Development of a Bench-Top Air-to-Water Heat Pump Experimental Apparatus

H. I. Abu-Mulaweh mulaweh@engr.ipfw.edu
Mechanical Engineering Department
Purdue University at Fort Wayne
Fort Wayne, IN 46805, USA

Abstract

A bench-top air-to-water heat pump experimental apparatus was designed, developed, and constructed for instructional and demonstrative purposes. This air-to-water heat pump experimental apparatus is capable of demonstrating thermodynamics and heat transfer concepts and principles. This heat pump experimental setup was designed around the vapor compression refrigeration cycle. This experimental apparatus has an intuitive user interface, reliable, safe for student use, and portable. The interface is capable of allowing data acquisition by a computer. A PC-based control system which consists of LabVIEW and data acquisition unit is employed to monitor and control this experimental laboratory apparatus. This paper provides details about the development of this unit and the integration of the electrical/electronic component and the control system.

Keywords: Heat pump, laboratory apparatus. water heater

1. INTRODUCTION

One of the important applications of the subjects of thermodynamics and heat transfer is heat pump systems. Exposing thermal engineering students to heat pump will enhance their understanding of the principles and concepts of thermodynamics and heat transfer.

There are many are many heating, ventilating, and air-conditioning (HVAC) systems, but very few of them are appropriate for undergraduate education [1, 2]. Some of these systems have computer data logging equipment. However, the computer data logging applications are exclusively standalone and not compatible with PC based data processing. In addition, these systems tend to be rather large and expensive. Recently, Abu-Mulaweh [3] has designed, developed, and constructed a bench-top air-conditioning experimental apparatus for instructional and demonstrative purposes.

Acquiring new instructional laboratory apparatus is 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 “high tech” experimental laboratory apparatus for demonstrating heating and refrigeration processes. It was decided to develop and build a cost effective system that can be employed to demonstrate and monitor refrigeration cycle, as well as some fundamental concepts in heat transfer, thermodynamics, and heat exchangers.

Hot water heaters come in various sizes and either gas fired or electric. Using a heat pump water heater to supply hot water for residential and commercial usage, is a much more efficient and energy conservative method. Heat pump water heaters can be either water source or air source. The heat pump is an electrically powered mechanical device that transfers heat from a lower-temperature source to a higher-temperature body, such as an air conditioner. The feasibility and the effectiveness of heat pump water heaters have been examined in the past [4-7].

The coefficient of performance (COP) of heat pump water heaters is typically in the order of three. This implies that the energy consumption can theoretically be reduced by two-thirds when resistance heaters are replaced by heat pumps. The installed electrical capacity is also reduced by almost two-thirds due the COP. To the building owner, this would mean a reduction in both the direct cost of units of energy consumed and the monthly peak demand charges.

The replacement of resistance heaters with heat pumps water heaters will also result in a reduction in the peak electrical demand imposed on the national electricity supply grid. To the utility, this could mean a reduction in the marginal cost of supplying each new unit of power since the need to build new power stations may be deferred.

2. SYSTEM SPECIFICATIONS

The design process that the students follow in the capstone senior design project is the one outlined by Bejan et al. [8] and Jaluria [9]. 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.

In order for the bench-top air-to-water heat pump to function as a useful piece of lab equipment, the following requirements and specifications need to be met. These include requirements that will make the heat pump useful for demonstrating thermal science and fluid dynamics principles as well as ensure the heat pump will operate safely.

- Construction – The air-to-water heat pump is to be designed to operate based on a vapor-compression cycle.

- Instrumentation – The instrumentation requirements have two distinct sets of necessary specifications.

    1. The heat pump must be fully instrumented with autonomous gages so that it may demonstrate its principles without needing to be hooked up to an outside computer.
    2. Although it may operate without an external computer, the heat pump must also be outfitted with a data acquisition (DAQ) bus that can be connected to an external DAQ board or software system. This bus must be able to supply to the external DAQ system the measurements that will be shown on the onboard instrumentation. In addition, the measurements must be logged by the DAQ.

- Safety – The safety considerations deal primarily with the fact that the design requires both large amounts of electrical equipment and liquids to be in close proximity. For this reason the following are required of the electrical design scheme:

    1. Residual current circuit breaker.
    2. Combined double pole main switch and overload cut-out.
    3. All components connected to common earth conductor.

3. EXPERIMENTAL APARATUS

A bench-top air-to-water heat pump, shown in Figure 1, was designed, developed, and constructed for instructional and demonstrative purposes. This heat pump was designed around the vapor compression refrigeration cycle. The bench-top air-to-water heat pump has an intuitive user interface, reliable, safe for student use, and portable. The interface is capable of allowing data acquisition by an existing laboratory computer. The unit is capable of warming the water 10ºC in an open or closed configuration, and cool it back down if desired. The system fully controls and monitors the fluid properties at key points in the refrigerant and water loops.

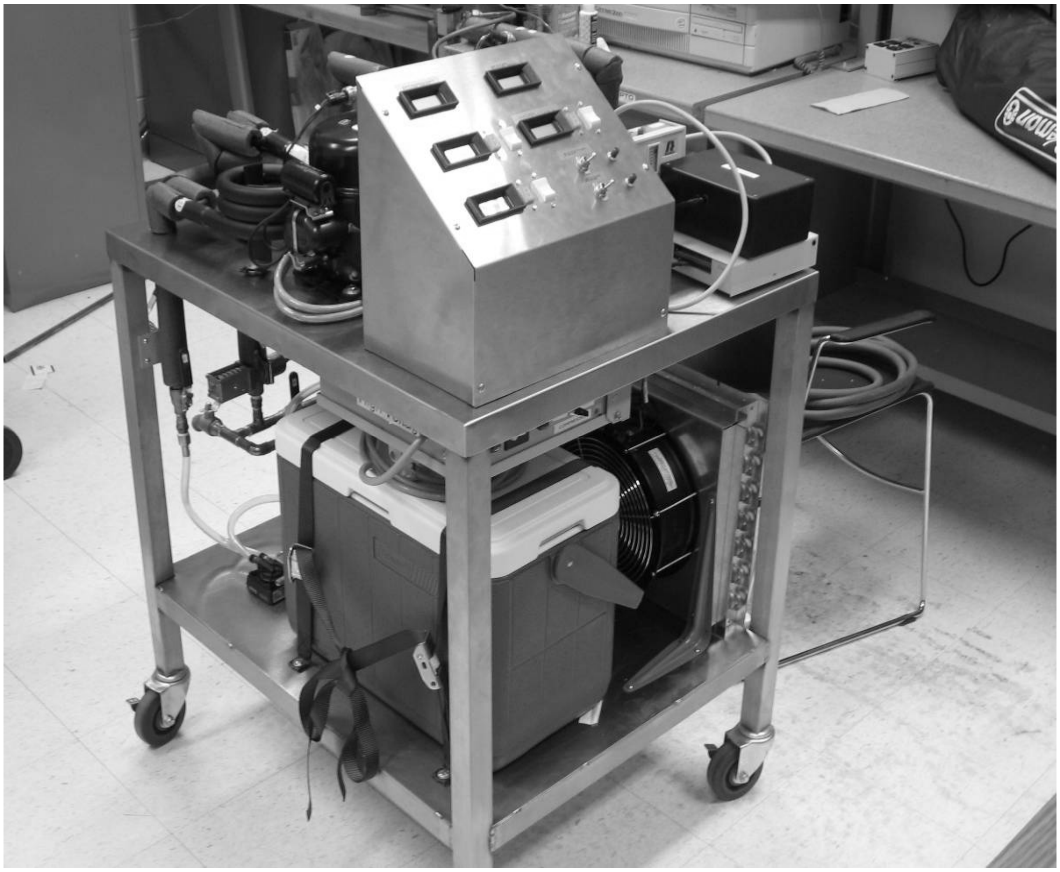

FIGURE 1: Experimental apparatus

3.1 Mechanical Concepts Selection

To select properly sized components for the heat pump, parametric studies were completed using the EES model and plots of the important operating variables were generated. Because the entire heat pump apparatus needs to operate off of the power provided by a single 115V, 15A wall circuit, the amount of steady-state power required by the compressor was limited to 800 W (2732.14 BTU/hr). This power constraint is imposed in order to leave sufficient reserve power for start-up energy requirements as well as sufficient power to run the rest of the powered devices that will be used on the heat pump. For the heat pump to meet its water heating performance requirements the water flowing through the condenser must experience at least a 10 °C (18 °F) temperature rise between the inlet and exit.

3.2 Refrigeration Cycle Components

Condensing Unit: A Tecumseh model AEA4440YXAXW water cooled condensing unit was chosen as the basis for the heat pump. At the nominal operating conditions anticipated, this condensing unit will deliver 0.53 GPM (3.34E-5 m^3/s) of water raised 13.5°C (24.3°F) when paired with a 4600 BTU/hr (1346.93 W) evaporator.

Evaporator & Fan: Knowing the requirements of the evaporator in terms of heat, a model 012-0850 evaporator was chosen from www.Rparts.com. This evaporator is rated for 7500 BTU/hr (2196.08 W) at an evaporating temperature difference of 15°C (27°F) and airflow of 200 CFM (0.09 m^3/s). The evaporating temperature difference is defined as the difference in temperature between the air entering the evaporator and the saturation temperature of the refrigerant within the evaporator. The evaporator is oversized to make sure that the compressor is never starved for refrigerant and oil, which is emulsified in the refrigerant. Excess evaporator heat can be reduced and adjusted for by decreasing the air flow across the coils or by blocking of a portion of the heat exchange surface with dampers. The selected fan for the evaporator is the Falcon model from Lytron. It is capable of providing up to 300 CFM (0.14 m^3/s) at 0.36 amps of running current.

Expansion Valve: The selection of the expansion valve, located right before the evaporator, is based on the capacity of the system. The target capacity of the evaporator is approximately 4600 BTU/hr (1346.93 W) which corresponds to 0.383 tons of refrigeration. Based on this value, a Danfoss expansion valve model 095-0200 (orifice part No. 095-0003) was selected. This model is externally equalized and the orifice is rated for up to 0.5 tons (6000 BTU/hr) of refrigeration.

Filter Dryer: To remove any moisture or contaminants that could potentially damage the system, a filter dryer from Sporlan was chosen (# 020-0052, Mod.C-082). This model will also neutralize any acid that might initially form from the interaction between the refrigerant and coils.

Sight Glass: A Sporlan sight glass (#077-0100, Mod. SA12) was chosen to provide a visual to warn of and diagnose excessively high moisture levels.

Tubing: Copper tubing of 3/8 inch (0.95 cm) inner diameter was selected for the refrigerant.

3.3 Water Cycle Components

Water Pump: The pumping force for the circulation of the water loop will come from a Delphi – Laing DC Pump, (Mod. DDC-1TPMP). This pump can supply water at a maximum pressure of 22 psi (151.68 kPa), and a maximum flow of 1.75 GPM (1.10E-4 m^3/s) at 13.2 VDC. It operates up to a temperature of 60ºC (140ºF).

Water Reservoir and Tubing: An insulated water cooler was used as a water reservoir. Bulkhead fittings were mounted on the cooler for pipes connections. The water piping was constructed from copper tubing.

Radiator & Fans: To cool the water back down, an appropriate radiator was selected to fit the requirements of this cycle. The radiator needs to move 6500 BTU/hr (1903.27 W) to cool the water down close to room temperature from 113ºF (45ºC), with a flow rate of 1 GPM (6.31E-5 m^3/s). The component is made by Lytron (Mod. M14-240). It has capacity of 373 BTU/hr ºF at the specified flow rate, with an air flow of 550 CFM (0.26 m^3/s). The radiator is equipped with two fans with a capability of 450 CFM (0.21 m^3/s) each, at a running current of 0.5 amps per fan.

4. INTEGRATION OF THE ELECTRICAL/ELECTRONIC COMPONENT

All of the low voltage electrical components were tested for functionality before assembly into their respective circuits. This was done by applying voltages to each chip and checking output for correctness. After these individual components were tested, each of the circuits were temporarily built on a breadboard and tested to verify that they worked as expected. This was proven by applying inputs of voltages or frequencies from lab equipment and measuring the output voltages with a handheld meter. The microprocessors were also programmed and tested.

In the second phase of the building process, the final assembly of the low voltage electrical system was performed. All of the circuits were laid out, built, and soldered together on a perforated proto-board. The circuits were then retested with lab equipment to verify that building and soldering was completed correctly. Once the circuits were built and soldered, more testing was done to determine the accuracy and percentage error associated with these circuits.

The fourth phase comprised the high voltage wiring of the mechanical system. All high voltage components were wired with a common ground, the ground fault interrupter (GFI) was placed on the high voltage wire coming directly from the wall outlet to protect against large surges of current, and the double pole single throw (DPST) circuit breaker was placed directly following the GFI. In addition to these original specifications, two lights were added to show the status of the high voltage power. The first light demonstrates that the system is connected to the high voltage power and the second light confirms the system is on and operational.

The final integration of the electrical/electronic system with the mechanical system consisted of running wires from the pressure circuits to the pressure transducers, connecting the thermocouple wires to the temperature circuits, and applying low voltage power to the water pump. The final step in the electrical/electronic building process was testing the DAQ functionality. Wires were run from the control box on the heat pump unit connecting to the DAQ board via a printer cable.

After the entire system was built and operational it was then connected to the SCB-68 break out box and then to the DAQ card, via the on-board DB-25 connector and modified printer cable. It was observed that the sensor signals dropped due to the voltage divider circuit created when the DAQ was applied to the system. To remedy this problem, fifteen LM741 operational amplifiers were employed as a non inverting amplifier and voltage followers. The non-inverting amplifier was used to amplify (magnitude of ten) the water flow signal, as it was observed that the DAQ was having difficulty accurately collecting the small signal. This signal isolation system was added to the cable that connects the control box to the DAQ.

5. INTERFACE AND CONTROL SYSTEM

The control requirements of this system consist of monitoring two of the pressures (the condenser pressure and the evaporator pressure) and switching the compressor and the evaporator fan on and off, depending on the levels of the pressure transducers. In order to control this system there are a few integral components; 1.) A PIC16F687, the microprocessor that will read run the control program. 2.) Two Solid State Relays (P/N 4062RL), used for switching on and off the motors. 3.) Two pressure transducer outputs (P/N 2CP5-50-1). The microcontroller runs the program that is flowcharted in Figure 2. This program utilizes the onboard 10-bit analog to digital converters to convert the pressure transducers' voltages into a usable digital value. The microprocessor compares the values that are produced from the pressure transducers to some preset values and then output control signals to the solid state relays to control the motors.

The microcontroller is programmed using the flow chart shown in Figure 2. This program starts both of the relays at zero output logic and initially checks the condenser pressure. If the condenser pressure is above the set point, both of the motors will remain at zero. The relays will remain at zero until the condenser pressure is below another preset value. Once this pressure drops to the set point the microprocessor will check the evaporator pressure, if this pressure is below a certain value the compressor will remain at zero and the evaporator pressure will continue to be polled until it rises to the specified suitable temperature. Once this temperature is achieved the compressor will be turned on and the evaporator pressure will be checked. If this pressure becomes too large the evaporator fans will remain at zero and the system will poll the evaporator pressure until it falls below the set point. Once the set point is achieved the evaporator fan will be turned on and the loop will continue to iterate at the check condenser pressure stage until the system is turned off.

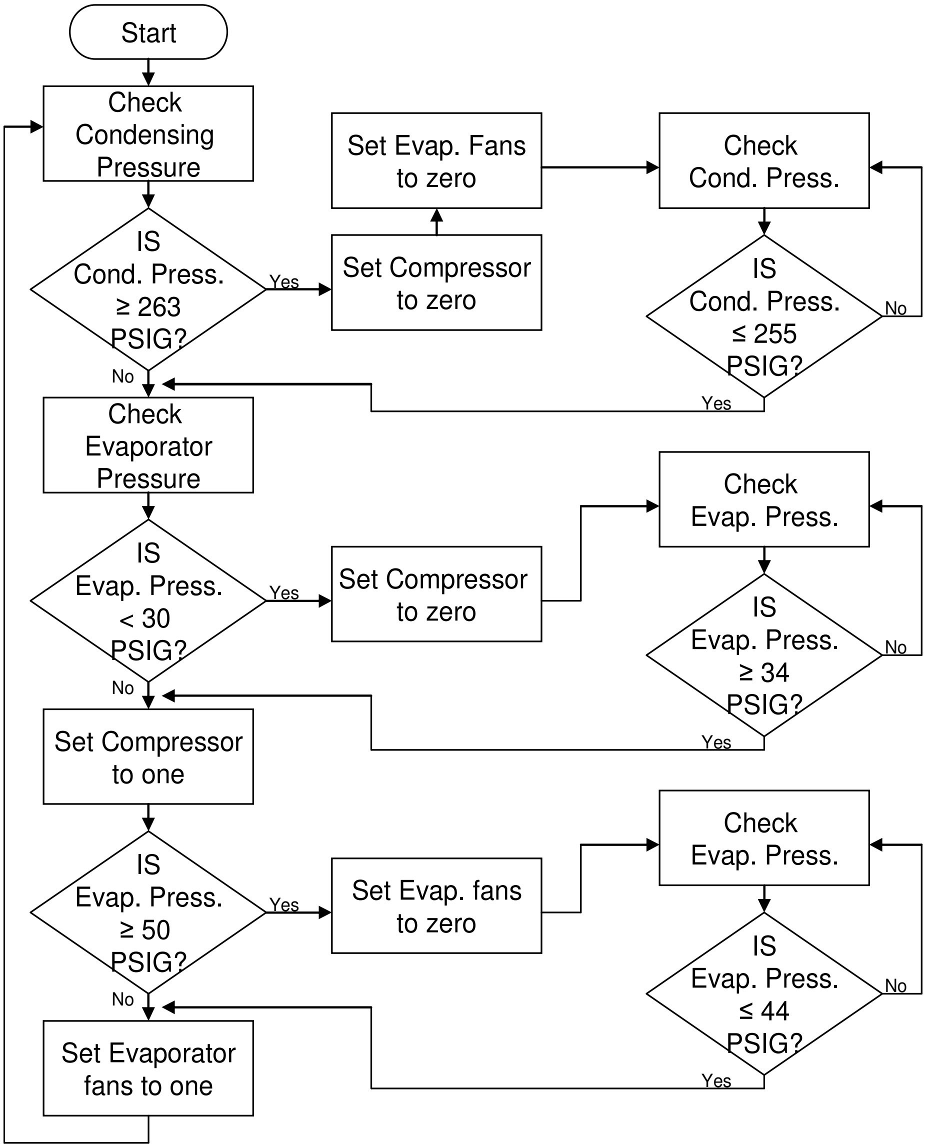

FIGURE 2: Flow Chart for Controller Program

6. PERFORMANCE OF THE APPARATUS

The heat pump experimental apparatus was designed to operate as an open water loop (external water supply) and as a closed water loop (onboard supply). Figure 3 the sensors locations for both the refrigerant and the water loops. The measurements are obtained from either the onboard instrument display or from a DQA.

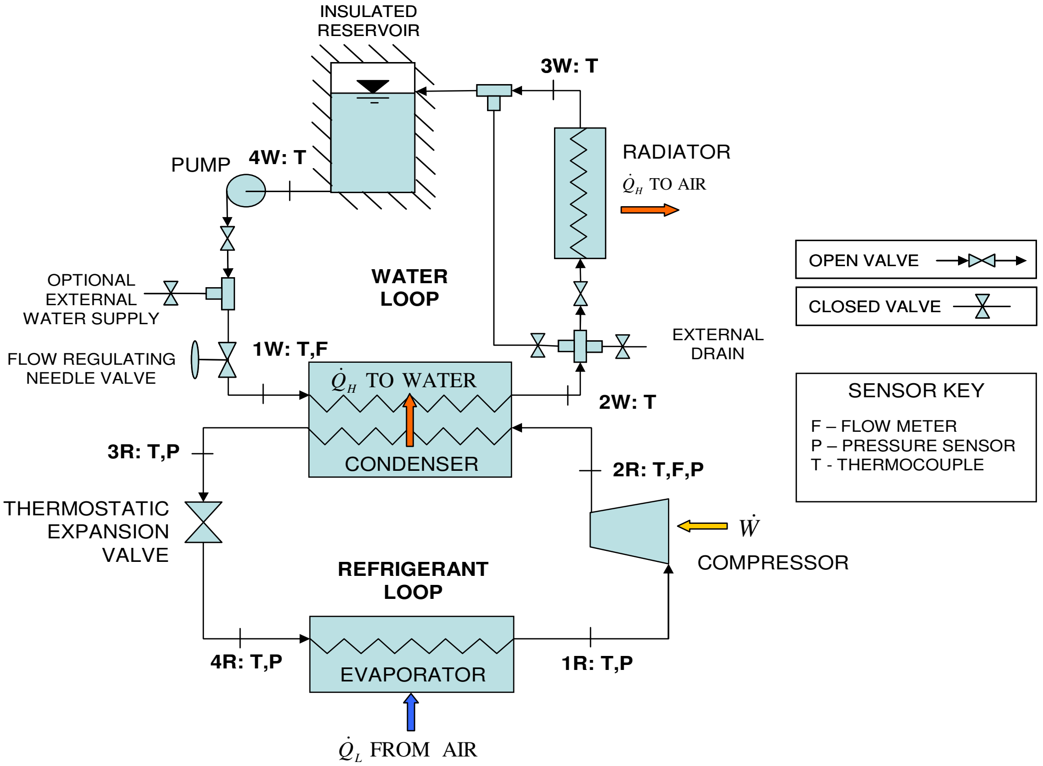

FIGURE 3: Sensor locations

6.1 Measurements

In each run the following measurements can be obtained:

1. Refrigerant Temperature – The temperatures at each of the four points in the vapor compression cycle will be measured using K-type thermocouples.
2. Refrigerant Pressure – The pressure at each of the four points in the vapor compression cycle will be measured using pressure transducers.
3. Refrigerant Flow Rate – The volume flow rate of the refrigerant will be measured using a paddle-wheel flow sensor.
4. Water Temperature – The temperature of the water will be measured at the inlet and outlet of the condenser and in the reservoir using K-type thermocouples.
5. Water Flow Rate – The volume flow rate of the water will be measured using a turbine-type flow sensor.
6. Ambient Temperature – Ambient temperature will be measured using a K-type thermocouple as well.

6.2 Calculations

From the measured data the following calculations can be performed:

1. Mass flow rate of water

$$\dot{m}_w = \dot{V} \cdot \rho \,.$$

2. Heat transferred in the condenser

$$\dot{Q}_H = \dot{m}_w (h_{2w} - h_{1w})$$

3. Using the heat transfer to the water and points R2 and R3 in the refrigerant loop (see Fig.3), the mass flow of the refrigerant can be determined.

$$\dot{m}_R = \frac{\dot{Q}_H}{h_{2R} - h_{3R}}$$

4. Heat transferred in the evaporator

$$\dot{Q}_L = \dot{m}_R (h_{1R} - h_{4R})$$

5. Calculate the work done by the compressor.

$$\dot{W}_{compressor} = \dot{m}_R (h_{2R} - h_{1R})$$

6. Isentropic efficiency of the compressor.

$$\eta_{comp} = \frac{h_{2sR} - h_{1R}}{h_{2R} - h_{1R}}$$

7. Determine the coefficient of performance.

$$CoP = \frac{\dot{Q}_H}{\dot{W}_{comp}}$$

6.3 Sample Results

The heat pump can be set up in four different configurations:

1. open loop
2. closed loop
3. closed system
4. system cooling

Open Loop: The open loop configuration makes use of water from a tap. Hoses are provided with the unit. The water comes in to the unit, travels through the heat exchanger and exits the heat pump. Water is expelled into a drain.

Closed Loop: The closed loop configuration does not require an outside water source. In this configuration water travels from the reservoir through the water loop and back into the reservoir. Heat added in the condenser is dissipated by the radiator.

Closed System: This configuration bypasses the radiator and allows the heat gained in from the condenser to be stored in the reservoir. The closed system does not require an outside water source.

System Cooling: Once the reservoir has been heated using the Closed System, it can be cooled down. This can be accomplished by using one of the hoses provided and turning off the compressor while letting the pump and radiator run.

Steady-state measurements, closed loop configuration are included in Table 1. To insure repeatability, three different runs were carried out. In each run measurements of the water temperatures, water flow rate, refrigerant temperatures and pressures were obtained (refer to Fig. 3 for sensor locations).

Figure 4 and 5 show pressure-enthalpy and temperature-entropy plots of the system, respectively. These plots indicate the vapor-compression cycle is operating correctly, with slight amounts of superheat and sub-cooling. Dotted lines in the P-h plot demonstrate the deviations from ideal refrigeration cycles. The irreversible process of the expansion through the valve and heat transfer to and from components account for this phenomena. Although in ideal situations, the expansion between R3 and R4 (see Figures 3) is a constant enthalpy process, the increase in enthalpy between these two states only amounts to approximately 12%. In the T-s diagram (Figure 4) these irreversibilities are depicted by dotted lines. In a standard cycle, the compression between R1 and R2 (see Figures 3) is an isentropic process. In this case, there is a 3% increase in entropy from R1 to R2 due to the irreversible nature of this process.

Location	Run 1	Run 2	Run 3
Ambient Temp. (℃)	23.6	23.8	24.1
W1 (℃)	28.2	28.2	28.9
W2 (℃)	37.9	39.0	38.2
W3 (℃)	27.5	27.8	28.3
W4 (℃)	27.8	27.8	28.5
Water Flow (gpm)	0.60	0.53	0.62
R1 (℃)	10.9	11.1	11.4
R2 (℃)	82.5	81.3	81.2
R3 (℃)	38.3	39.3	38.8
R4 (℃)	5.7	6.1	6.3
Refrigerant Flow (gpm)	0.101	0.101	0.101
P1 (psia)	59.1	59.0	59.9
P2 (psia)	170.8	176.5	174.1
P3 (psia)	171.0	175.3	172.8
P4 (psia)	57.6	58.2	57.8

TABLE 1: Steady-state measurements, closed loop configuration.

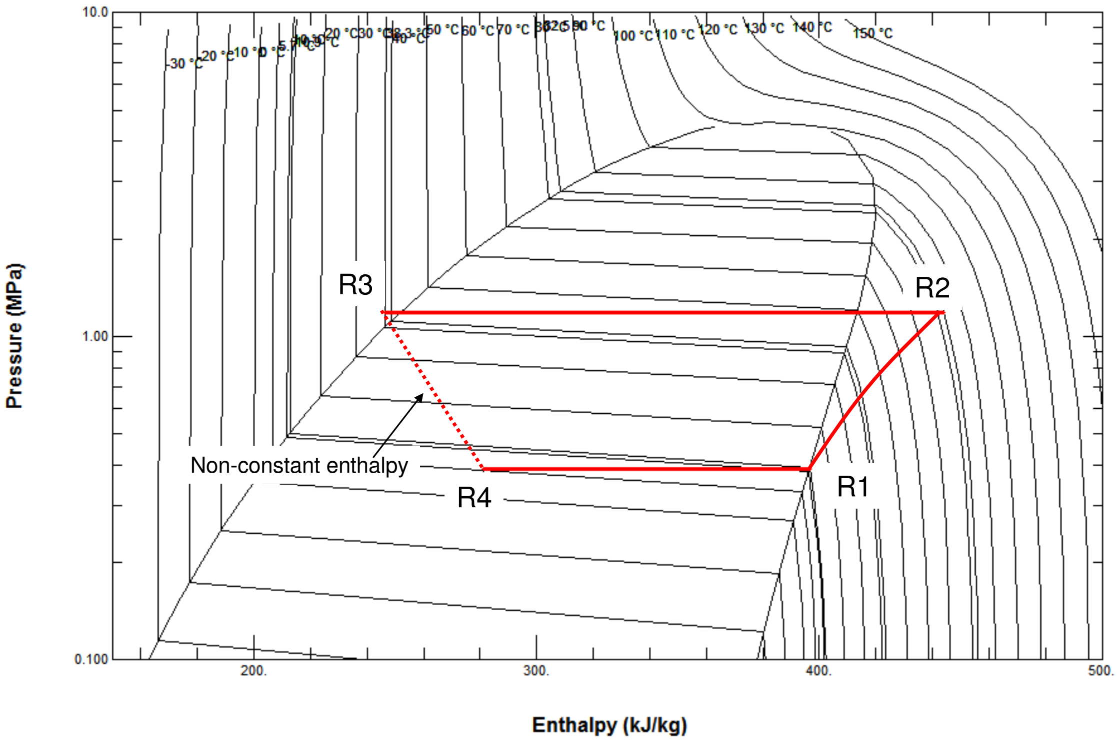

FIGURE 4: Operating points of the refrigeration system shown on a pressure-enthalpy chart

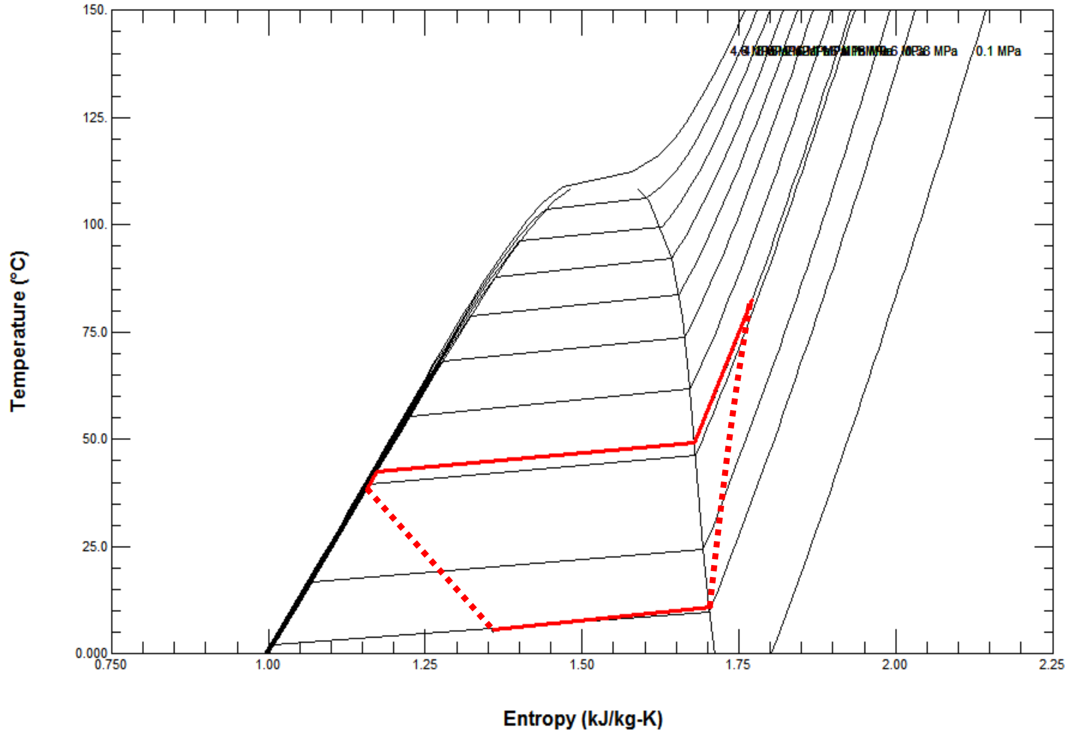

FIGURE 5: Operating points of the refrigeration system shown on a temperature-entropy chart

7. CONSLUSION

A portable air-to-water heat pump experimental apparatus was developed and built to demonstrate actual refrigeration cycle, as well as some fundamental concepts in heat transfer, thermodynamics, and heat exchangers. The system is fully instrumented and numerous aspects of the refrigeration cycle can be easily monitored. This experimental apparatus has an intuitive user interface, reliable, safe for student use. The interface is capable of allowing data acquisition by a computer. The unit is also instrumented with autonomous gages to be able to demonstrate heat transfer concepts/principles and thermodynamics processes without needing to be hooked up to a computer.

8. ACKNOWLEDGEMENT

The present study was supported by a grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc. (ASHRAE).

9. REFERENCES

1. Hamden Engineering Corporation, Mechanical Engineering Program, East Longmeadow, MA, USA, 2001.
2. Cuissons Educational Technology, Thermodynamics, TRA/2, distributed by Feedback Inc., Hillsborough, NC, USA,1997.

3. H.I. Abu-Mulaweh, “*Development and Performance Validation of Portable Air-Conditioning System Experimental Apparatus*”, In Proceedings of The Third International Conference on Thermal Engineering: Theory and Applications, Amman, Jordan, May 21-23, 2007.
4. B.A. Pritchard, W. A. Beckman, and J.W. Mitchell, “*Heat Pump Water Heaters for Restaurant Applications*”. International Journal of Ambient Energy, 12: 59-68, 1991.
5. P. Neksa, H. Rekstad, G.R. Zakeri, and P.A. Schiefloe, “*CO_2-Heat Pump Water Heater: Characteristics, System Design and Experimental Results*”. International Journal of Refrigeration, 21: 172-179, 1998.
6. B.J. Huang and J.P. Chyng, “*Integral-Type Solar-Assisted Heat Pump Water Heater*”. Renewable Energy, 16: 731-734, 1999.
7. C.W. Wood, “*Unsteady Temperature Distributions in Vertical Storage Tanks Heated with Heat pumps*”. Heat Transfer Engineering, 19: 43-52, 1998.
8. A. Bejan, G. Tsatsaronis, and M. Moran, “*Thermal Design & Optimization*”, *John Wiley & Sons, Inc.*, New York, 1996.
9. Y. Jaluria, “*Design and Optimization of Thermal Systems*”, *McGraw-Hill*, New York, 1998.