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Undergraduate mechanical engineering laboratory portable experimental apparatus for demonstrating heat recovery concepts

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ABSTRACT: A portable wastewater heat recovery system experimental apparatus was designed, developed and constructed for an undergraduate mechanical engineering laboratory at Indiana University-Purdue University Fort Wayne, Fort Wayne, USA. The purpose of the experimental apparatus is to demonstrate heat transfer principles and heat recovery concepts. In this article, the author presents an experimental set-up that will help the undergraduate mechanical engineering students in understanding basic heat transfer processes by utilising real life applications, such as a heat recovery system. This heat recovery system is a preheating unit for incoming cold water from residential and commercial (such as restaurants and hotels) hot water systems. It is designed to recover some of the heat of the wastewater flowing into the sewage system. This project was completed with the assistance of an Undergraduate Senior Project Grant from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

INTRODUCTION

In the not too distant future, the ever-increasing desires of first-world countries will no longer be able to be met by fossil fuels alone. Known, economically recoverable, worldwide fossil fuel reserves are limited. In fact, at the current rate of worldwide consumption, there is enough oil to last 45 years, enough natural gas to last 65 years and enough coal to last 224 years [1]. With increasing awareness of limited energy resources and the deteriorating environment, many countries have come to understand that using energy effectively and cleanly is the solution to some of the current energy and environmental problems. Energy consumption and environmental pollution can be reduced, without sacrificing comforts, by designing and employing energy saving equipment. Residential and commercial water heaters consume a substantial portion of the average utility bill. Restaurants and hotels are potentially attractive applications of a heat recovery system.

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. As such, it is essential for thermal engineers to understand the principles of thermodynamics and heat transfer and be able to employ the rate equations that govern the amount of energy being transferred. However, it is evident that the majority of students perceive these topics as difficult.

A portable refrigeration system experimental apparatus was designed, developed and constructed by Abu-Mulaweh to demonstrate thermodynamics processes and systems that are fundamental to understanding the basic concepts of thermodynamics [2]. Similarly, it was decided that an experimental apparatus designed to demonstrate heat exchanger principles and heat recovery concepts is needed. 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, which they learned in the classroom lectures, to real life applications. This approach could make the subject of heat transfer a more pleasant experience for undergraduate mechanical engineering students.

Indiana University-Purdue University Fort Wayne, Fort Wayne, USA, is a state-supported institution and thus the purchase of new instructional laboratory apparatus is subject 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. Thus, it was necessary to seek out, and search for, different venues to acquire a portable experimental laboratory apparatus for demonstrating heat transfer processes and principles. It was a requirement 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 Undergraduate Senior Project Grant Program from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). 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 processes and principles and heat recovery concepts began with an application to the ASHRAE Undergraduate Senior Project Program. The proposal was to design a refrigeration system for a small compartment. Subsequent to the awarding of the project grant in the amount of $1,835.00 from ASHRAE, a student senior design group was selected to work on the project.

THE DESIGN PROCESS

The design process that students follow in the capstone senior design projects is the one outlined by Bejan et al and Jaluria [3][4]. 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 heat recovery system should be based on a counter-flow heat exchanger concept.
- All components of the system must be visible and must be instrumented with thermocouples so as to measure the temperature and flow rate metres to adjust and measure the hot and cold flows. This is essential because, as mentioned above, the finished product would serve as an instructional laboratory apparatus for demonstrating heat recovery systems.
- The heat recovery system should increase the cold water by 5-7^{o}C.
- The material should endure flow and temperature variations, and should also be resistant to corrosion.
- The surfaces of the heat recovery system (heat exchanger), such as tubes and gaskets that are affected by fouling factors like soap and dirt, should be cleaned or replaced with easy access.
- 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 $1,835.00.

After the problem statement was formulated, several conceptual designs were considered and evaluated. Each design concept was evaluated by the following criteria: effectiveness as an instructional laboratory apparatus, cost, safety, simplicity and size.

Two final conceptual designs were chosen, namely a plate-and-frame heat exchanger and a shell-and-tube heat exchanger. Plate-and-frame heat exchangers are typically used for exchanging heat between two liquid streams and are very effective for water-to-water applications. Shell-and-tube heat exchangers are also commonly used in heat exchange between two liquid streams.

EQUIPMENT DESCRIPTION

The heat recovery system instructional laboratory apparatus that was designed, developed and constructed is shown in Figure 1. The inlet and outlet temperatures of both the hot and cold water streams were measured using T-type thermo-couples. The volume flow rates of both streams were measured using two rotameters. These measurements allowed for the determination of the various thermodynamics properties needed to demonstrate the thermodynamics and heat transfer principles.

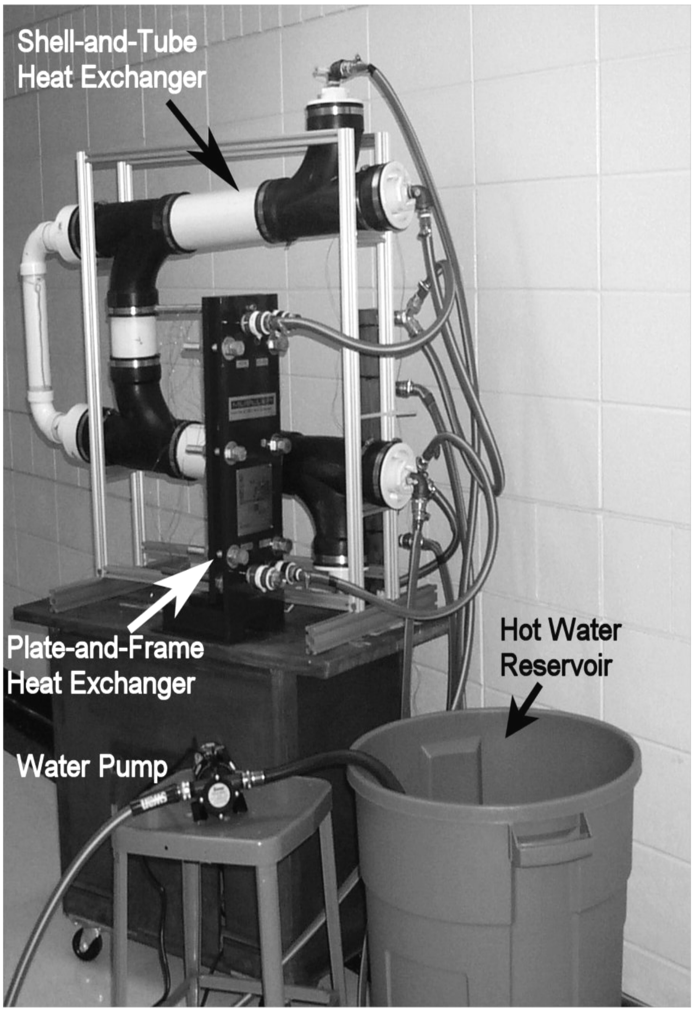

Figure 1: Heat recovery system experimental apparatus.

The plate-and-frame heat exchanger was made by Mueller Accu-Therm® according to the design parameters. It is comprised of 11 rectangular thin plates that are held together in a frame by tie bars or screws and are fitted with sealing gaskets. The plates are usually constructed of corrosion resistant materials, such as brass, copper, aluminium or steel. The plates often have a chevron or washboard corrugated pattern to increase turbulence and give mechanical rigidity. A prototype of a plate is shown in Figure 2. However, the plate-and-frame heat exchanger needed to be instrumented with thermocouples at the inlets and outlets of both streams, and also proper fittings were added to it.

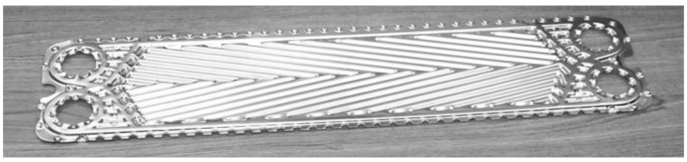

Figure 2: A Single plate of the plate-and-frame heat exchanger.

The shell-and-tube heat exchanger was constructed by the design team (students). Standard inexpensive components and materials were chosen for the construction of this heat exchanger. For instance, standard 4" and 2" PVC pipe was used as the shell. Basic $^{3}/_{8}$" (OD) copper tubing was used for all internal tubes. In order to make the tube bundles of the shell-and-tube heat exchanger, some end plates and support dividers were needed. These plates were constructed using a water-jet machine and the multiple holes were created with a drill press.

ACE Radiator of Fort Wayne, USA, assisted the design team in welding the individual tubes to the copper plates and dividers to complete the tube bundles.

Figure 3 shows a picture of a prototype of a tube bundle assembly for the shell-and-tube heat exchanger. Once the tube bundles were constructed, the PVC lengths were cut and fitted to the correct sizes. The tube bundles were then placed inside the 4" PVC and the remaining sections of the heat exchanger were assembled with PVC primer and glue. Upon completion of the shell-and-tube, fittings were added and it was instrumented with thermocouples at the hot and cold-water inlets.

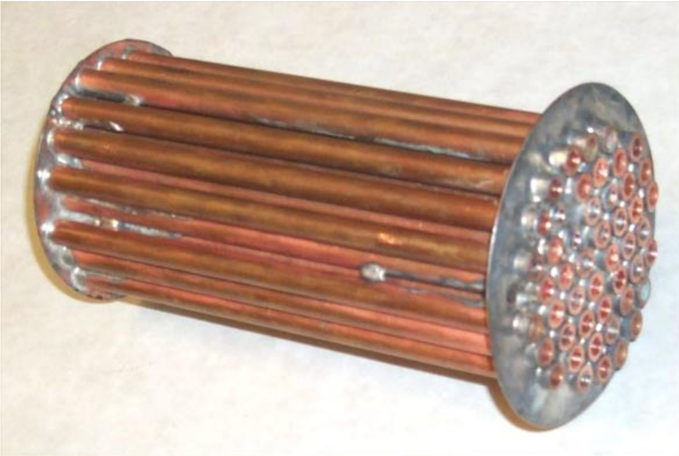

Figure 3: Tube bundle assembly for the shell-and-tube heat exchanger.

TESTING PROCEDURE AND SAMPLE RESULTS

Testing procedure was the same for both heat exchangers. A plastic container was filled with hot water at approximately 35°C temperature. This temperature was chosen to resemble the temperature of the wastewater from which heat was to be recovered. This hot water was then pumped through the heat exchanger by utilising a water pump. The hot water flow rate was adjusted and measured by the flow-rate meter (rotameter). The cold water supply hose was connected to the faucet. Also, the cold water flow rate was measured using another rotameter. Measurements were taken when the system reached steady state conditions.

The measured data (temperatures at the inlets and outlets of both streams) was collected utilising a data acquisition system. This approach allowed students to observe and determine when steady state condition was reached. Table 1 shows sample data that was obtained from the shell-and-tube heat exchanger for a cold water flow rate of 2 GPM, where $\dot{V}_{hot}$ is the waste hot water volume flow rate, $T_{cold\ in}$ is the inlet cold water temperature, $T_{cold\ out}$ is the outlet cold water temperature, $T_{hot\ in}$ is the inlet waste hot water temperature, and $T_{hot\ out}$ is the outlet hot water temperature.

From the measured data, several quantities of interest can be determined using energy balance for steady-flow systems, which can be found in any heat transfer textbook (see for example, Özisik, and Incropera and Dewitt [5][6]). These quantities include: mass flow rate of the hot stream, $\dot{m}_{hot}$, mass flow rate of the cold water stream, $\dot{m}_{cold}$, rate of heat lost from the hot stream, $\dot{Q}_{hot}$, and rate of cold water stream heat gain, $\dot{Q}_{cold}$. These quantities of interest are determined from the following relations:

$$\dot{m}_{hot} = \rho_{hot}\dot{V}_{hot} \quad (1)$$

$$\dot{m}_{cold} = \rho_{cold}\dot{V}_{cold} \quad (2)$$

Assuming negligible heat transfer between the system and its surroundings, negligible kinetic and potential energy changes, no phase change and constant specific heats, the application of energy balance gives the following:

$$\dot{Q}_{hot} = \dot{m}_{hot}C_{hot}(T_{hot\ in} - T_{hot\ out}) \quad (3)$$

$$\dot{Q}_{cold} = \dot{m}_{cold}C_{cold}(T_{cold\ out} - T_{cold\ in}) \quad (4)$$

where ρ and C are the density and specific heat of the water, respectively.

Table 1: Shell-and-tube heat exchanger.

$\dot{V}_{hot}$ (GPM)	$T_{cold\ in}$ (°C)	$T_{cold\ out}$ (°C)	$T_{hot\ in}$ (°C)	$T_{hot\ out}$ (°C)
1.0	21.2	25.9	34.8	24.7
1.5	21.2	26.8	35.0	26.7
2.0	21.2	27.3	35.1	28.6
2.5	21.2	28.1	34.9	29.0
3.0	21.2	28.7	35.1	29.7
3.5	21.2	29.4	35.0	30.1

The sample results of the shell-and tube heat exchanger are illustrated in Figures 4 and 5. Figure 4 shows the increase in the cold water temperature between the inlet and the outlet. The amount of heat gain by the cold water as a result of heat recovered from the waste hot water is shown in Figure 5.

Both of these figures clearly show that the change in the cold water temperature between the inlet and outlet and the heat gained by the cold water increase with an increasing hot flow rate. It should be noted that a similar trend was also observed for the case of the plate-and-frame heat exchanger. It should also be noted that students were also asked to perform some calculations to estimate the yearly savings based on the local utility cost.

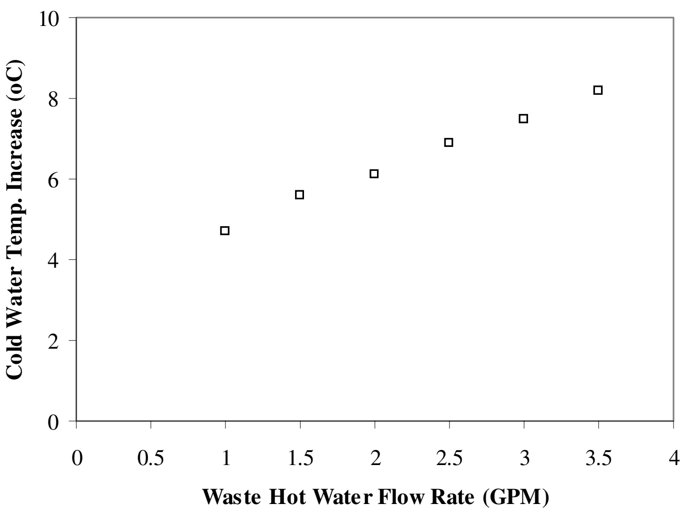

Figure 4: Shell-and-tube heat exchanger.

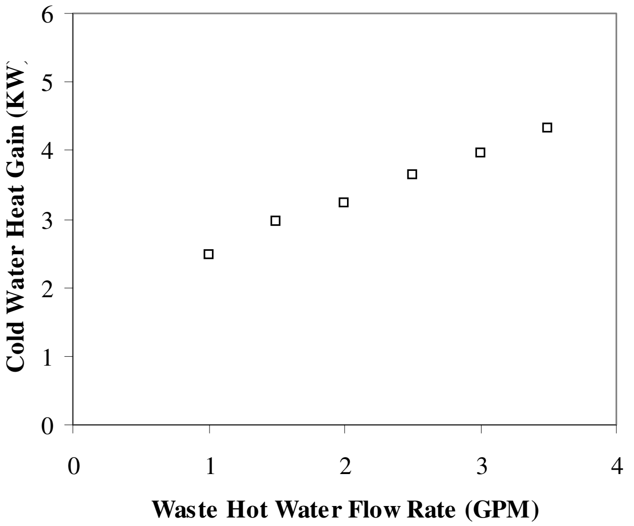

Figure 5: Shell-and-tube heat exchanger.

CONCLUSION

The portable 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 the ASHRAE and the efforts of a capstone senior design team. Furthermore, 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 heat recovery concepts.

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