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Design and development of solar water heating system experimental apparatus

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ABSTRACT: The design and development of experimental apparatus for demonstrating solar water heating is described in this article. 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; and 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 utilising thermosiphon is attractive because it eliminates the need for a circulating pump.

Keywords: Design, laboratory, solar heating

INTRODUCTION

Acquiring new instructional laboratory apparatus is a challenge due to typical budgetary limitations. In addition, the apparatus designed by companies specialising in education equipment may not exactly reflect the educational objective intended by the faculty. These obstacles had forced the author to seek and search different venues to acquire experimental laboratory apparatus for demonstrating heat transfer principles. It was 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 the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Undergraduate Senior Project Grant Program. The purpose of this ASHRAE's article is to fund equipment for undergraduate engineering senior projects on ASHRAE-related topics.

Solar water heaters can operate in any climate [1-4]. 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 systems; see for example and the references cited therein [5-10]. Very recently, Jaisankar et al reported a comprehensive review on solar water heaters [11]. 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, a passive solar water heating system moves the heated water through the system without pumps. This type of a 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.

The thermosiphon effect for solar hot water heating has been 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 used a fuzzy model system to predict the outlet water temperature of a thermosiphon solar water heating system [15].

This article 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; and 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 utilise 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 programmable logic controller (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 standardised 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 Figure 1.

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.

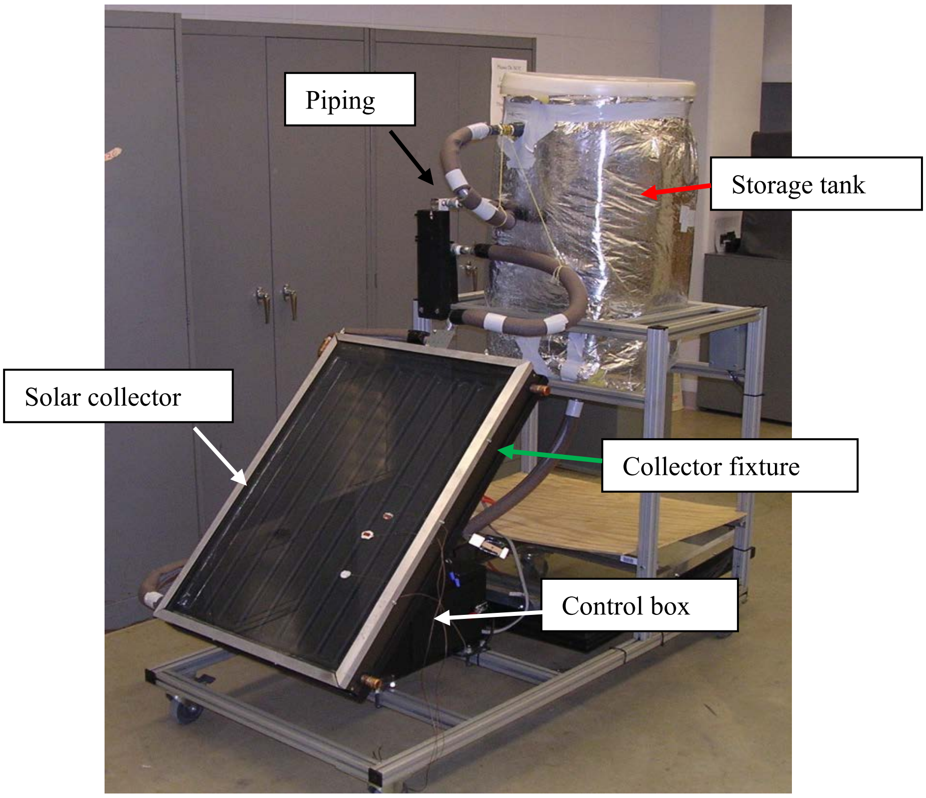

Figure 1: Solar water heating experimental apparatus.

The tank that was purchased had a 40 gallon capacity. 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 were to 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 should 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 of 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 utilising 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 the tank. 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 the 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 utilising the PLC, a relay circuit was developed. This circuit, which required two contact relays (CR) to be connected to the motor, allowed the leads to be switched, resulting in motor reversibility. This circuit is shown in Figure 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.

Figure 2: Thermocouples location in the storage tank.

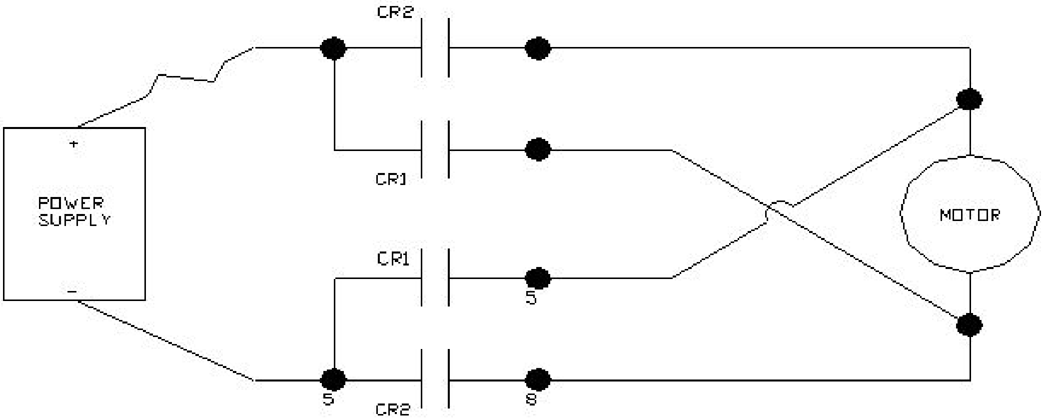

Figure 3: Control circuit.

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 laboratory 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 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 analogue card was added to the base PLC. The base inputs only allow ON/OFF inputs; the analogue card allows for the use of analogue inputs, which give outputs proportional to the inputs.

The analogue 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 at 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, except for a hole with a 5/16" diameter. This minimised the amount of light on the sensors, and improved functionality greatly.

Collector Fixture/Control Box

A collector fixture 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 motor's 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.

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 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 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 Figure 4.

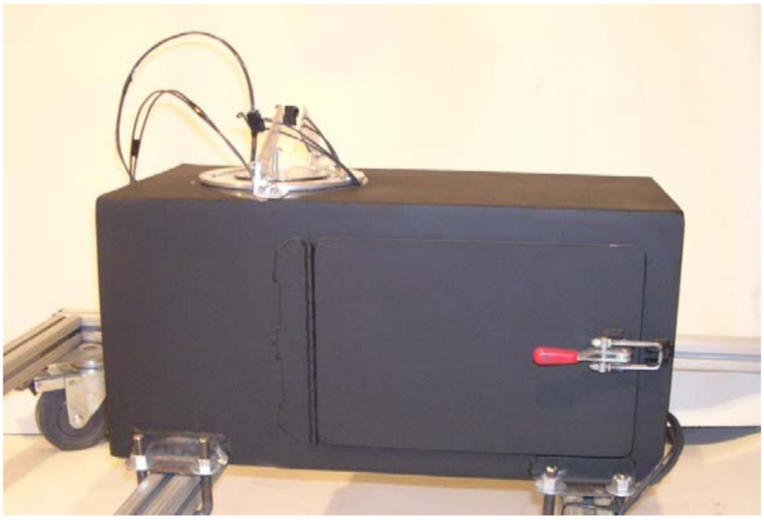

Figure 4: Control box.

TESTING PROCEDURE AND SAMPLE RESULTS

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

1. Ensure that all piping is connected.
2. Add water to the 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 Figure 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*. 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*.

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 analysed 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 Figure 5. 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.

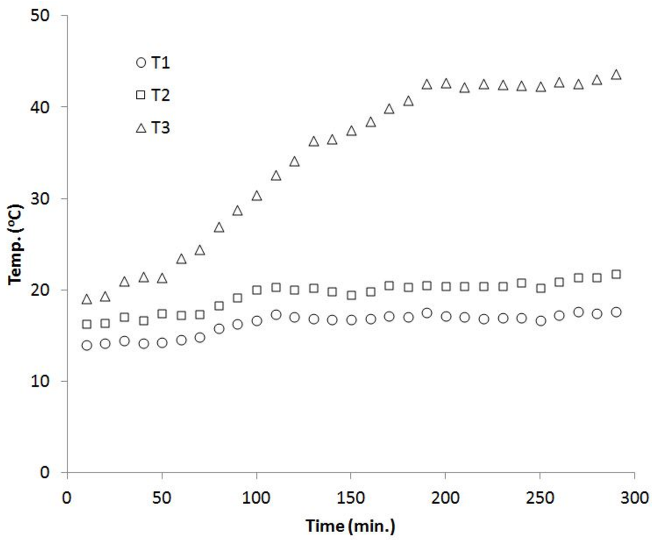

Figure 5: Temperature variation in the storage tank in heating water.

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 has 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 a 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 utilising 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.

Furhtermore, the experimental apparatus described in this article 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.

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REFERENCES

1. Langniss, O. and Ince, D., Solar water heating: a viable industry in developing countries. *Refocus*, 5, 18-22 (2004).
2. Kaldellis, J.K., El-Samani, K. and Koronakis, P., Feasibility analysis of domestic solar water heating systems in Greece. *Renewable Energy: An Inter. J.*, 30, 659-682 (2005).
3. Houri, A., Solar water heating systems in Lebanon: current status and future prospects. *Renewable Energy: An Inter. J.*, 31, 663-657 (2006).
4. Gastli, A. and Charabi, Y., Solar water heating initiative in Oman energy saving and carbon credits. *Renewable & Sustainable Energy Reviews*, 15, 1851-1856 (2011).
5. Atkinson, G. and Colvin, T., Solar hot-water heating system. *ASHRAE J.*, 51, 44-53 (2009).
6. Michaelides, I.M. and Eleftheriou, P.C., An experimental investigation of the performance boundaries of a solar water heating system. *Experimental Thermal & Fluid Science*, 35, 1002-1009 (2011).
7. Sutthivirode, K., Namprakai, P. and Roonprasang, N., A new version of a solar water heating system coupled with a solar water pump. *Applied Energy*, 86, 1423-1430 (2009).
8. Pillai, I.R. and Banerjee, R., Methodology for estimation of potential for solar water heating in a target area. *Solar Energy*, 81, 162-172 (2007).
9. Dehghan, A.A. and Barzegar, A., Thermal performance behavior of a domestic hot water solar storage tank during consumption operation. *Energy Conversion & Manag.*, 52, 468-476 (2011).
10. Bojić, M., Kalogirou, S. and Petronijević, K., Simulation of a solar domestic water heating system using a time marching model. *Renewable Energy: An Inter. J.*, 27, 441-453 (2002).
11. Jaisankar, S., Ananth, J., Thulasi, S., Jayasuthakar, S.T. and Sheeba, K.N., A comprehensive review on solar water heaters. *Renewable & Sustainable Energy Reviews*, 15, 3045-3050 (2011).
12. Huang, B.J. and Hsieh, C.T., A simulation method for solar thermosyphon collector. *Solar Energy*, 35, 31-44 (1985).
13. Morison, G.L. and Braun, J.F., System modeling and operation characteristics of thermosyphon solar water heaters. *Solar Energy*, 35, 389-406 (1985).
14. Parent, M.G., van der Meer, T.H. and Hollands, K.G.T., Natural convection heat exchangers in solar water heating systems: theory and experiment. *Solar Energy*, 45, 43-52 (1995).
15. Kishor, N., Das, M.K., Narian, A. and Prakash, V., Fuzzy model representation of thermosyphon solar water heating system. *Solar Energy*, 84, 948-955 (2010).
16. Bejan, A., Tsatsaronis, G. and Moran, M., *Thermal Design & Optimization*. New York: John Wiley & Sons, Inc., (1996).
17. Jaluria, Y., *Design and Optimization of Thermal Systems*. New York: McGraw-Hill (1998).

BIOGRAPHY

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