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DESIGN OF A SOLAR COLLECTOR EXPERIMENT FOR AN UNDERGRADUATE HEAT TRANSFER LAB

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ABSTRACT

Renewable energy sources and systems have become popular topics of study for engineering students. In this article, the authors present a renewable energy project that they have integrated in a junior-level heat transfer laboratory at Indiana University-Purdue University Fort Wayne. In the proposed project, students are asked to design an experiment which uses a solar collector to heat water in a reservoir and determine the efficiency of the process. The solar collector is equipped with a pump, on/off switch, liquid reservoir, flow meter, pressure relief valve, and thermocouples. With the current setup, liquid can be placed in the reservoir tank and pumped through the collector at flow rates between 0.5 GPM and 3.5 GPM while recording the liquid temperatures at the inlet and outlet of the collector. This type of activity serves to enhance the understanding of the transfer of thermal energy by undergraduate mechanical engineering students, while also exposing them to several important concepts involved in heat transfer, fluid mechanics, and thermodynamics.

1. INTRODUCTION

Due to environmental issues and limited fossil fuel resources, more and more attention is being given to renewable energy sources (Goswami, *et al*., 2004). The energy of solar radiation is one form of renewable energy sources. Solar radiation can be widely used for water heating in hot water systems, swimming pools as well as a supporting energy sources for central heating installations. The energy of the solar radiation is in this case converted to heat with the use of solar panel (Zima and Dziewa, 2010). Using the sun's energy to heat water is not a new idea. More than one hundred years ago, black painted water tanks were used as simple solar water heaters in a number of countries. Solar water heating technology has greatly improved during the past century. Today there are more than 30 million square meters of solar collectors installed around the globe (RETScreen, 2012).

The simplicity and wide use of the solar collector makes it a useful piece of equipment to study the applications of the renewable energy in the undergraduate programs of mechanical engineering. Solar collectors are the key component of active solar-heating systems. They gather the sun's energy, transform its radiation into heat, and then transfer that heat to a fluid (usually water or air).

There are a large number of solar collector designs that have shown to be functional. These designs are classified in two general types of solar collectors:

- Flat-plate collectors – the absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays.
- Concentrating collectors – large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors are used to heat a liquid or air to temperatures less than 80°C (Srtckmann, 2008). The performance and operation of a flat-plate collector is governed by the fundamental laws of thermodynamics and relationships from heat transfer and fluid mechanics.

Thermal-fluid topics such as heat transfer, fluid mechanics, and thermodynamics are very important subjects and have long been an essential part of mechanical engineering curricula all over the world. Real-world applications, such as a solar collector, studied in a laboratory setting can be useful to help certain types of student learners understand some of the important concepts.

The Design-Build-Test (DBT) concept has been used in undergraduate engineering laboratories. Traditional undergraduate heat transfer laboratories in mechanical engineering expose students to thermal-fluid concepts presented in lecture classes, but do not provide them with experiences similar to what they might face as thermal engineers in industrial positions, such as design of device or experiments. In a recently published study (Abu-Mulaweh, *et al.*, 2011), the authors described the implementation of the DBT concept in an undergraduate-level heat transfer laboratory.

In this article, the authors present a renewable energy project that they have integrated in a junior-level heat transfer laboratory at Indiana University-Purdue University Fort Wayne (IPFW). In the proposed project, students are asked to design an experiment which uses a solar collector to heat water in a reservoir and determine the efficiency of the process by doing the required performance analysis. The solar collector is equipped with a pump, on/off switch, liquid reservoir, flow meter, pressure relief valve, and thermocouples. With the current setup, liquid can be placed in the reservoir tank and pumped through the collector at flow rates between 0.5 GPM and 3.5 GPM while recording the liquid temperatures at the inlet and outlet of the collector. This kind of activity serves to enhance the understanding of the transfer of thermal energy by undergraduate mechanical engineering students, while also facilitating to expose them to several important concepts involved in heat transfer, fluid mechanics, and thermodynamics.

2. EQUIPMENT AND INSTRUMENTS

Figure 1 shows the basic experimental set-up. The equipment and instruments utilized were as follows:

- SunMaxx flat plate solar collector mounted on a wooden frame at a 45 degree angle. The assembly is mounted on a cart to facilitate experimental setup movement.
- 12 V DC, 1/12 horsepower Shurflo diaphragm water pump rated at 3 GPM
- Pressure relief valve to avoid the overload pressure on the pump at the low flow rates
- Flow meter to control the water flow rate in the range of 0.3–3.5 GPM
- Reservoir made of plastic tub with a hose fitting attached
- Type-T thermocouples mounted in several locations on the collector
- SDL-1 Solar Data Logger measures the solar irradiance
- HH1384 data logger multi-input thermometer
- Photovoltaic (PV) panel mounted horizontally in a wooden frame behind the solar collector to power the water pump.
- Two rechargeable 12 V batteries connected to the PV panel

Note that the photovoltaic panel was not used in the activity described in this paper. It has been used for other similar types of projects and has recently been incorporated into a new adjustable fixture.

Figure 1: Setup of the Experiment

3. PROBLEM STATEMENT

Over the semesters, different variations on this assignment have been given to students. Student teams have been instructed to design, develop, and construct a portable experimental apparatus for an undergraduate heat transfer laboratory that met the following requirements and specifications:

- Utilize an existing flat plate solar collector (shown in Figure 1) to heat a certain amount of tap water (say, for example, 15 kg) contained in a reservoir.
- The experimental setup should have the capability of handling various flow rates.
- The experimental setup should have the necessary instrumentations to allow for the temperature and flow rate measurements needed for heat transfer calculations, such as the amount of heat gained by the water over a period of time.
- Utilize the SDL-1 Solar Data Logger to quantify the total solar insolation.
- Run and test the experimental setup,analyze the system performance, and submit a written report.

The most recent assignment asked teams of three or four students to devise an experiment to determine the efficiency of the solar collector under various conditions.

4. DESIGN AND BUILD PROCESS

To heat up the water in the reservoir using solar energy that is absorbed by the solar collector, the water will have to be pumped from the reservoir into the inlet of the solar collector (at the bottom of the collector) up through the tubes of the collector, out of the collector outlet at the top and back to the reservoir. The reservoir is simply a plastic tub with a hose fitting. The first task is the selection of a suitable pump. A Shurflo diaphragm pump (12 V DC, 1/12 horsepower, rated at 3 GPM) from MSC Industrial Supply Co. was selected (Figure 2). An on-off switch and inline fuse are mounted next to the flow meter on the solar collector's frame.

Figure 2: Close-up view of the water pump

A flow meter was attached between the pump and the solar collector (Figure 3) to adjust and measure the flow rate through the system. The flow meter has a built-in control knob with a range of 0.3 - 3.5 GPM. However, lowering the flow rate below 1.8 GPM put too much pressure on the pump, so a relief valve (Figure 4) was installed between the pump and the flow meter. This relief valve can be opened to let excess liquid bypass the flow meter and run back into the reservoir. With this valve installed, the flow rate can be lowered to 0.5 GPM.

Figure 3: Flow meter

Type T thermocouples were installed at the inlet (Figure 5) and outlet of the solar collector. The tip of each thermocouple was placed directly in the flow stream by poking a small hole in the flexible hose and putting the wire through. The hole was sealed using Magic Match Patch and covered with tape. The pressures in the hoses are low enough that there is no leakage.

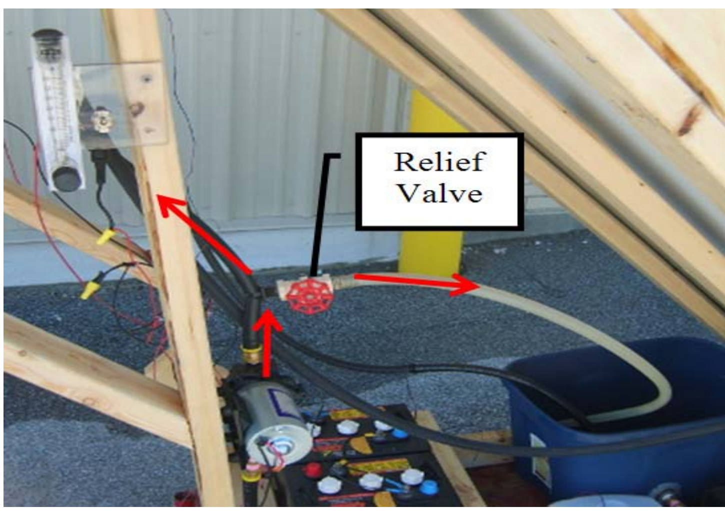

Figure 4: Relief valve and flow path

Figure 5: Thermocouple in the hose (solar collector inlet)

To read out and record the water's inlet and outlet temperatures during the experiment, the HH1384 data logger 4-input thermometer model from Omega Engineering, Inc. (Figure 6). This instrument is a digital, 4-input thermometer and data logger that accepts any K, J, E, T, R, S, N, L, U, B and C Type thermocouple temperature sensors. Powered by 6 "AA" batteries or DC 9V AC adaptor, comes with an USB interface with Windows Software, memory and read function (99 Sets) and 512 KB auto data logging capacity with adjustable logging interval (Silicon Solar, 2008).

Figure 6: HH1384 data logger 4-input thermometer

In order to calculate the input energy to the system the SDL-1 Solar Data Logger model from Micro Circuit Labs Co. was selected to measure the sun's irradiance at regular time intervals (Figure 7). It is powered by a slandered Alkaline battery. Its USB interface allowed the data to be loaded to the computer. The communications program Hyper Terminal was used to capture logged data to a text file to be analyzed and plotted using a spreadsheet program. The SDL-1 also reports the cumulative incident solar energy that it receives during deployment (Micro Circuit Labs, 2010).

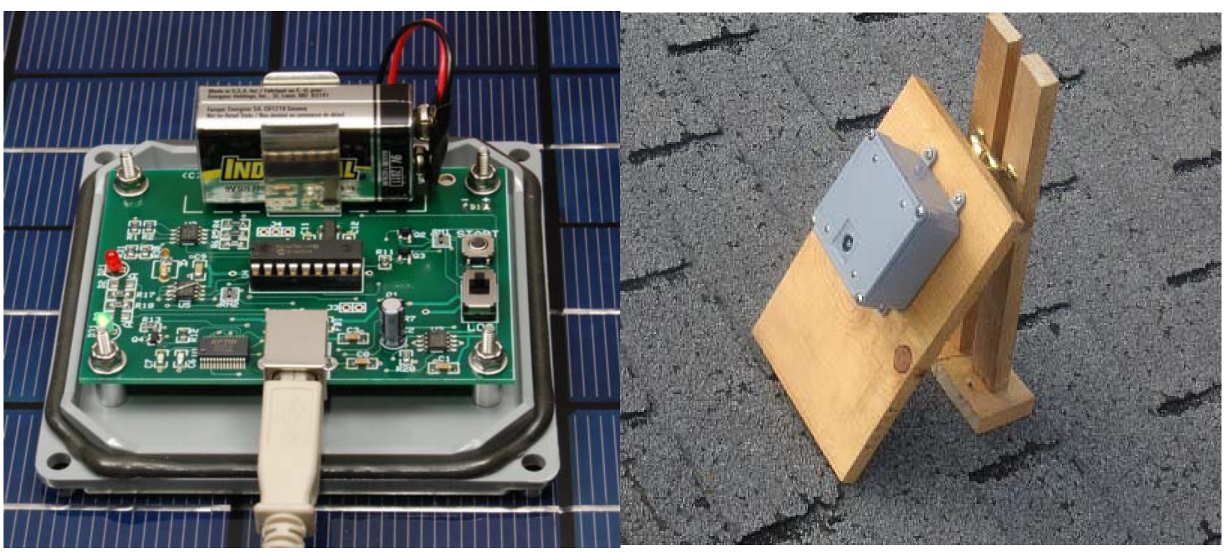

Figure 7: SDL-1 Solar Data Logger

5. TESTING PROCEDURE AND SAMPLE RESULTS

A typical test procedure is as follows:

1. Move the SunMaxx Solar Collector into the sun.
2. Fill the reservoir with the desired amount of liquid.
3. Ensure that the outlet hose from the top of the collector and the relief valve hose will empty into the reservoir.
4. Open the flow meter's control valve most of the way.
5. Close the relief valve.
6. Connect the thermocouple leads to the data logger thermometer.
7. Switch on the pump. It will take a few seconds for air to be pushed out of the system.
8. If needed, open the relief valve and use it to get the flow rate close to the desired value.
9. Use the control knob on the flow meter to fine-tune the flow rate.
10. Start the SDL-1 Solar Data Logger and place it on the wooden frame parallel to the face of the solar collector
11. Read and record the temperatures of the water at the inlet and outlet of the solar collector along with the time interval.
12. To empty the system, turn off the pump and move the collector's outlet hose from the reservoir to a safe area for drainage. Turn the pump on to pump the liquid out of the system. The reservoir can be removed using the dry-lock connector between it and the pump to dump any remaining liquid.
13. Stop the solar data logger and the thermometer data logger and transfer the data to the computer.

The experimental setup was tested for two different flow rates (1.1 GPM and 2.0 GPM). For each flow rate, the water temperature at the the inlet and outlet of the solar collector was recorded every one minute using the thermometer data logger. Figures 8 and 9 show the variation of water temperatures with time at the inlet and outlet of the solar collector for a water flow rates of 1.1 GPM and 2.0 GPM respectively. The amount of water in the reservoir was 15 kg. It can be seen from the figure that the water temperature at both the inlet and outlet of the solar collector increase as time passes, indicating that the water in the reservoir is being heated as a result of heat transfer through the solar collector. The heat gained by the water in the reservoir, Q, during the period shown in the figure can be calculated from (Incropera and DeWitt, 2006):

at 1.1 GPM $$Q = m\, C_p\, \Delta T = 484\ kJ$$

at 2.0 GPM $$Q = m\, C_p\, \Delta T = 427\ kJ$$

where m is the mass of the water in the reservoir, C_p is the water specific heat, and $\Delta T = T_{final} - T_{initial}$ (at the inlet of the solar collector). As it was expected the total heat energy gained by the water at low flow rate was higher than the high one.

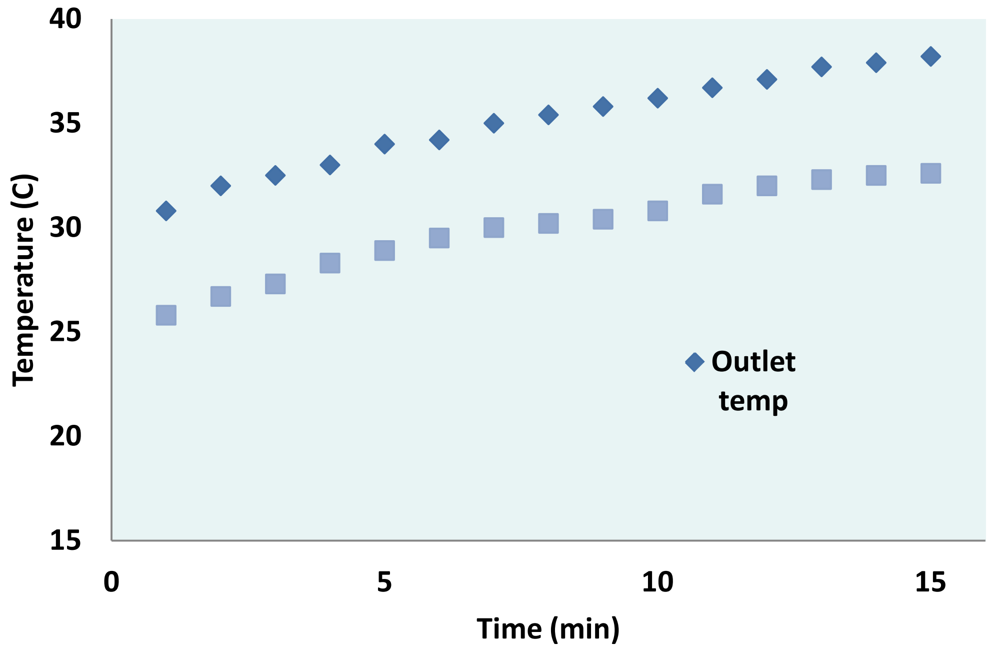

Figure 8: Variation of water temperature at the inlet and outlet of the solar collector with time for 1.1 GPM

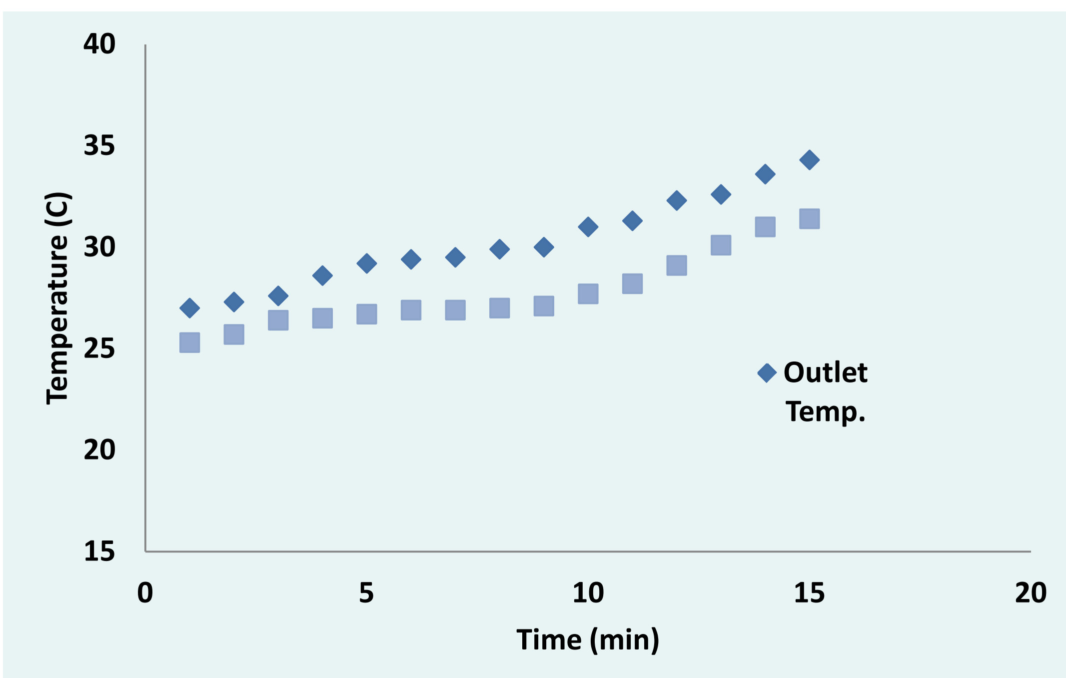

Figure 9: Variation of water temperature at the inlet and outlet of the solar collector with time for 2.0 GPM

The Solar Data Logger was used to determine the total input solar energy to the solar collector—the average amount of the sun's irradiance over the same time interval found to be 963.4 W/m^2. This amount is used to compute the total amount of energy input using $Q_{rad} = q_{rad} \mathrm{x} A_{collector}$ (Incropera and DeWitt, 2006) where Q is the total radiation energy, q is the flux per unit area and A is the SunMaxx surface area (A=1.828 m^2) (Silicon Solar, 2008).

Finally, the efficiency of the solar collector for each flow rate is found using the general formula:

$$Efficiency\ (\eta) = \frac{output\ energy}{input\ energy} * 100\%$$

at 1.1 GPM $\eta = 30\%$

at 2.0 GPM $\eta = 27\%$

This result appears to agree with published optimum flow rate value for the SunMaxx solar collector which is equal to 1 GPM.

6. CONCLUDING REMARKS

This paper describes a practical example of a common device and activity that involves a renewable energy source. The set-up is flexible to avoid repeating the same activities from semester to semester. The set-up and the activity can be used to illustrate many thermal-fluid concepts and can be used to initiate discussions involving renewable energy and other contemporary issues. While no formal survey was given to the students to assess specific learning from this activity, established assessment tools indicate that students are pleased with the experience.

7. REFERENCES

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