
Portable experimental apparatus for demonstrating thermodynamics principles

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Abstract A refrigeration system for use as experimental apparatus was designed, developed and constructed. Its purpose was to demonstrate to mechanical engineering undergraduates the basic concepts of thermodynamics, such as the first and second laws. In addition, the apparatus demonstrates a vapor compression refrigeration cycle. This paper presents a set of experiments in which the first and second laws of thermodynamics are employed to determine the heat gained by the refrigerant in the evaporator, the heat rejected from the refrigerant in the condenser, and the isentropic efficiency of the compressor. The objective of these experiments is to help students understand the basic thermodynamics processes by utilizing real-life applications.

Keywords thermodynamics; laboratory; refrigeration system

Introduction

Thermodynamics has long been an essential part of mechanical engineering curricula all over the world. The principles of thermodynamics are based on people's everyday experiences and observations. However, the majority of students perceive thermodynamics as a difficult subject. Mechanical engineers use thermodynamics principles in their study and design of a wide variety of energy systems, such as jet engines and rockets, refrigeration systems, air conditioning systems, chemical processes, and power plants.

It was decided that an experimental apparatus designed to demonstrate thermodynamic processes and systems was needed. Such an apparatus would enhance the teaching (and learning) of thermodynamics. Students would be able to apply thermodynamics principles, such as the first and second laws, learned in the classroom lectures, to real-life problems. This approach could make the learning of thermodynamics a more pleasant experience for undergraduate mechanical engineering students.

Indiana University–Purdue University Fort Wayne (IPFW), is a state-supported institution and thus the purchase of new instructional laboratory apparatus is subject to typical budgetary limitations. Also, apparatus designed by companies specializing in education equipment may not exactly reflect the educational objective intended by the faculty. Thus it was decided that the apparatus be designed, developed and constructed 'in house', within a budget. Advantage was taken of the Capstone senior design project and the Undergraduate Senior Project Grant Program of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). The purpose of the ASHRAE 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 not only helps in terms of budget but also provides the students with high-quality real-life design projects to work on. The task to design, develop and construct an instructional laboratory apparatus to demonstrate thermodynamic processes and principles therefore began with an application to the ASHRAE Undergraduate Senior Project Grant Program. The proposal was to design a refrigeration system for a small compartment. Subsequent to the awarding of a grant of \$1775 from ASHRAE, a student senior design group was selected to work on the project.

The design process

The design process that the students follow in the Capstone senior design projects is the one outlined by Bejan *et al.* [1] and Jaluria [2]. The first essential and basic feature of this process is the formulation of the problem statement. This 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 the guidelines for the apparatus:

- (1) The system must be based on the vapor compression refrigeration cycle.
- (2) All components of the system must be visible and the different states must be instrumented with thermocouples to measure the temperature, and pressure gages to measure the pressure.
- (3) The inside dimensions of the compartment should be 38 cm by 38 cm by 50 cm, with a square base.
- (4) The system should keep the refrigerated compartment at approximately $-5^{\circ}\text{C} \pm 2^{\circ}\text{C}$.
- (5) The working fluid for the system (i.e., the refrigerant) must be environmentally friendly.
- (6) The system should operate on regular 110 V, single-phase, grounded, 60 Hz AC power from a standard outlet.
- (7) The system should be rigid and stable (i.e. not likely to tip over accidentally).
- (8) The cost of the system should not exceed \$1775.

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.

The design chosen was a rotary screw compressor single-stage vapor compression refrigeration cycle. The refrigerant selected was R-134a. This refrigerant is considered to be safe to the environment. Details of the vapor compression refrigeration cycle can be found in any textbook on the fundamentals of thermodynamics, such as that by Sonntag *et al.* [3], and a schematic of this cycle is shown in Fig. 1. The compressor is used to compress (raise the pressure of) the refrigerant from a saturated vapor to a superheated vapor (points 4–1 in Fig. 1). The superheated vapor is then channeled into the condenser, where heat is removed from the fluid to the surroundings, causing the working fluid to revert from a superheated vapor to a satu-

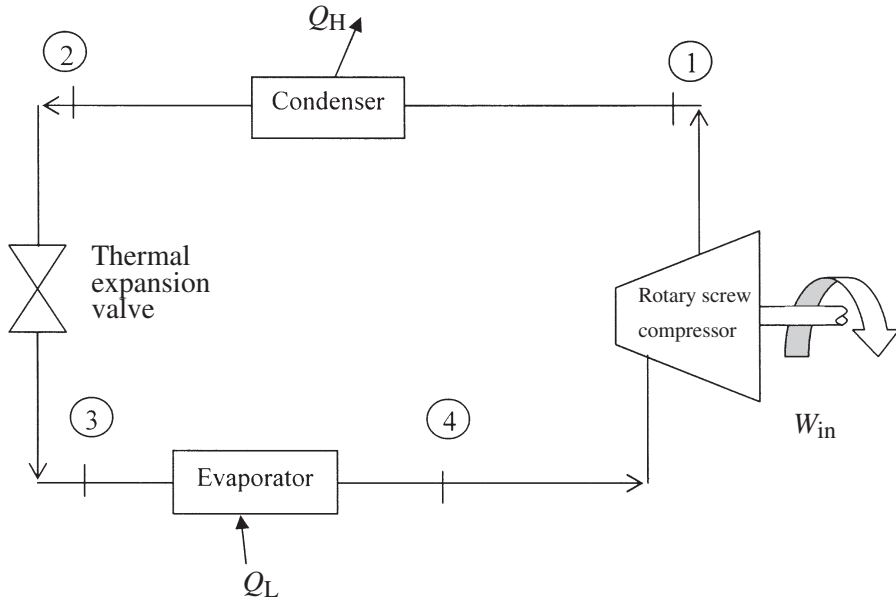


Fig. 1 A schematic of the rotary screw compressor vapor compression cycle.

rated liquid (1–2). The saturated liquid then enters the expansion valve, where it undergoes expansion (2–3). This lowers the temperature of the fluid to the desired temperature for the evaporator. At this point, the refrigerant is in the saturated region. The evaporator is used to remove heat from the compartment of the system to the working fluid, which changes to a saturated vapor and is then returned to the compressor (3–4).

Equipment description

The refrigeration system that was designed and constructed as instructional laboratory apparatus is shown schematically in Fig. 2. The temperature and pressure of the working fluid (R-134a) can be measured at the four different points indicated in Fig. 1. In addition, the mass flow rate of the refrigerant can be measured using a flow meter. The measurements of the temperature and pressure at points 1–4 allow the determination of the various thermodynamic properties needed to demonstrate thermodynamics principles such as the first and second laws.

All the components are located on a bench top. This kind of arrangement makes the apparatus easy to move from one location to another using a cart. The bench top is made of a $\frac{3}{4}$ " melamine shelving, which was purchased precut to 24" \times 48". The compressor chosen is a rotary screw type that has a capacity of 470 BTU/h and was purchased from Copeland. Both the condenser and the evaporator coils were constructed by HeatCraft Inc. according to the design parameters. The evaporator is

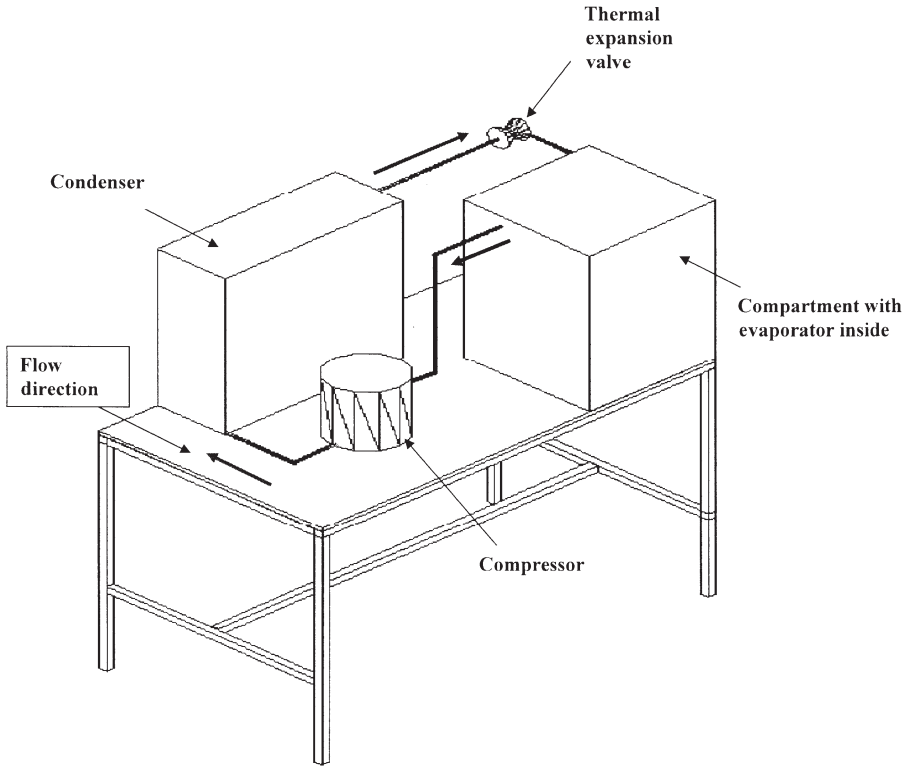


Fig. 2 Schematic of the overall refrigeration system apparatus.

installed next to the ceiling inside the refrigerated compartment. Two holes were drilled through the back of the compartment to allow the evaporator lines to pass through. After the evaporator was installed in the compartment, and the lines were connected to the thermal expansion valve and the compressor, the drilled holes were filled with spray-in insulation. The condenser is installed outside the compartment and is supported on the bench top by a wooden frame. A fan assembly is installed behind the condenser to enhance the heat loss.

The walls of the compartment consist of three layers: a formed 20-gage sheet metal interior, a $\frac{3}{4}$ " thick 'blue board' (extruded R-4 insulating board) liner, and a formed 20-gage metal exterior. Assembly of the compartment began by having the individual sheet metal components professionally fabricated. The exterior of the compartment was the first to be assembled. With the bottom and three sides screwed together, pieces of the insulating blue board were custom cut to fit. After placing the blue board, all three of the interior panels were installed. Each panel was screwed to the adjacent panels using self-tapping sheet metal screws. The top was the last panel to be attached to the main compartment.

The choice of the thermal expansion valve (TXV) was based on the following requirements: adequate capacity, and the ability to provide the required pressure drop, to tolerate the refrigerant, and to operate within the temperature range. The model chosen was from Alco Products. Its inlet and exit line sizes were somewhat larger than the lines that were used, so suitable couplings were needed at each junction. In addition to the inlet and outlet lines, there were two other connections to be made with the chosen expansion valve. One connection was from the pressure tap on the valve to the exit line of the evaporator. This connection serves to monitor the pressure of the line connecting the evaporator and the compressor. The other connection (5 ft long) led to the remote sensing bulb, and did not make contact with the refrigerant. Its function is to monitor the temperature of the tube on the compressor side of the evaporator and this is accomplished by measuring the pressure of the working fluid inside the bulb as it changes with the temperature of the line to which it is connected. The purpose of this type of thermal expansion device is to monitor the state of the refrigerant entering the compressor and to maintain a given level of superheating in order to avoid compressor damage. In addition, a filter dryer was installed directly after the TXV to dry the refrigerant that leaves the TXV by removing any water vapor that entered the system during assembly.

The tubing that was used in this experimental apparatus was type L, $\frac{3}{16}$ " OD copper tube. It is rated at a maximum of 300 psi at 180 °F. The maximum pressure at any point in the system is 112 psi. This gives a safety factor of 2.68 for the tube. All joints were brazed. It should be noted that the tube was sized as recommended by the ASHRAE guidelines for line sizing. After all the components were assembled, the copper lines were checked for leaks and then the system was charged using refrigerant R-134a and an oil charge of 2 oz. In addition, the copper lines were insulated and wrapped with either red or blue duct tape, indicating hot line or cold line, respectively.

The control system consisted of an on/off switch from Ranco actuated by a temperature-sensing bulb, to regulate the temperature inside the compartment. Since the operating point is -5°C , the control system will turn the motor on at -4°C and off at -6°C . The TXV is also considered a part of the control system, as it maintains and controls the amount of superheat exiting the evaporator. This device was installed to the side of the compartment using several brackets, and it controls the compressor by utilizing a sensing bulb placed inside the compartment to read the internal compartment temperature. A type T thermocouple to read the internal temperature and a sensing bulb were placed inside the compartment, through a hole drilled in its side. Thereafter, the access hole was spray-foamed to seal the compartment.

Testing procedure and sample results

The locations at which the temperature and pressure of the refrigerant are to be measured are summarized below and illustrated in Fig. 3. In addition, a thermocouple is used to monitor the temperature inside the compartment.

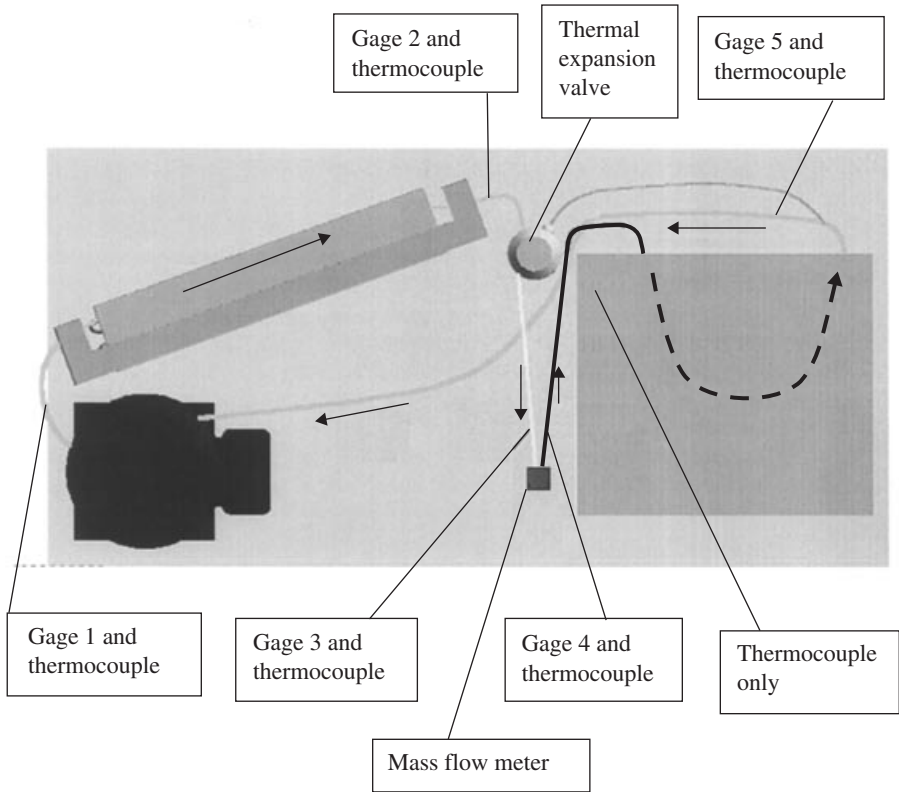


Fig. 3 Location of pressure gages and thermocouples.

- (1) Gage 1 and thermocouple – condenser inlet/compressor outlet
- (2) Gage 2 and thermocouple – condenser outlet/thermal expansion valve inlet
- (3) Gage 3 and thermocouple – thermal expansion valve outlet/flow meter inlet
- (4) Gage 4 and thermocouple – flow meter outlet/evaporator inlet
- (5) Gage 5 and thermocouple – evaporator outlet/compressor inlet
- (6) Thermocouple only – compartment interior.

The setting of the TXV (i.e., the pressure drop across it) greatly affects performance. The TXV is a purely mechanical, closed-loop control device. It adjusts the amount of pressure drop between the high-pressure and low-pressure sides of the system based on pressure and temperature inputs from the evaporator exit. The reaction time of this device manifests itself in the sinusoidal nature of the pressure and temperature variations, and this is known as hunting. In an unstable system, the hunting is severe and can lead to inefficiency and premature component failure. Small and relatively uniform oscillations are indicative of a stable, appropriately

sized system. The pressure drop across the TXV can be adjusted by turning a small screw at the bottom. Several runs were carried out to find a suitable setting.

The measured data were collected utilizing a data-acquisition system. Table 1 shows a sample of the data that were obtained. The data represent the final measurements taken before the compressor was started by the control system, as a result of the temperature inside the compartment reaching the operating point.

From the measured data, several quantities of interest can be determined using the first law and the second law of thermodynamics. These quantities include the following.

The heat transfer into the evaporator, Q_L :

$$Q_L = h_4 - h_3$$

The heat rejected from the condenser, Q_H :

$$Q_H = h_1 - h_2$$

The actual work required, W_a (the input work to the compressor):

$$W_a = h_4 - h_1$$

The ideal work required, W_s :

$$W_s = h_4 - h_{1s}$$

$$s_4 = s_1 \text{ (from the second law)}$$

The isentropic efficiency of the compressor, η_c :

$$\eta_c = W_s/W_a = (h_4 - h_{1s})/(h_4 - h_1)$$

The coefficient of performance (COP) of the refrigeration system:

$$\text{COP} = Q_L/W_a$$

A summary of these results is shown in Table 2.

Fig. 4 illustrates the T-s diagram with the vapor dome of the actual vapor compression refrigeration cycle for the current system, based on the data shown in Table

TABLE 1 *Measured data*

Gage location	Temperature (°F)	Pressure (psi)
1	127.7	99.7
2	67.71	99.7
3	1.13	22.6
4	-5.12	21.8
5	18.73	17.7
Compartment	19.58	
Flow rate	0.0054lbm/s	

TABLE 2 Summary of results

Q_c (BTU/h)	Q_H (BTU/h)	W_a (BTU/h)	W_s (BTU/h)	η_c (%)	COP
1422.1	1782.5	360.4	321.5	89.2	3.95

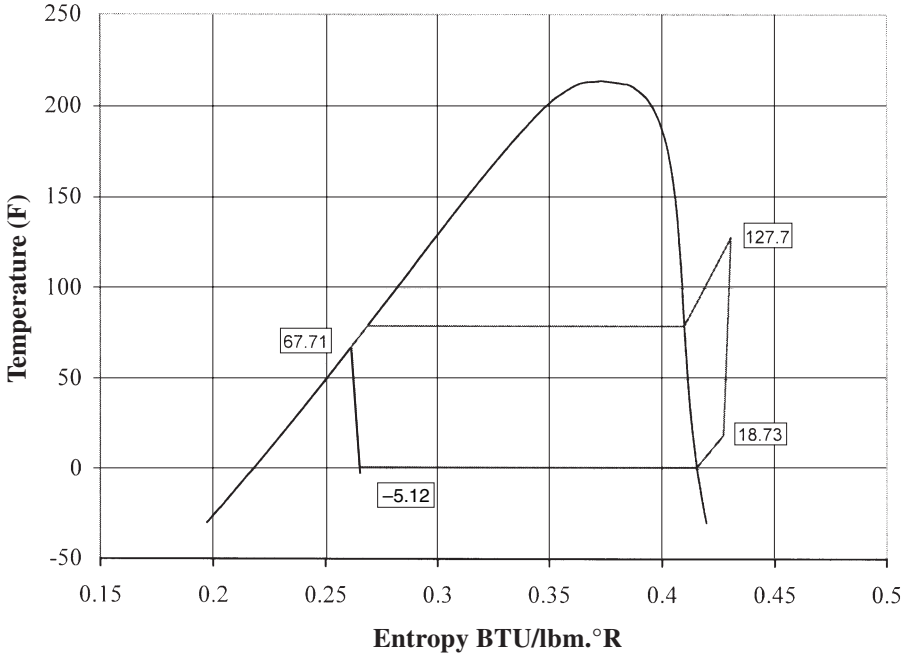


Fig. 4 The actual vapor compression refrigeration cycle.

1. As can be seen from the figure, the actual cycle is somewhat different from the familiar ideal refrigeration cycle [3, p. 398]. This is due to heat gain through exposed tubes, pressure losses in lines and fittings, and a pressure drop through the orifice in the flow meter. In addition, there is a slight amount of superheat between the evaporator output and the compressor inlet, in order to ensure that no liquid enters the compressor. This additional superheat is a built-in safety factor, and is regulated by the TXV.

Conclusion

The 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 IPFW. The experimental apparatus is portable

and can be used for laboratory experiments and classroom demonstrations. The sample results show that the apparatus is well designed for its intended purpose of demonstrating basic thermodynamic processes and principles.

Acknowledgement

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