the motor.

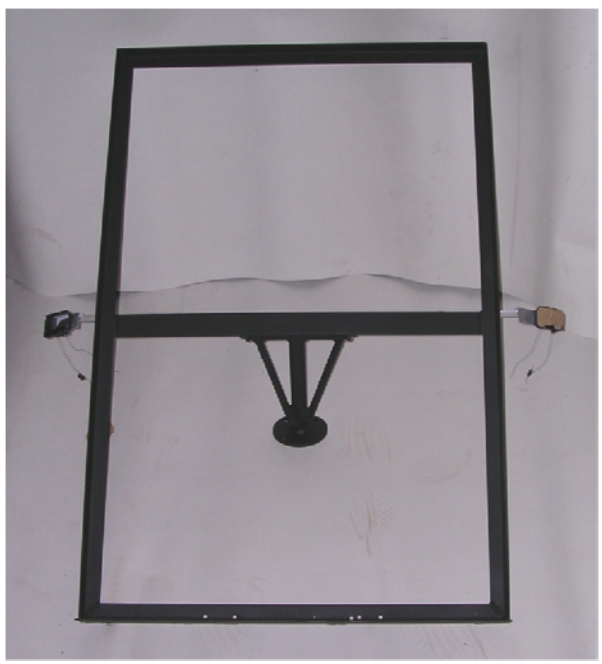

Fig. 5: Solar collector fixture

The control box was created to house the PLC, motor, relays, and all other electrical components required by the control system. The control box serves as the housing, and also protects all of the electrical components from water. The dimensions of the control box were determined based on the size of the motor, PLC, and other components that were to be housed inside of the control box. The control box was designed to have an access door on one side to allow for maintenance of the electrical devices. Holes were located on the top of the control box to allow for the motor to be inserted, secured, and exposed for proper fixation with the solar collector fixture. The holes' sizes and locations were determined based on the geometry of the motor. Also, the control box was fitted with brackets that would allow for the box to be secured to the cart. Again, the cart dimensions were used to formulate the configuration of the brackets. Since the control box would be supporting the weight of the solar collector, glass addition, and solar collector fixture, the control box was constructed of steel and was formed with a steel frame. A picture of the control box is shown in Fig. 6.

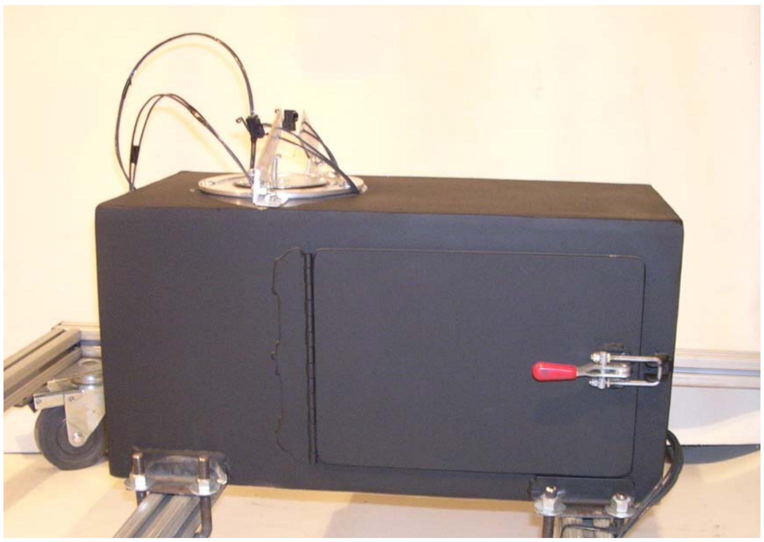

Fig. 6: Control box

Testing Procedure and Sample Results

The experimental apparatus was set up as shown in Fig. 1. The testing procedure is straight forward. It consists of the following steps:

1. Ensure that all piping is connected.
2. Add water to storage tank until the tank-inlet opening is completely submerged.
3. Connect thermocouples to thermocouple selector; noting which thermocouple is placed into which port.
4. Place the tank thermocouple assembly into the storage tank as shown in Fig. 2 and then place the lid on the storage tank.
5. Place the apparatus in the desired testing location, ensuring that sufficient sunlight is available.
6. Point the "Auto / Manual" switch toward "Manual" as shown in Fig. 4a. Using the toggle switch beneath the "Auto / Manual" switch, rotate the solar collector until it points in the approximate direction of the sun.
7. Flip the "Auto / Manual" switch to "Auto" as shown in Fig. 4b.
8. When testing is complete, point the "Auto / Manual" switch to "Manual", and rotate the

collector until it faces the front of the cart; this will ensure the apparatus fits through doorways.

Thermocouples were connected to the data acquisition board. Measured temperatures were collected and analyzed using a data acquisition system.

The solar water heating system was tested several times. Temperature water measurements in the storage tank were recorded every 10 minutes and lasted for 5 hours. During the test, the solar collector was observed being rotating as the sun position/angle was changing, indicating the functionality of the control system that was designed to achieve this task.

Thermosiphon Effect: Temperature in the storage water tank is a function of the buoyancy-induced flow of heated water in from the solar collector. Due to the very slow buoyancy-induced flow rate, there will be a heated water front progressing downward through the tank. The rate of progression depends on the strength of the thermosiphon effect. The temperature variation in the water storage tank is shown in Fig. 7. In this figure, T1 is the temperature of the water at the middle of the tank, T3 is the temperature of the water at the top of the tank, and T2 is in between the two. As can be seen from the figure, the temperature distribution rose during the operating time. It should be noted that the temperature of the water was also measured at two more locations below where T1 was measured. However, the temperature measurements at these two locations are not shown in the figure as they exhibited little change throughout the testing process. This indicates that the thermal stratification retained well.

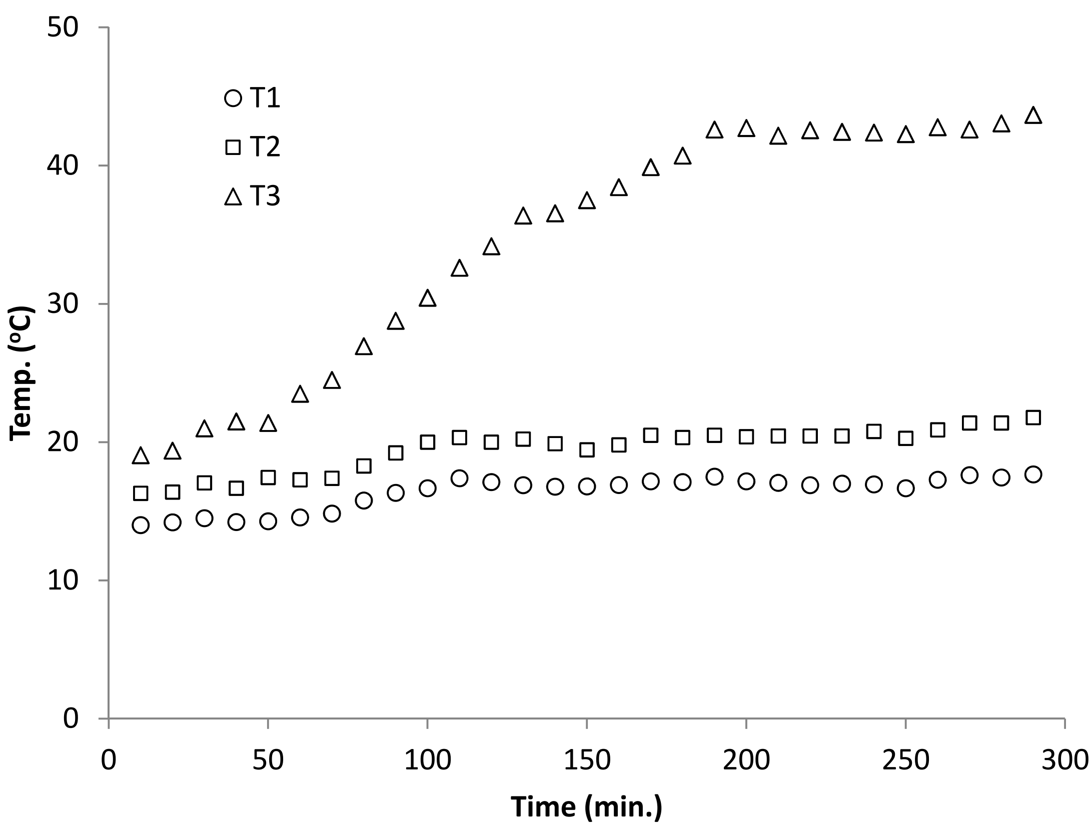

Fig. 7: Temperature variation in the storage tank in heating water

Implementation and Assessment

The apparatus has been in use in our undergraduate heat transfer laboratory and in a thermal technical elective course. The heat transfer laboratory is a junior level class. The thermal technical elective course is a senior level course entitled; Sustainable Energy Sources and Systems. This experimental apparatus has been used as a regular experiment in which they follow an existing procedure and report the results. Also it's been used as a design of experiment exercise in which the students' team is asked to modify the experimental set up, develop a testing procedure, test the modify apparatus and report the results.

Feedback from students has been positive. They like the design of experiment approach. They feel it gives them more opportunity for hands on approach.

Conclusions

A prototype of a solar water heating system was constructed and tested. The solar collector rotated as the sun position/angle was changing, indicating the functionality of the control system that was design to achieve this task. Experimental measurements indicate that the water in the tank was heated by the solar energy being absorbed by the solar collector. Moreover, the water temperature measurements at different heights in the storage tank show the thermosiphon effect. Solar water heating utilizing thermosiphon is attractive because it eliminates the need for a circulating pump. Results indicate that the design of the thermosiphon solar water heating system was a success.

Moreover, the experimental apparatus described in this paper is a valuable addition to the undergraduate mechanical engineering laboratory. The experimental apparatus is portable and it can be used as an instructional experimental apparatus for demonstrating basic heat transfer principles and thermo-siphon concept.

Acknowledgement

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