World Transactions on Engineering and Technology Education
Vol.4, No.1, 2005
© 2005 UICEE

A portable experimental apparatus for demonstrating the thermo-siphon heat recovery system concept

Hosni I. Abu-Mulaweh

Indiana University-Purdue University Fort Wayne
Fort Wayne, United States of America

ABSTRACT: A portable thermo-siphon heat recovery system experimental apparatus was designed, developed and constructed for the undergraduate mechanical engineering laboratory at Indiana University-Purdue University Fort Wayne in Fort Wayne, USA. The purpose of this experimental apparatus is to demonstrate heat transfer principles and the concept of thermo-siphon heat recovery system. In this article, the author presents an experimental set-up that will help undergraduate mechanical engineering students in understanding the basic heat transfer processes by utilising real life applications, such as using waste heat from a window type air conditioner to heat water for residential and commercial use. Heat recovery from an air conditioner by thermo-siphon is attractive because it eliminates the need for a circulating pump. This project was completed with the assistance of an Undergraduate Senior Project Grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc. (ASHRAE).

INTRODUCTION

Heat transfer is a basic and very important topic that deals with energy and has long been an essential part of mechanical engineering curricula all over the world. Heat transfer processes are encountered in a large number of engineering applications such as heat recovery systems. It is essential for thermal engineers to understand the principles of thermodynamics and heat transfer and be able to employ the right equations that govern the amount of energy being transferred. However, the majority of students perceive these topics as difficult.

Recently, Abu-Mulaweh designed, developed and constructed a portable refrigeration system experimental apparatus to demonstrate thermodynamics processes and systems that are fundamentals to understanding the basic concepts of thermodynamics [1].

Abu-Mulaweh also designed, developed and constructed a portable experimental apparatus for demonstrating heat recovery concepts [2]. This heat recovery system was a preheating unit for the incoming cold water of a residential and commercial (such as restaurant and hotels) hot water systems. It was designed to recover some of the heat of the wastewater going into the sewage system.

Similarly, it was decided that an experimental apparatus designed to demonstrate heat transfer principles and the concept of thermo-siphon heat recovery system is needed. This kind of system will recover the heat rejected by a window air conditioner and use it to heat water for use in residential or commercial applications in which the thermo-siphon effects are utilised (ie no water pump is required). Such an apparatus would enhance and add another dimension to the teaching/ learning process of the subject of heat transfer. Students would be able to apply convective heat transfer principles and heat recovery concepts that they had learned in the classroom lectures to real life applications. This approach could make the subject of heat transfer a more pleasant experience for the undergraduate mechanical engineering students.

INSTRUCTIONAL LABORATORY APPARATUS

Indiana University-Purdue University Fort Wayne in Fort Wayne, USA, is a state supported institution. This makes acquiring new instructional laboratory apparatus a challenge due to typical budgetary limitations. In addition, the apparatus designed by companies specialising in education equipment may not exactly reflect the educational objectives intended by the faculty. These obstacles had forced different venues to be searched in order to acquire experimental laboratory apparatus to demonstrate heat transfer principles and the concept of a thermo-siphon heat recovery system. It was concluded that such an apparatus could be designed, developed and constructed *in house* within a manageable budget. This could be successfully accomplished by taking advantage of the capstone senior design project and an ASHRAE Undergraduate Senior Project Grant Program. The purpose of this ASHRAE programme is to fund equipment for undergraduate engineering senior projects on ASHRAE-related topics. Obtaining these types of grants to support the design, development and construction of instructional laboratory apparatus would greatly help the normally stressed department's equipment budget. In addition, it would provide students with quality and real life design projects to work on.

The task to design, develop and construct an instructional laboratory apparatus to demonstrate heat transfer principles and the concept of thermo-siphon heat recovery system began with an application to the ASHRAE Undergraduate Senior Project Program. Subsequent to the awarding of the project grant in the amount of $3,155.00 from ASHRAE, a student senior design group was selected to work on the project

Energy consumption and environmental pollution can be reduced, without sacrificing comforts, by designing and employing energy saving equipment. Hot water is a necessity in today's lifestyle. Residential and commercial water heaters consume a substantial portion of the average utility bill.

Generally, heat is rejected from an air conditioner to the outside air. A water heating system can be designed to recover the rejected heat by adding a heat exchanger, as shown schematically in Figure 1. The heated water can be stored in a tank for later use. The water heating heat exchanger is referred to a water heater henceforth.

Thermo-siphon Effects

Thermal stratification is formed when the water is heated by the superheated refrigerant passing through the water heater (ie heat exchanger). By separating the water heater from the water storage tank, as shown in Figure 1, a thermo-siphon circulating loop connecting the water heater and the water storage tank can be established. In the water heater (ie heat exchanger), water is heated by the passing superheated refrigerant and the hotter water flows upward through a connecting pipe into the top of the storage tank buoyancy force. As the hot water leaves the heat exchanger, cold water is added from the bottom of the storage tank to the bottom of the heat exchanger. In this arrangement, whenever refrigerant flows in, the coil water circulates between the water heater and the storage tank.

The thermo-siphon effect for hot water heating is also 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, and Morison and Braun [3][4]. This can also be achieved indirectly via a heat exchanger [5]. In these cases, the thermo-siphon induced flow is a result of the incident solar radiation but is also affected by the hot water removal pattern.

THE DESIGN PROCESS

The design process that students follow in the capstone senior design project is that outlined by Bejan et al and Jaluria [6][7]. 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, as well as any additional considerations arising from safety, financial, environmental or other concerns. The following is a summary of these guidelines:

- The heat recovery system will serve as a retrofit for an existing air conditioning unit.
- It must include provisions for bypassing the heat recovery system; these bypasses must allow normal operations of the air conditioner and water heater without heat recovery.
- The heat recovery system must not require pumps; it should utilise thermo-siphon effects.
- All components of the system must be visible and must be instrumented with thermocouples, pressure transducers and flow rate meters. This is essential because, as mentioned above, the finished product would serve as an instructional laboratory apparatus for demonstrating heat recovery systems.
- The material should endure flow and temperature variations and be resistant to corrosion.
- The heat recovery system components, such as tubes and fittings, must be standardised to lower the cost.
- The cost of the system should not exceed $3,155.00.

After the problem statement was formulated, several conceptual designs were considered and evaluated. Each design concept was then evaluated using the following criteria: effectiveness as an instructional laboratory apparatus, cost, safety and size. Two final conceptual designs were chosen: a concentric heat exchanger and a coiled heat exchanger (see Figures 2 and 3).

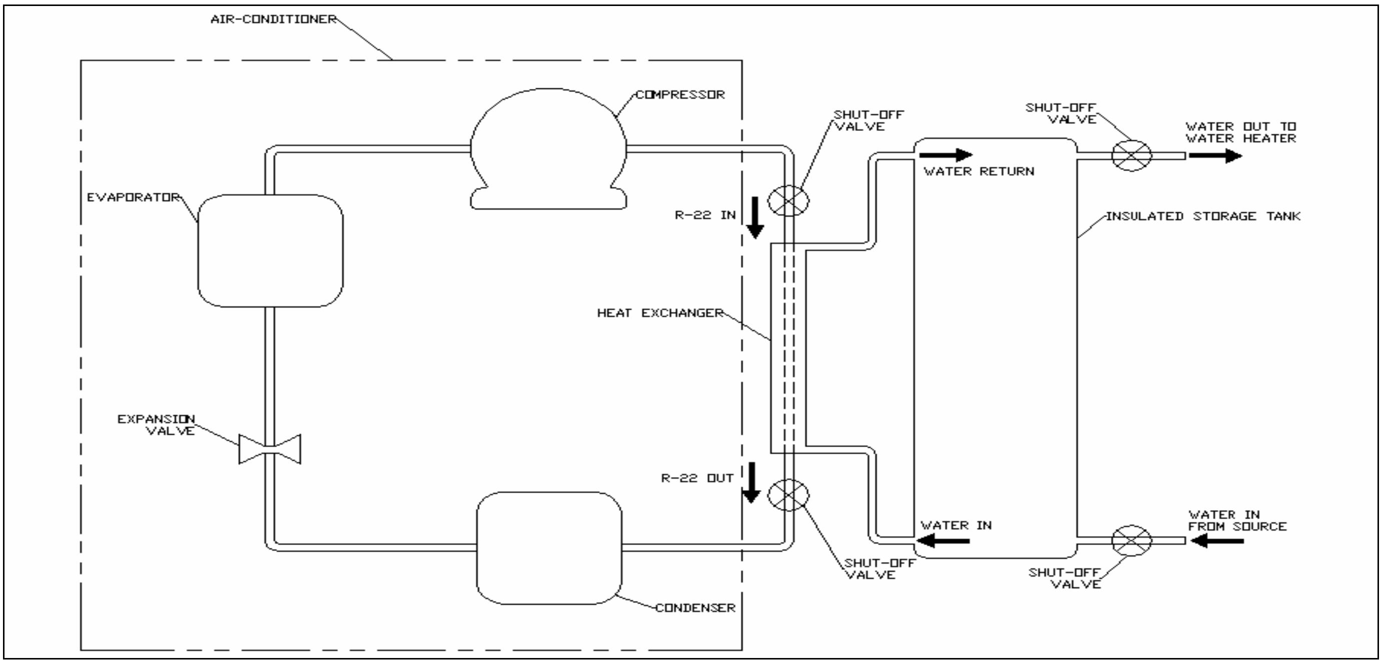

Figure 1: Schematic of the thermo-siphon heat recovery system.

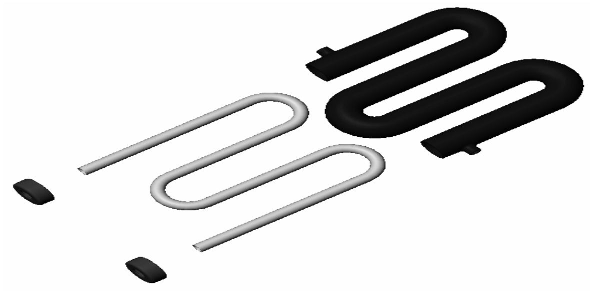

Figure 2: Schematic of the concentric heat exchanger.

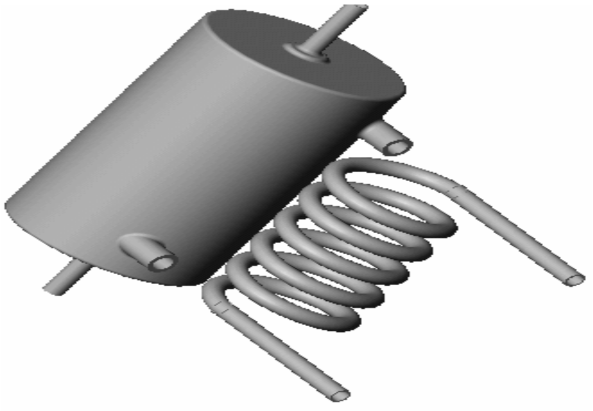

Figure 3: Schematic of the coiled heat exchanger.

EXPERIMENTAL APPARATUS

The thermo-siphon heat recovery system instructional laboratory apparatus that was designed and constructed is shown in Figure 4. A commercial window air conditioner with cooling capacity of 12,000 Btu/hr (3.5 kW) was purchased and used in this experimental apparatus. The refrigerant that the air conditioner used as working fluid was R22. Both concentric and coiled heat exchangers (water heaters) were built using PVC pipes, copper pipes, vinyl hoses, hose clamps, silicon, epoxy, and various pipe fittings. For each heat exchanger, the material was cut to length and soldered or glued together. Silicon was used as a seal at several locations. An epoxy was used in areas that required a tight seal and strength. The heat exchangers were fitted with thermocouples at both ends to measure the temperatures of both the water and the refrigerant at the inlet and outlet. Both heat exchangers operated in counter-flow mode.

Water Heater Design: The total heat transfer, Q_w, from the refrigerant to the water is

$$Q_w = U\ A\ (LMTD) \qquad (1)$$

Where U is the overall heat transfer coefficient, A is the required heat transfer area, and LMTD is the logarithm mean temperature difference. The values for the U term can be found or estimated from published literature [8-11]. Equation (1) was utilised to obtain some necessary sizing estimates, such as the required transfer area in the heat exchanger. Also, heat removed from the refrigerant for water heating can be expressed as:

$$Q_w = m_w\ C_p\ (T_{w,\ out} - T_{w,\ in}) \qquad (2)$$

Since the U value is different for different types of heat exchangers, the selection of the heat exchanger (ie water heater) is important. In this study, two types of heat exchangers, shown in Figures 2 and 3, were used.

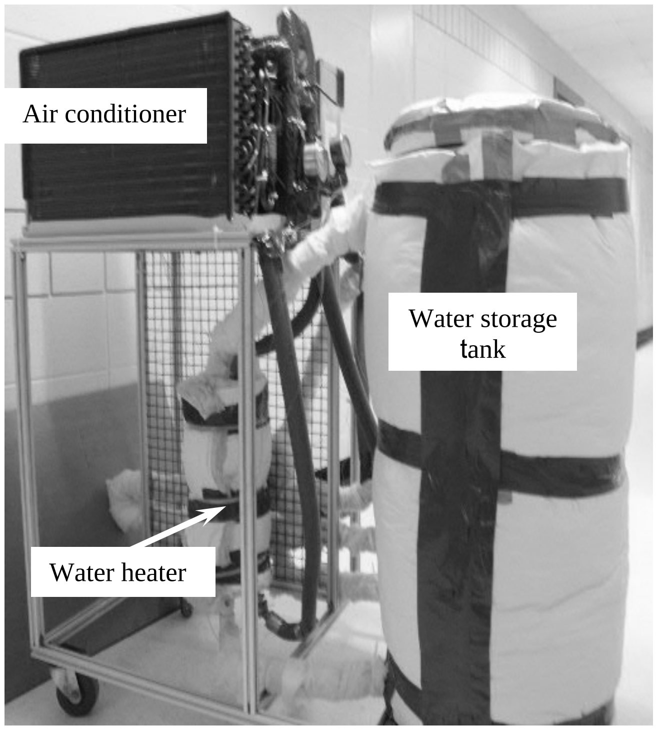

Figure 4: Thermo-siphon heat recovery experimental apparatus.

Specification of the Concentric Heat Exchanger: This heat exchanger was divided into two segments of 35 cm. The segments were joined together by one semi-circular segment with a diameter of 15 cm. The inner tube was fabricated from Standard 1-inch copper pipe and the shell was constructed from Standard 2-inch Schedule 40 PVC pipe and fittings.

Specification of the Coiled Heat Exchanger: In this heat exchanger, the inner tube was formed into a coil. The coil consisted of loops. Each loop was 35 cm in diameter. The coils were spaced 5 cm apart to allow for ample water flow outside the coil. The coil was made of 5/8-inch copper tubing. The shell was 40 cm long and made of Standard 8-inch PVC pipe and fittings.

The storage water tank (90 cm in height and 40 cm in diameter) was constructed from a polyethylene tank, PVC fittings, foam insulation, fibreglass insulation and epoxy. Two holes, one near the top and another near the bottom of the storage tank, were cut in the side of the tank. One hole was at the bottom and the other at the top of the tank. A 1-inch PVC male end was threaded into each hole and sealed with silicon and epoxy. The heated water entered the top of the storage tank. The tank was instrumented with three thermocouples in order to measure the water inside the storage tank. The locations of these thermo-couples were at 0.75, 42.5 and 85 cm from the bottom of the tank.

The air conditioner, as shown in Figure 5, was modified in order to be retrofitted with the heat exchangers (ie the water heaters) on a bypass line between the outlet of the compressor and before the condenser. Also, valves had to be installed in order to allow the refrigerant to be replaced. After the refrigerant in the system was collected, the refrigerant line was cut at the outlet of the compressor. The original design intention was to simply install one heat exchanger at a time, meaning that the lines had to be cut and the system recharged with refrigerant each time the heat exchangers were switched. It was decided that this was not acceptable and a system of valves was designed and built to allow easy switching between heat exchangers. The valve assembly also allowed for the air-conditioner to function without the heat exchangers including using a bypass circuit.

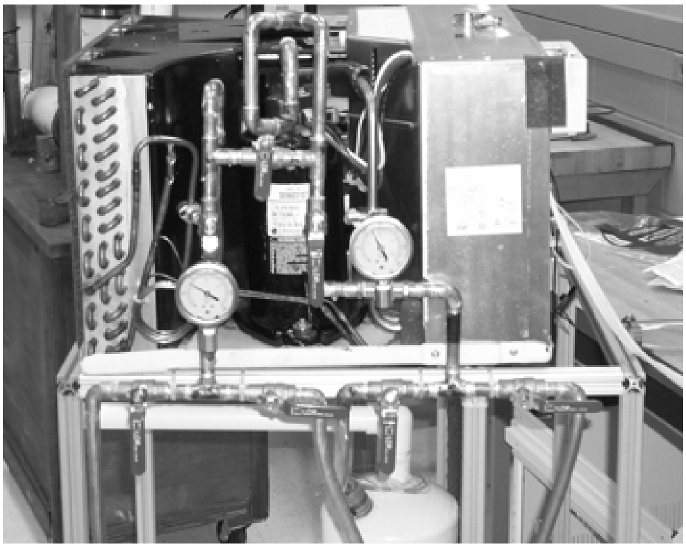

Figure 5: The retrofit and valves assembly.

The lines were instrumented with pressure gauges to measure the pressure of the refrigerant at the inlet and outlet of the heat exchangers. After assembly, the refrigerant lines were tested for leakage by drawing a vacuum on the system. After all leakages were sealed, the system was filled with refrigerant. The water lines from the heat exchanger to the storage tank were made from clear vinyl hose. These were simply cut to the proper length and installed using hose clamps. Once all of the assembly was complete, the system was insulated. All water and refrigerant lines and heat exchangers were insulated with fibreglass. The refrigerant lines were insulated with foam pipe wrap. All components of the thermo-siphon heat recovery system experimental apparatus (air conditioner, water heater, water storage tank) were assembled on a cart (refer to Figure 4). This kind of arrangement makes the apparatus portable.

TESTING PROCEDURE AND SAMPLE RESULTS

The experimental apparatus was set up as shown in Figure 4. The testing procedure was the same for both water heaters (ie heat exchangers). The storage water tank was filled with water. The inlet water hose of a given heat exchanger was connected with the bottom port of the storage tank and the outlet water hose was connected with the top port. Thermocouples were connected to the data acquisition board. The air conditioner was then turn on. Temperatures were measured and analysed using a data acquisition system.

Thermo-siphon Effect: The temperature in the storage water tank is a function of the flow of heated water in from the water heater. 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 thermo-siphon effect. The temperature variation in the water storage tank for both water heaters, concentric and coiled heat exchangers, are shown in Figures 6 and 7, respectively. As can be seen from the two figures, the temperature distribution rose during the operating time. It is interesting to note that the temperature at the top and the bottom of the tank remained about 10^{o}C apart, even after eight hours in the case of the concentric heat exchanger and four hours in the case of the coiled heat exchanger operation. This indicates that the thermal stratification retained well. It can also be clearly seen that only after about 3.5 hours of operation in the case of concentric heat exchanger, and two hours in the case of coiled heat exchanger operation, that the temperature at the bottom of the storage tank began to rise.

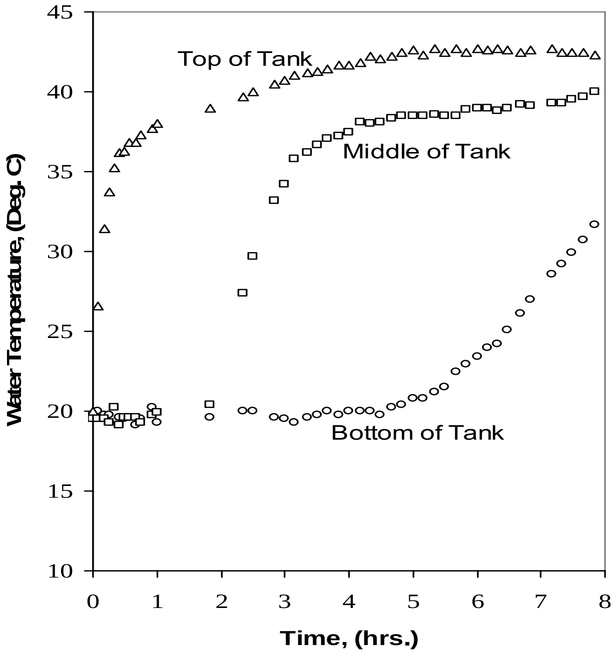

Figure 6: Temperature variation in the storage tank in heating water (concentric heat exchanger).

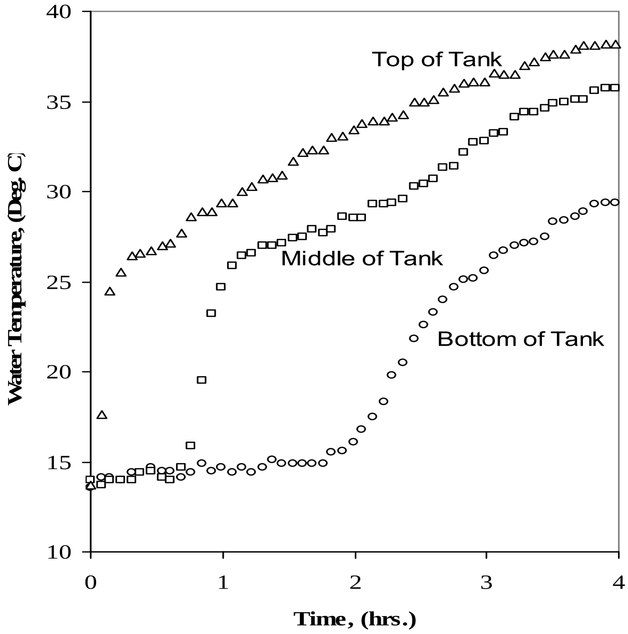

Figure 7: Temperature variation in the storage tank in heating water (coiled heat exchanger).

Figures 8 and 9 present the inlet and outlet water temperature of the concentric and coiled heat exchangers, respectively. The figures show that the outlet temperatures of both heat exchangers are higher than the inlet temperatures. This is due to the heat recovered from the hot refrigerant. Also, the figures show that the inlet temperature started to increase only after about 3.5 hours in the case of concentric heat exchanger and two hours in the case of coiled heat exchanger into operation. This is because the temperature at the bottom of the storage tank began to rise only after about 3.5 hours in the case of concentric heat exchanger and two hours in the case of coiled heat exchanger into operation, as was stated above. It should be noted, as can be seen from Figures 5-8, that the water temperature at the top of the storage tank was slightly less than the temperature at the water heater outlet. This was because some heat loss occurred in the piping and, along with heat losses from the storage tank.

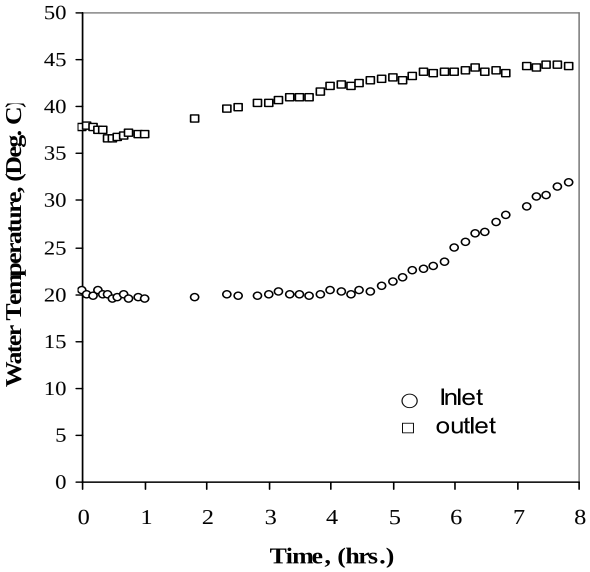

Figure 8: Concentric heat exchanger inlet and outlet temperature.

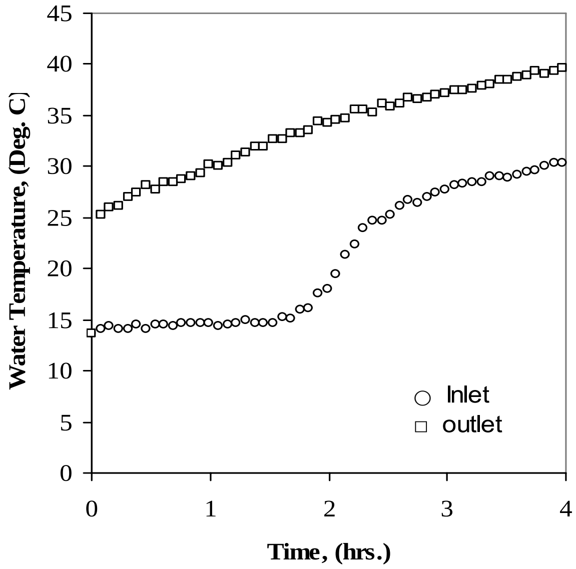

Figure 9: Coiled heat exchanger inlet and outlet temperature.

Finally, it should be noted that, besides the possible savings in obtaining *free* hot water for the price of a small heat exchanger, the attraction of using the thermo-siphon effect, compared to other heat recovery systems, is that it eliminates a source of potential mechanical problems and noise, namely the circulating water pump.

CONCLUSION

The thermo-siphon heat recovery system experimental apparatus described in this article is a valuable addition to the undergraduate mechanical engineering laboratory. This was accomplished with zero cost to the engineering department at Indiana University-Purdue University Fort Wayne. This was made possible for two main reasons: the financial support from ASHRAE and the effort of a capstone senior design team.

The experimental apparatus is portable. The sample results prove that the instructional experimental apparatus is well designed for its intended purpose of demonstrating basic heat transfer principles and thermo-siphon heat recovery system concept.

ACKNOWLEDGEMENT

This work was supported by a grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE).

REFERENCES

1. Abu-Mulaweh, H.I., Portable experimental apparatus for demonstrating thermodynamics principles. *Inter. J. of Mechanical Engng. Educ*. (in press), (2005).
2. Abu-Mulaweh, H.I., Undergraduate mechanical engineering laboratory portable experimental apparatus for demonstrating heat recovery concepts. *World Trans. on Engng. and Technology Educ.*, 3, **2**, 265-268 (2004).
3. Huang, B.J. and Hsieh, C.T., A simulation method for solar thermosyphon collector. *Solar Energy*, 35, 31-44 (1985).
4. Morison, G.L. and Braun, J.F., System modeling and operation characteristics of thermosyphon solar water heaters. *Solar Energy*, 35, 389-406 (1985).
5. 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 (1990).
6. Bejan, A., Tsatsaronis, G. and Moran, M., *Thermal Design and Optimization*. New York: John Wiley & Sons (1996).
7. Jaluria, Y., *Design and Optimization of Thermal Systems*. New York: McGraw-Hill (1998).
8. Shah, M.M., A general correlation for heat transfer during film condensation inside pipes. *Inter. J. of Heat and Mass Transfer*, 22, 547-556 (1979).
9. Nakayama, W., Enhancement of heat transfer. *Proc. 7th Inter. Heat Transfer Conf.*, 1, 223-240 (1982).
10. Roach, G.H. and Wood, R.M., Shell-and-tube exchangers having improved design features. *Heat Transfer Engineering*, 7, 19-24 (1986).
11. Kays, W.M. and London, A.L., *Compact Heat Exchangers* (3rd edn). New York: McGraw-Hill (1976).