Combination unit to support instruction in Thermodunamics, Fluid Mechanics, and Heat Transfer

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1. Introduction:

It is common knowledge, and has been demonstrated by numerous studies, that the combination of theory and hands-on experience is a critical component of engineering education[1-5]. Hands on, i.e. open-ended laboratory experiences can be delivered in various ways. They are either integrated into courses that contain both lectures and lab components or offered separately as lab courses which may, in turn, be formal group-based activities or singular individual project-based. In an effort to give students the full benefit that they can gain from in-depth laboratory activities, departments devote money and effort to purchase or upgrade lab facilities. However, commercialized laboratory equipment can be costly and is often designed for single purpose. Moreover, the decline in the economy has led to severe budget constraints at many universities, which has limited their ability to improve lab facilities. The ability to develop affordable and multi-purpose equipment is a challenge in all of the engineering disciplines. It may be even more critical for courses in thermal sciences.

Thermodynamics, fluid mechanics, and heat transfer are key disciplines in thermal sciences with wide industrial applications. These courses are interrelated; the foundational theorems are intertwined with each other. In mechanical engineering these subjects are traditionally taught as four separate courses over four semesters. Students tend to treat these courses as four loosely related but distinct disciplines. This issue is discussed in the literature[3]. A good method to provide the vertical integration of these thermal science courses is through a variety of laboratory exercises. However, new equipment in the thermal sciences can be very expensive, so innovative methods are needed to be used to obtain necessary equipment[4]. Carefully designed and constructed student projects can be a good vehicle for developing such equipment. This paper describes a project in which an air conditioning unit was modified to support instruction in all of the basic thermal science courses.

2. Combined unit construction

Air conditioning, climate control, heating, and refrigeration all rely on principles of thermodynamics, fluid mechanics and heat transfer. To demonstrate these principles and their applications, a system was designed and constructed to study the operating characteristics and system design theory of an air conditioner/heat pump unit. The theoretical cycle can be illustrated in figure 1 with four basic components: compressor, condenser, expansion valve and evaporator. The refrigerant flows counter-clockwise through the cycle. The compressor raises the pressure of the refrigerant, which exits as superheated vapor. Ideally, the superheated vapor condenses to liquid at constant pressure in the condenser by rejecting heat. The expansion valve throttles the refrigerant's pressure down, so it leaves as a two phase mixture in general. The refrigerant absorbs heat while flowing through the evaporator, and returns to the compressor as saturated (in theory) or superheated (in practice) vapor.

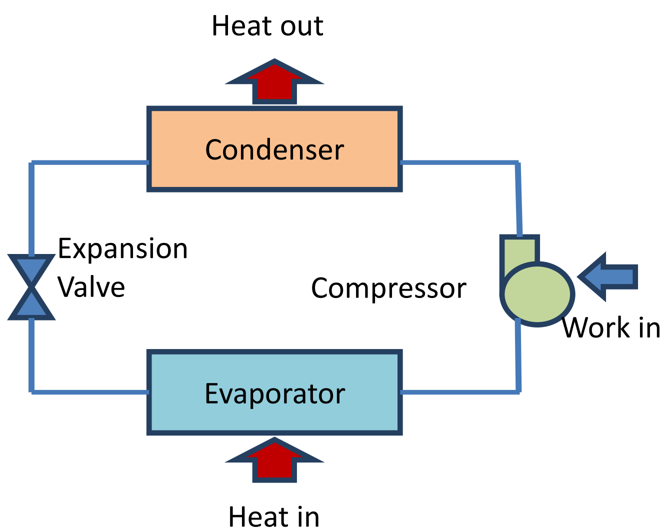

Figure 1. Illustration of refrigeration cycle

2.1 Design of combined unit

Figure 2 shows a basic diagram of the unit. A wooden box was constructed to simulate the external atmosphere. The evaporator was placed into the box with a fan to circulate the air.

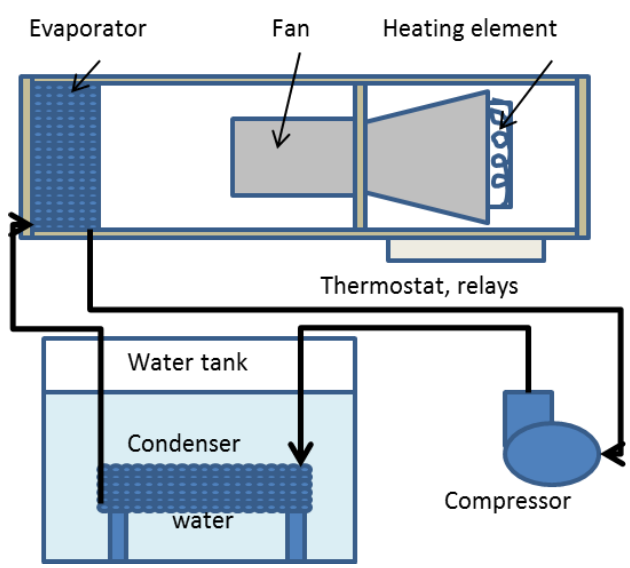

Figure 2. A close representation of the elements and configuration of the unit

A resistive heating element was placed in in the chamber. A thermocouple and other instrumentation allowed the temperature inside the box as well as the power required to heat it by Joule heating to be monitored. This was compared to the energy which the heat pump needed to perform the same operation. The condenser was placed in a water tank and the change in temperature of the water was also monitored. This demonstrates the heat exchange between the refrigerant and the water. The unit can also be used to compare the heat exchange process at the evaporator, where the heat exchange happens between the refrigerant and the air.

A 24V thermostat was used in conjunction with three 24 V single pole relays, to switch their respective devices on and off as shown in figure 3. A 120/24 V transformer was used to provide the proper 24VAC to the relays.

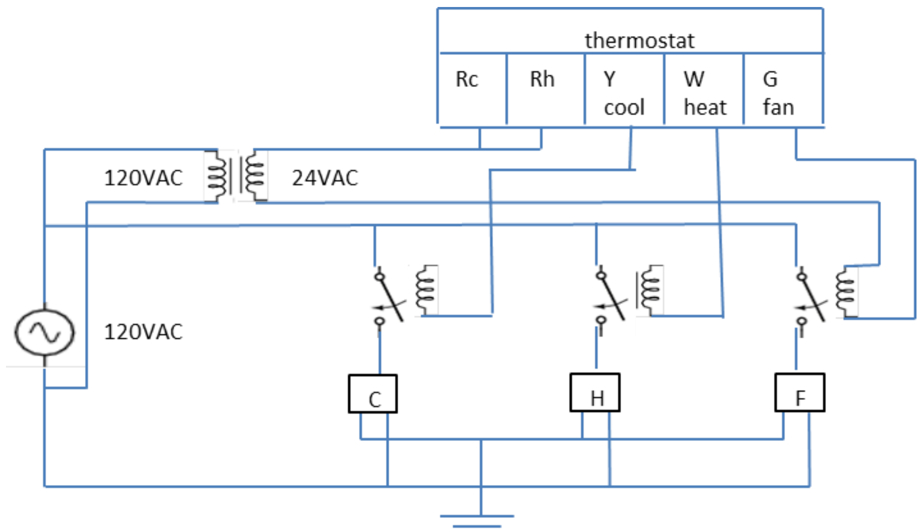

Figure 3. Schematic circuit diagram of thermostat and relays configuration used to control the heater, air conditioner and fan.

2.2 Construction of combined unit

An old 6000 BTU window unit air conditioner was dissembled and modified to build this unit. The refrigerant R22 was recovered first to a recovery tank. The pipes were cut, and the evaporator, condenser and compressor were separated and cleaned.

The chamber was built out of ¾" Baltic birth plywood and 1/4" luan. The structure was framed with plywood. Luan was used for panels. This structure minimizes weight and materials while maintaining a relatively sturdy structure.

The compressor, condenser, evaporator, and capillary tube were reassembled with the evaporator in the box with the fan, the condenser in the water tank, the compressor on top of the box, and the capillary tube connecting condenser and evaporator. A filter was added in the system to filter out any impurities in the refrigerant before the entered the compressor. The R22 refrigerant was recharged back into the unit although it is being phased out and is no longer in production in the United States due to its ozone depleting properties. This refrigerant choice was made because different refrigerants require different lubrication. Charging a different refrigerant into a system that a compressor was not designed for is not good practice.

The modified unit is shown in figure 4. It can be used in all thermal science courses. Its application to those courses is describe in the next section.

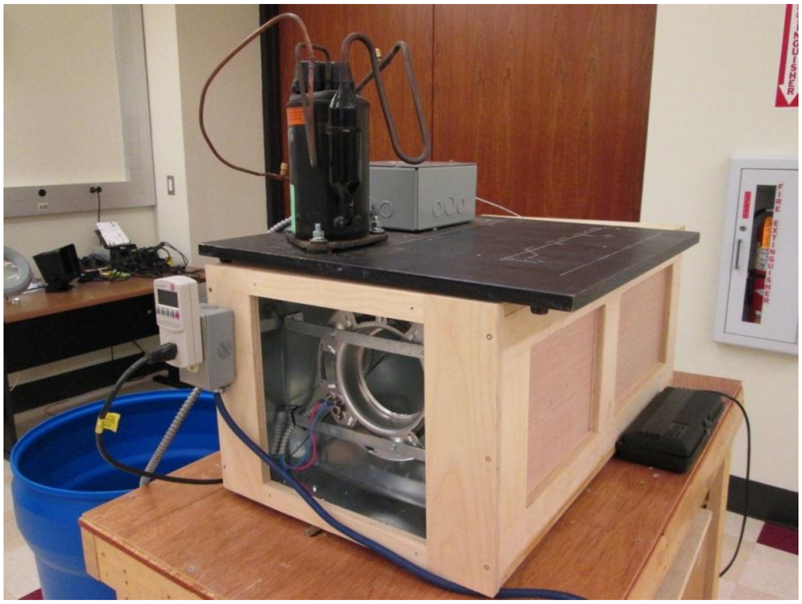

Figure 4: Picture of the air conditioning unit

3. Thermodynamics applications

Multiple experiments can be performed on this unit for thermodynamics instruction. During these experiments students actually learn how to operate the refrigeration and heat pump unit, collect and analyze the data and relate the results to thermodynamic theory.

3.1 Pure substance states

The greatest difficulty students have in thermodynamics is the conceptual understanding of abstract ideas. To understand the state of substances and be able to identify compressible liquids, saturated mixtures and superheated vapor is critical to the study and understanding of thermal cycles. By measuring temperature and pressure at the inlets and outlets of the compressor, the condenser, the capillary tube and evaporator, students can determine whether the refrigerant is a saturated mixture, superheated vapor, or sub-cooled liquid. From the property table, students can also determine other thermal properties such as enthalpy and entropy. A pressure-volume or temperature-entropy graph for this experiment can be plotted based on the measured data.

3.2 Thermodynamics first law— energy balance

Students measure the data needed to determine the energy required to operate this unit and the energy exiting from the unit to demonstrate the first law of thermodynamics. Students will need to understand the boundary of the system, and identify what energy crosses the boundary into the environment and what is within the system. Students are asked to explain why the measured energy in is not exactly same as the measured energy out. Figure 5 gives an example that can be used for this purpose. By measuring the power input into the system, and the temperature increase in the water tank, using the specific heat of water students can calculate the energy which was required to heat the water and therefore determine that there are other energy sinks in the system such as the fan, heat transfer from piping system, and air flowing through the chamber etc. They can also be asked to discuss the possible sources for error in measurement, and possible methods to improve the accuracy of their measurement. One advantage of the particular construction of the unit is that all parts are readily accessible for measurement both of power input and of temperature.

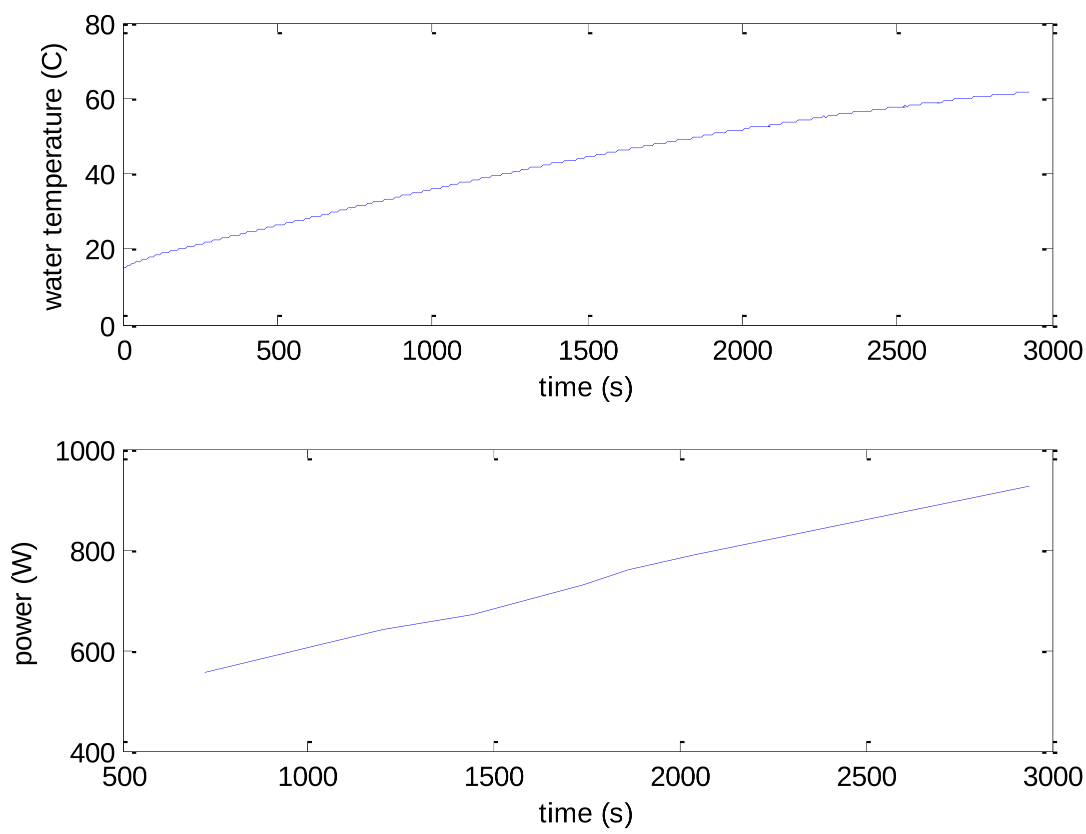

Figure 5. Input power increases while the water tank temperature increases

3.3 Refrigeration and heat pump cycle

The unit, whether operated as an air conditioner or as a heat pump, can be modeled as shown in figure 6. Instead of efficiency, the performance of a refrigeration/heat pump system is described by the coefficient of performance (COP) value. The purpose of a heat pump is to provide heat Q_H to a desired space. The purpose of an air conditioner is to move heat Q_L from a desired space. Therefore the COP can be calculated by following equations:

$$COP_{Refrigeration} = \frac{Q_L}{W_{net}} \qquad COP_{Heat\ Pump} = \frac{Q_H}{W_{net}}$$

The Temperature-Entropy graph can be obtained experimentally, and the COP can be calculated and compared to the values predicted by the Carnot Cycle. Methods for improving the performance of the unit can be discussed. The energy dissipated by the heating element can also be compared to that dissipated by the heat pump, thereby demonstrating the utility of heat pumps.

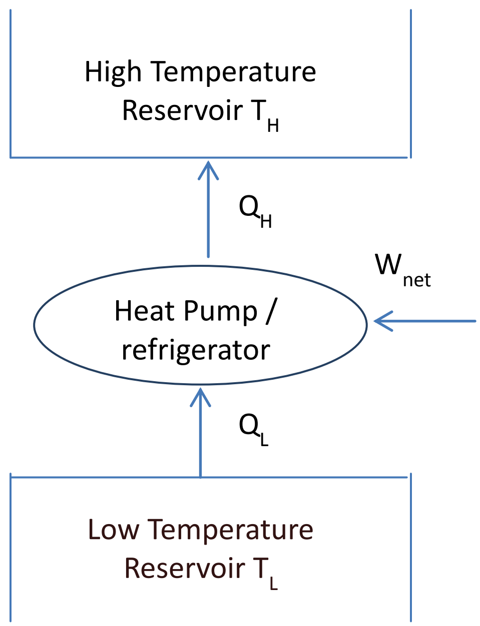

Figure 6: Interaction diagram for a heat pump or refrigerator

4. Fluid mechanics application

The capillary tube used in air conditioning or refrigeration systems is a simple refrigerant liquid metering device, which regulates the flow of refrigerant from the high pressure side into the low pressure side. The refrigerant flow rate is determined by the length of the tubing and the internal diameter of the bore. The capillary tube is located after the condenser; it is sometimes formed into a tight coil around the suction line. The flow rate through the capillary tube is fixed and is a function of the tube length, diameter, and the operating pressure at which the liquid refrigerant is being delivered. By measuring the temperature and pressure of the refrigerant before entering and after leaving capillary tube, students can study the pressure drop between inlet and outlet, and identify the state of the refrigerant.

5. Heat transfer applications

There are many heat transfer principles can be demonstrated by this unit. Two examples of experiments that can be introduced by this unit are as follows:

5.1 Heat exchanger: refrigerant to air and refrigerant to fluid

The evaporator is placed at one end of the wooden chamber. A fan is used to drive an air flow through the fins to enhance the heat exchange between the refrigerant and the air. The condenser is placed in a water tank to form a refrigerant- to- water heat exchanger. When the unit runs in air conditioner and heat pump modes, the heat exchange coefficients and heat exchange rates can be studied and compared to those between air and water.

5.2 Natural convection vs. forced convection

A fan in the chamber and a pump in the water tank provide the opportunity to study natural convection and forced convection of both air and water. By changing the speed of the fan and pump, the relationship of the heat transfer rate to the flow rate can be studied.

6. Conclusion

The experiments described above are designed for different courses, so students can have experiences which support (or sometimes obscure) the concepts presented in the lectures. At the same time, since many different experiments dealing with the different areas of the thermal sciences can be performed on the same unit, students are given the important, but sometimes not obvious, concept that all of the thermal sciences which they study are interrelated. This unit can also be used to provide a comprehensive project for students on optimum design. For example, adding a fan in the chamber and a pump in the water tank will improve the heat exchange at the expense of consuming more energy. Students can make an evaluation of whether the overall COP will be benefit from this addition and if so, at what cost? The coefficient of performance can also be improved by changing the states of the refrigeration cycle, again, at what cost? This unit is certainly cost effective, and has the potential to deliver hands-on experience to students.

Acknowledgement

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