Portable Experimental Apparatus for Demonstrating Heat Recovery Concepts

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Abstract

A waste water heat recovery system experiment apparatus was designed, developed, and constructed for the undergraduate mechanical engineering laboratory at Indiana University-Purdue University at Fort Wayne. The purpose of the experimental apparatus is to demonstrate heat transfer principles and heat recovery concepts. This paper presents an experimental setup that will help the undergraduate mechanical engineering students in understanding the basic heat transfer processes by utilizing real life applications such as waste water heat recovery system. This heat recovery system is a preheating unit for the incoming cold water of a residential and commercial (such as restaurant and hotels) hot water systems. It is designed to recover some of the heat of the waste water going 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).

I. Introduction

The ever increasing desire for energy by the first-world countries will no longer, in the not too distant future, be able to be met by fossil fuels alone. The 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 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 Hotels are a potentially attractive application 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. 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, the majority of students perceive these topics as difficult.

A Portable refrigeration system experimental apparatus was designed, developed and constructed by Abu-Mulaweh [2] to demonstrate thermodynamics processes and systems which are fundamentals to understanding the basic concepts of thermodynamics. Similarly, it was decided that an experimental apparatus designed to demonstrate heat exchangers 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. The students would be able to apply convective heat transfer principles and heat recovery concepts that they learned in the classroom lectures to real life application. This approach could make the subject of heat transfer a more pleasant experience for the undergraduate mechanical engineering students.

Indiana University-Purdue University Fort Wayne is a state supported institution. Thus makes the purchase of new instructional laboratory apparatus 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 a portable experimental laboratory apparatus for demonstrating thermodynamics processes and 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. 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 the 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 recovery principles and heat transfer processes 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 $1835.00 from ASHRAE, a student senior design group was selected to work on the project.

II. The Design Process

The design process that the students follow in the capstone senior design projects is the one outlined by Bejan et al. [3] and Jaluria [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 will be based on a counter-flow heat exchanger concept.
- All components of the system must be visible and must be instrumented with thermocouples to measure the temperature and flow rate meters 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 to 7^{o}C.
- The material should endure flow and temperature variations and should be resistant to corrosion.
- The surfaces of the heat recovery system (heat exchanger) such as tubes and gaskets that are affected by fouling factors such as soap and dirt should be cleaned or replaced with easy access.
- The heat recovery system components such as tubes and fittings must be standardized to lower the cost.
- The cost of the system should not exceed $1835.00.

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: 1) Plate-and-Frame Heat Exchanger, 2) 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.

III. Equipment Description

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

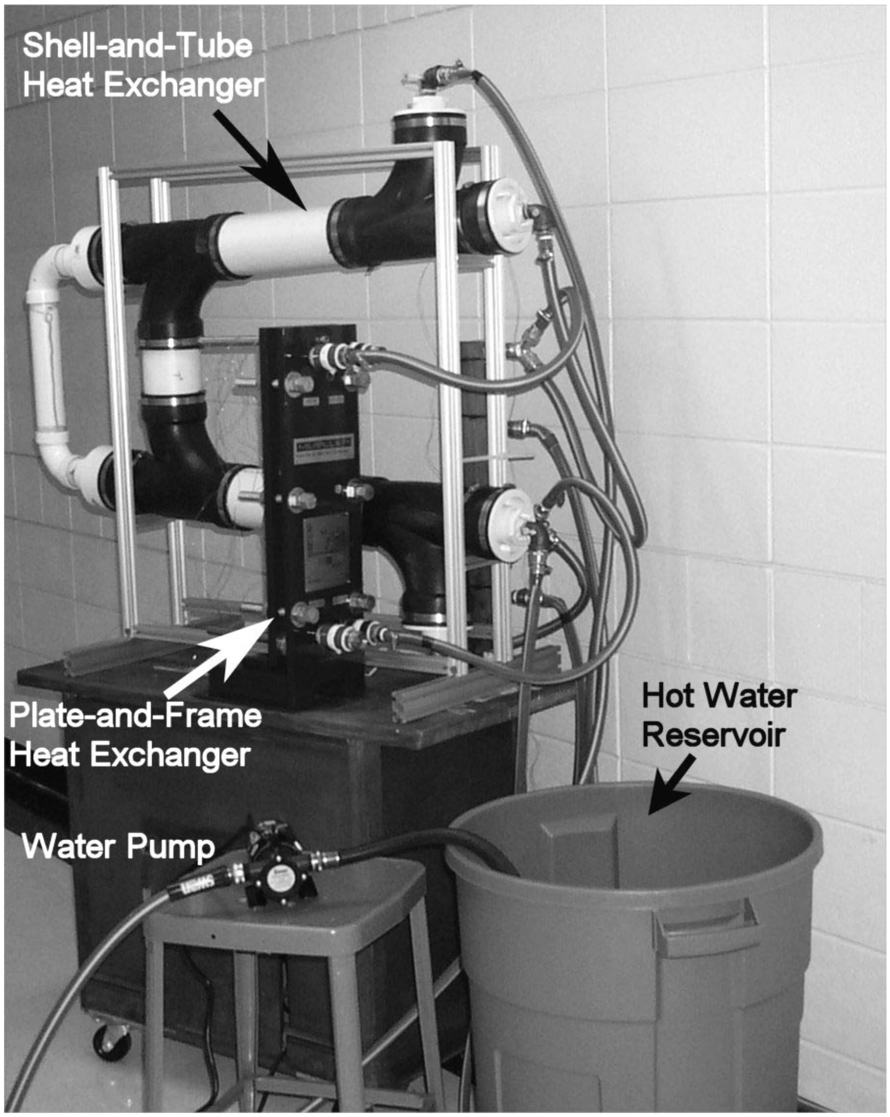

Figure 1: Heat Recovery System Experimental Apparatus.

The Plate-and-Frame Heat Exchanger was made by MUELLER ACCU-THERM® according to the design parameters. It is comprised of eleven 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, aluminum or steel. The plates often have a chevron or washboard corrugated pattern to increase turbulence and to give mechanical rigidity. A prototype of a plate is shown in Figure 2.

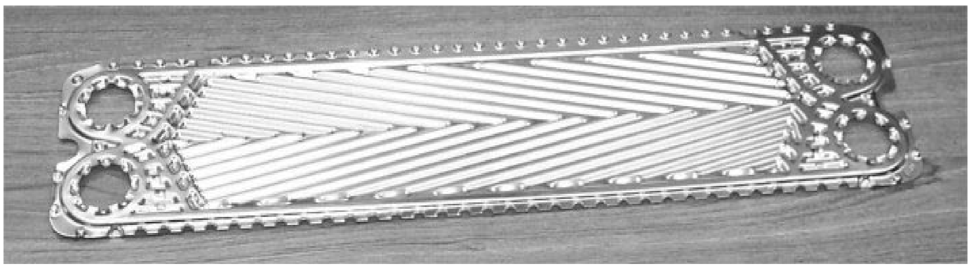

Figure 2: A Single plate of the plate-and-frame heat exchanger

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.

The Shell-and-Tube Heat Exchanger was constructed by the design team (students). Standard inexpensive components and materials where chosen for the construction of this heat exchanger. For instance, standard 4” and 2” PVC pipe was used as the shell. Basic 3/8” (O.D.) 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, IN 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.

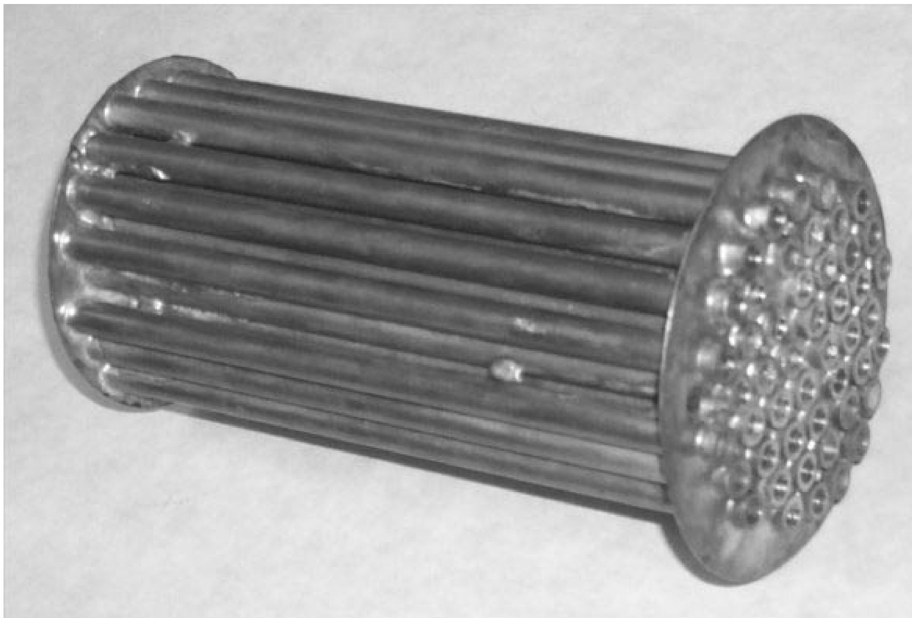

Figure 3: Tube bundle assembly for the shell-and-tube heat exchanger

IV. Testing Procedure and Sample Results

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

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

Figures 4 and 5, respectively, show the increase in the cold water temperature and the amount of heat gain by the cold water as a result of heat recovered from the waste hot water. The figures clearly show that the cold water temperature and the energy gained by the cold water increase with increasing waste water flow rate.

Table 1: Shell-and-Tube Heat Exchanger

$\dot{V}_{hot}$ (GPM)	$T_{cold\ in}$ (^oC)	$T_{cold\ out}$ (^oC)	$T_{hot\ in}$ (^oC)	$T_{hot\ out}$ (^oC)
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

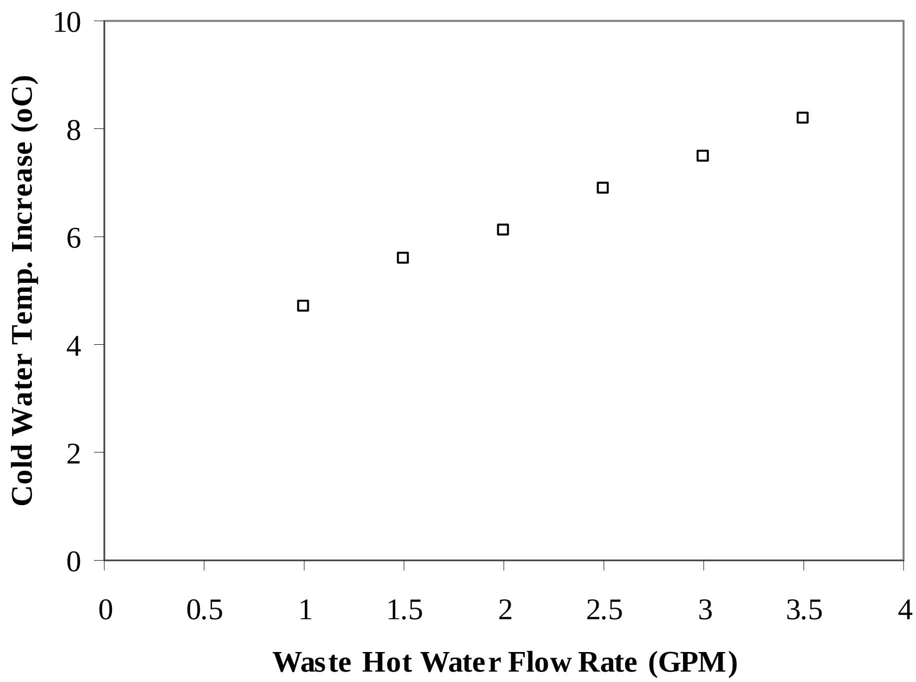

Figure 4: Shell-and-Tube Heat Exchanger

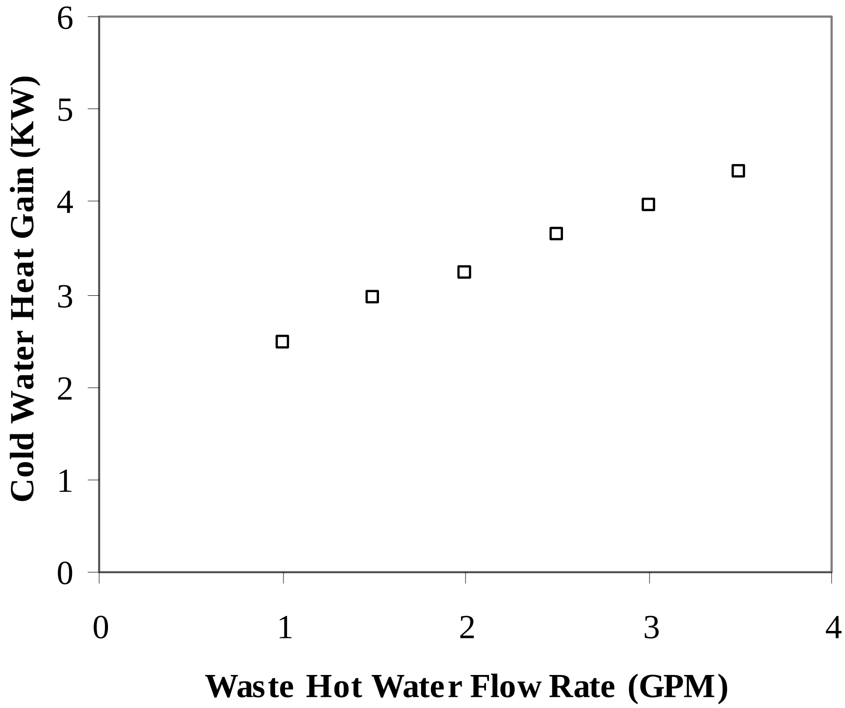

Figure 5: Shell-and-Tube Heat Exchanger

V. Conclusion

The heat recovery system experimental apparatus described in this paper 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 heat recovery concepts.

Acknowledgement

This project was completed with the assistance of an Undergraduate Senior Project Grant from ASHRAE. The members of the capstone senior design team are Patrick Baugh and Aaron Rees.

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