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Refrigeration Cycle Educational Training Unit Development

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ABSTRACT

Refrigeration cycles are vital in today's industrial and domestic life. Many applications including, but not limited to, residential air conditioning, shopping malls heating ventilation and air conditioning, and food and liquid refrigeration operate with refrigeration cycles. Students graduating with a mechanical engineering technology degree, such as associate, bachelor, or technical certificate need to have sufficient hands on experience with refrigeration cycle operation, trouble shooting, analysis and optimization.

An ASHRAE grant was awarded to modify a 12,000 BTU "TRIPP LITE" portable air-conditioning unit to setup a teaching laboratory experiment related to refrigeration cycles. The experiment was equipped with pressure and temperature sensing apparatus to help in analyzing, troubleshooting, and operating various refrigeration cycles

Thermodynamics and heat transfer principles are applied to evaluate cycle efficiency, compressor power, and temperature rise and drop though the evaporator and condenser. The relative working pressures are plotted on pressure-enthalpy diagram of R410A refrigerant which was used inside the refrigeration cycle. Experimental informational outcomes will help students to understand theoretical principles in an experimental environment besides learning how to use some other equipment such as sensors, pressure gages, mass flow meter, and multi-meters. This paper presents thermodynamic refrigeration equations, experimental setup and a case study with different input variables.

Students in different courses would apply thermodynamics and heat transfer principles to evaluate cycle efficiency, compressor power, and temperature rise and drop across the evaporator, condenser, compressor, and throttling valve. The experiment not only will help the students visualize the cycle on a P-h diagram but will also provide an opportunity to compare the theoretical values, such as power consumed, EER, COP of the cycle, to the actual values obtained by the running unit.

INTRODUCTION

Experimental design and testing of theoretical aspects in a lab oriented class is an effective approach used in technological applications and research and development. Some applications include design and development of electric motors [1], medical devices, and technological processes [2-4], aircraft engines [5] and bike-frames [6].

Thermodynamic refrigeration cycles are widely used in many applications such as air conditioning systems, thermal storage systems, supermarkets, district cooling, industrial refrigeration, domestic fridges, bottle coolers, heat pumps, and automotive air conditioning systems. The basic elements of a refrigeration cycle are shown in Figure 1 while operating under summer conditions providing cold air to an enclosed space and rejecting hot air to the surrounding environment. This cycle could be reversed to supply hot air to the same enclosed space during winter season when hot air is required. The later is called a heat pump.

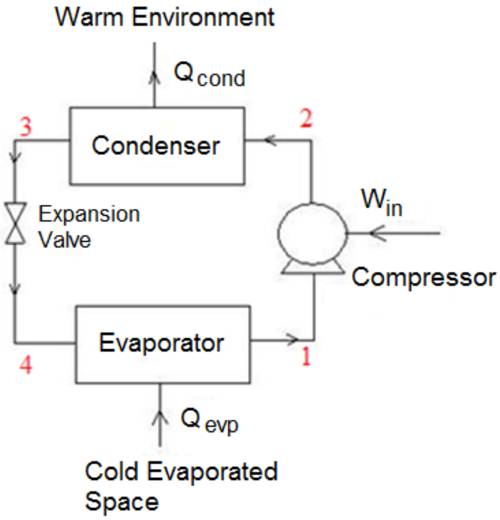


Figure 1. Refrigeration cycle basic elements operating in summer season providing cool air to an enclosed space

Relation between the cycle performance and air temperatures going through the evaporator and condenser is of interest for designers and application engineers when selecting a cooling unit for a specific place. Changing a single control parameter while keeping the others fixed is usually used although it does not provide the most accurate results. This one-factor approach usually provides advantages only under specific condition [7].

The different thermodynamic properties of the refrigerant operating the cycle are usually plotted on a P-h (pressure-enthalpy), P-T (pressure-temperature) diagrams and charts or T-s (temperature-entropy) as shown in Figure 2. Students usually work an in-class example during their course work and most of the cycles that they analyze are theoretical.

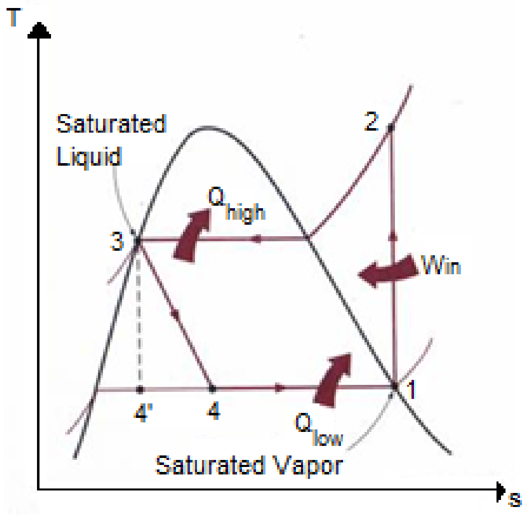


Figure 2. An example of the relations between different thermodynamic properties of the refrigerants

Most refrigeration or air conditioning units built for educational purposes would cost between $28,000 [8] (such as ET 915 HSI training system refrigeration and air conditioning technology, base unit) to $58,000 [9] (such as ET 411 C – Compression refrigeration system) excluding shipping and other auxiliary cost. Many departments are lacking the required funds to purchase such units and thus the students might miss the opportunity of dealing with hands on activities to measure pressures, temperatures, compressor works, etc. if no module is available. A small grant of $4,250 was awarded by ASHRAE (American Society for Heating, Refrigeration and Air-conditioning Engineers Inc.) to the author of this paper to modify and upgrade an existing portable 1-ton air-conditioning unit developing a refrigeration trainer unit. The trainer unit would help students analyze a one stage refrigeration compression cycle (RCC). Applications of the RCC systems are wide and include domestic and industrial or residential and non-residential buildings. The ultimate objective was for the students to understand the relation between pressure, temperature, and enthalpy under various air temperatures. This would ultimately help the students have an understanding of the energy consumption and the coefficient of performance of the cycle. The following are the expected learning outcomes for students who conduct the experiment using the modified unit:

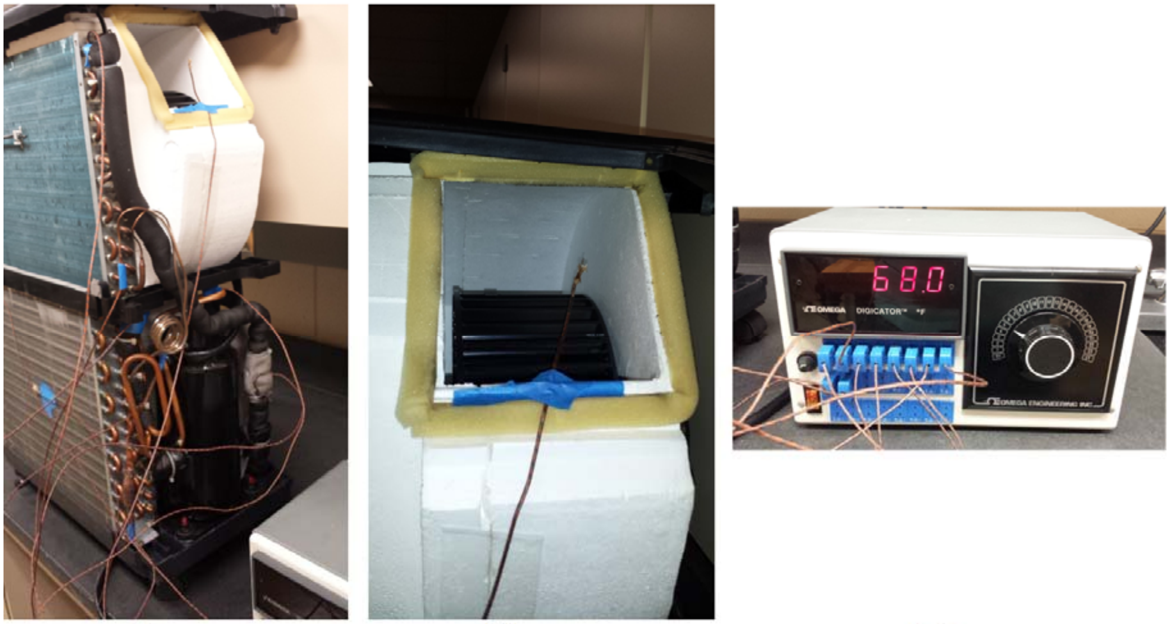
I. Understanding thermodynamic and other relations that govern refrigeration cycles
II. Improving students' measurements and control skills
III. Improving students' computer skills and simulation capabilities
IV. Improve students' understanding of other topics such as heat transfer and fluid dynamics

EXPERIMENTAL SETUP

A portable air-conditioning unit with a 12000 Btu capacity, brand Tripp Lite and model SRCOOL12K was used as the testing unit as shown in Figure 3. The following are the brands and models for the main units inside the AC unit: compressor model is LR3 – KA-C115ABBC-E (115 V – 50 A), fans are LIAN DA, Evaporator is MD781AL and condenser is MD711AL.

Figure 3. Portable AC unit modified to build the air-conditioning trainer

Seven thermocouples were initially installed after removing the outer shell of the unit (Figure 4a and 4b). The thermocouples were connected into a 24-channel omega thermocouple temperature reader in Figure 4c.



(a) (b) (c)

Figure 4. Thermocouples installed at different positions (a & b) and plugged into a thermocouple temperature reader (c)

Pressure quick disconnects were welded to the refrigerant lines as shown in Figure 5 and 6. Pressure gages are currently installed to allow pressure reading and the pressure disconnects would allow future pressure transducer installation which could be connected to an Arduino or a DAQ system that allows bigger data storage and analysis. Six pressure gages were installed as shown in Figures 7 and 8. The project cost was around $4,295 as shown in Table 1.

Figure 5. Quick disconnect connectors welded into the refrigerant pipes

Figure 6. Pressure gage with quick disconnect welded into its inlet connection

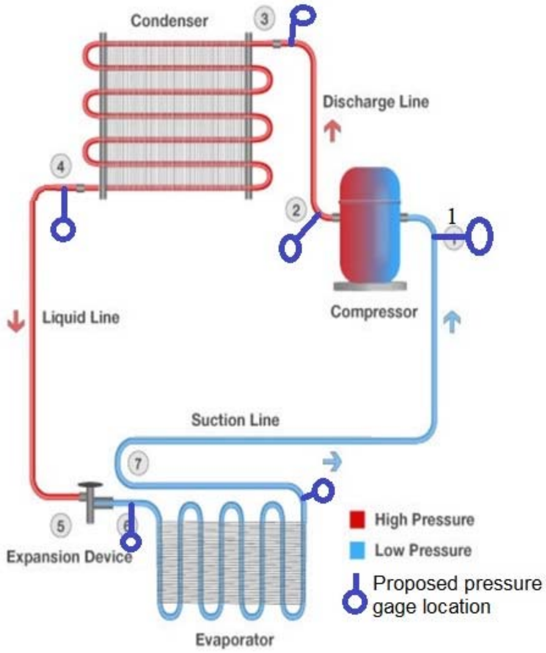


Figure 7. Pressure gage locations with reference indexing to be used in the analysis equations

Figure 8. Pressure gages welded into the refrigerant pipes

Table 1. Bill of materials

Part Name / Work	**Qty**	**Unit Cost**	**Cost**
Quick connectors	7	$ 35	$ 245
Pressure gages	7	$ 55	$ 385
Pressure transducers	7	$ 85	$ 595
Arduino	2	$ 50	$ 100
DAQ System	1	$ 600	$ 600
Welding and other work	1	$ 1,000	$ 1,000
Refrigerant discharge and recharge	1	$ 400	$ 400
Flow meter	1	$ 150	$ 150
Multi-meter & power meter	2	$ 35	$ 70
Consumables	1	$ 750	$ 750

Expected Learning Outcomes and Link to the Project Objectives

Students were given several set point temperature to set the unit at and were asked to record the pressures and temperatures along the refrigerant lines, before and after the evaporator, condenser and compressor, the flow rate of air entering and leaving the condenser and evaporator, and the power consumed by the compressor and the unit. The following are more specific learning outcomes categorized as per the objectives listed in the "Introduction" section of this paper.

1) Objective # I: Understanding thermodynamic and other relations that govern refrigeration cycles
    a. Reading pressures and temperatures
    b. Plotting the points on p-h diagram
    c. Estimating the cooling load by applying energy balance across the evaporator

$$\mathrm{q_{evp}} = \mathrm{\dot{m}_{ref} C_{p,ref}(T_7 - T_6)} = \rho_{air}\mathrm{\dot{Q}_{air} C_{p,air} \Delta T_{evp}} \tag{1}$$

where qevp is the evaporator heat transfer rate, $\dot{m}_{ref}$ is the refrigerant mass flow rate, C_p is the specific heat, $(T_7 - T_6)$is the temperature difference across the evaporator as defined in Figure 7, ρ_{air} is the density of air, $\dot{Q}_{air}$is the volumetric flow rate of air entering and leaving the evaporator, and ΔT_{evp} is the temperature difference of air across the evaporator. The later temperature difference was measured by taking the average of several temperature readings across the evaporator inlet surface and by measuring the temperature at the air supply outlet as shown in Figure 4b. The volumetric flow rate was measured by taking multiple air speed measurements using a digital anemometer and multiplying it by the corresponding area as shown in equation (2).

$$\dot{Q}_{air} = A.V \tag{2}$$

where A is the cross sectional area of the evaporator unit or the supply air duct and V is the velocity. Since the velocity changes between the center of the evaporator cross section and the cross section, it was recommended to measured it at different points and then average the readings (meets Objective II as well: Measurements Skills)

    d. Evaluating the coefficient of performance COP of the cycle using equation (3).

$$\mathrm{COP} = \frac{q_{evp}}{W_{in}} \tag{3}$$

where W_{in} is the total power consumed by the unit and is measured using a power meter plugged directly to the power inlet or using a multi-meter and measuring the voltage and current at different points (meets Objective II as well: Measurements Skills)

2) Objective # II: Improving students' measurements and control skills
    a. Measuring pressures and temperatures and installing pressure transducers to be all connected to an Arduino and storing the data.
    b. Measuring voltage, current and power at different points.
    c. Estimating the airflow rate entering and leaving each of the condenser and evaporator.

3) Objective # III: Improving students' computer skills and simulation capabilities
    a. Plotting the COP versus load and set temperature: Simulation can be then done by changing the evaporator air outlet and inlet temperatures and checking on the COP change of the cycle. This would give the students an understanding of the cycle efficiency. At the same time, the students would evaluate the work into the compressor, the load removed by the evaporator, the load rejected by the condenser and enthalpy drop in the capillary tube using the P-h diagram.
    b. Assigning projects to connect the thermocouples into ARDUINO unit and connecting it to a computer to download the data.

4) Objective # IV: Improve students' understanding of other topics such as heat transfer
    a. Reading the enthalpies from P-h diagram
    b. Repeating the above procedures while setting the unit set temperature to different set points and comparing the COP and making observations and conclusions.
    c. Setting the unit to a higher set temperature than the actual surrounding temperature while in cooling mode and analyzing the performance of the compressor.
    d. Applying heat balance for the compressor, evaporator, and condenser.
        i. Evaporator: reading the enthalpies h_7 and h_6 and comparing the answer using equation (4) to that in equation (1), the refrigerant mass flow rate would be determined. The State subscripts for each enthalpy is as indicated in Figure 7.

$$q_{evp} = \dot{m}_{ref}(h_7 - h_6) \tag{4}$$

        ii. Compressor: Reading the two enthalpies before and after the compressor from the plotted p-h diagram and using it in equation (5), the work done by the compressor could be determined. Subtracting the total power from the compressor power would indicate the remaining power being consumed by the fans and other auxiliary components.

$$W_{compressor} = \dot{m}_{ref} \times (h_2 - h_1) \tag{5}$$

iii. Fans: using a multi-meter, the voltage, current and power across each auxiliary fan could be measured. A total power consumption could be done using the measured power for each fan and for that by the compressor and compared to the power being pulled by the unit using a power meter plugged to the power inlet into the AC unit main power cord.

iv. Condenser: similar to the evaporator, an energy balance across the condenser could be done as shown in equations (6) and (7).

$$\mathrm{q_{condenser}} = \dot{\mathrm{m}}_{\mathrm{ref}}\, \mathrm{C_{p,ref}}\, (\mathrm{T_3} - \mathrm{T_4}) = \rho_{air}\, \dot{\mathrm{Q}}_{\mathrm{air,c}}\, \mathrm{C_{p,air}}\, \Delta\mathrm{T_{air,c}} \tag{6}$$

$$\mathrm{q_{condenser}} = \dot{\mathrm{m}}_{\mathrm{ref}}\, (\mathrm{h_2} - \mathrm{h_1}) \tag{7}$$

where $\dot{\mathrm{Q}}_{\mathrm{air,c}}$ is the air volumetric flow rate passing through the condenser unit or leaving through the exhaust out from the unit and $\Delta\mathrm{T_{air,c}}$ is the air temperature different between the inlet at the condenser face and the exhaust port from the unit.

Numerical Example

The following data was recorded using the modified unit. Voltage and amperes across different components would need to be measured and compared to the system measurements for further analysis.

Compressor		
Volumetric Flow Rate	0.12	m^3/hr
Inlet Pressure (P1)	180	psi
Outlet Pressure (P2)	230	psi
Inlet Temperature (T1)	62.8	F
Outlet Temperature (T2)	150	F
		Watts
		Amp (A)

Evaporator		
Ref. Flow Rate	0.12	m3/hr
Inlet Pressure (P6)	180	psi
Inlet Temperature (T6)	47.6	F
Outlet Temperature (T7)	53.2	F
Air Flow Rate	372	CFM
Fan		V
		Amp (A)

Condenser		
Ref. Flow Rate	0.12	m3/hr
Outlet Pressure (P4)	230	psi
Inlet Temperature (T3)	120	F
Outlet Temperature (T4)	72.1	F
Air Flow Rate	418	CFM
Fan		V
		Amp (A)

	Measure		
Temperatures	T1	62.8	F
	T2	150	F
	T3	120	F
	T4	72.1	F
	T5	75.2	F
	T6	47.6	F
	T7	53.2	F
Pressures	P1	180	psi
	P2	230	psi
	P4	230	psi
	P6	180	psi

System		volts
		Amps
	520	Watt

After measuring the different temperatures and pressures, the enthalpy at different states were read and recorded in Table 2.

Table 2. Enthalpies read from R410A p-h diagram

h1	134	Btu/lb
h2	146	Btu/lb
h2s	143	Btu/lb
h3	137	Btu/lb
h4	45	Btu/lb
h5	42	Btu/lb
h6	42	Btu/lb
h7	127	Btu/lb

Conclusions

A relatively low cost affordable educational air-conditioning and refrigeration trainer unit was developed to assist students in the mechanical engineering technology program apply thermodynamic relations and heat transfer principles in an active learning environment. The unit was developed to allow pressure and temperature reading which would allow the determination of actual performance of the unit and the efficiency when using the power consumed by the unit. Compared to commercially available similar models, the developed unit provides a very attractive tool for educators especially when funding is limited as it provides a similar educational unit with an approximate cost that is 5-10 times less.

Several component performances could be evaluated through the usage of the developed unit such as the evaporator, condenser, the compressor and the system in whole. Through the different applications and activities, the students learn the principles in an applied environment, experience the challenges and characteristic of each component and make observations based on experimental and actual data rather than just theoretical principles.

This paper provides a tool that can be used in many courses such as heat transfer, heat and power, thermodynamics, refrigeration and air-conditioning, and fluid mechanics.

Acknowledgement

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