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A Simple, Economic Refrigeration Lab for Thermal/Fluids Courses

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Abstract

Commercially available laboratory equipment is often expensive, may have long acquisition times, and often serves a narrow or single purpose. In order to enrich the student learning experience with hands-on experiments, as opposed to computer-based simulations and virtual experiments, engineering programs often dedicate considerable resources to obtain or modernize laboratory equipment. There are competing resources from budget administrators and lab space managers while constantly trying to provide the best learning environment for the students. Typical refrigeration training systems can cost well over $10,000 and require significant lab space. In this paper, a simple, low-cost, and portable refrigeration exercise for undergraduate thermal/fluids laboratories is presented. The purpose of the refrigeration apparatus is to elucidate thermodynamic processes and make connections to real-life systems, which are essential to understanding the basic concepts of thermodynamics, such as the first and second laws of thermodynamics. This paper presents the concept and the design for an inexpensive experimental kit that makes the dynamic study of thermodynamic processes more accessible to undergraduate mechanical engineering students. The proposed laboratory device requires easy modification of inexpensive, commercially available consumer equipment. A portable ice maker, digital multimeter, and a thermocouple are the only required pieces of equipment. Students are supplied a multimeter and thermocouple and tasked to measure the temperature between all four components of a simple vapor compression system. They are required to use refrigeration tables to determine parameters such as coefficient of performance or refrigeration capacity. It allows the students to connect the theoretical equations and look-up tables used to model a process and observe the true performance experimentally. The hands-on nature provides a link between the mathematical representation and the physical experiment to increase student understanding. The total system costs less than $300, and the equipment can easily be stored from year to year. Sample lab data, analysis, and questions are provided for the interested reader. Lab objectives are mapped to ABET student outcomes as well.

Introduction

Lab exercises are an essential component in engineering education. Students develop a deeper understanding of the subject through a hands-on approach with real-world items. However, lab activities sometimes become too focused on equipment rather than learning. Lee and Ceylan [1] note how student learning becomes passive rather than active when students follow cookbook approaches with large pieces of equipment and no prior operating experience. From an administrative standpoint, what is the point in purchasing and maintaining costly and large experimental equipment that students will only interact with for a few hours during their entire undergraduate education? The ASME Vision 2030 [2] suggests that Mechanical Engineering curricula must encourage and provide opportunities for active discovery-based learning in order to meet the demands of the profession into the future.

Each successive generation is more comfortable with technology than the last [3], but that also leads to shorter attention spans, a lower threshold for boredom, and a resistance to memorization and homework [4]. Learning styles of these students are more visual and active rather than verbal.

Given the characteristic preferences of these students, educators are exploring different and innovative teaching strategies that effectively address students in terms that they easily recognize and comprehend. For effective instruction to follow, educators should accommodate the needs of the learner. Brown suggested that authentic learning requires the learner to communicate detailed understanding of a problem or issue rather than memorize sets of isolated facts, and it must result in achievements that have relevance beyond the classroom [5].

Background

Instructors and students often dislike solving simple textbook problems that have limited relevance to the real world. To increase student interest, creativity, and to promote the hands-on experience, open-ended labs were developed at The Citadel to foster problem-solving skills. This approach allows students to formulate and investigate their own realistic, inventive, and complex problems. This methodology has not only increased student enthusiasm, but has allowed many to further investigate a real world problem they had encountered or to implement new ideas into their senior design projects.

Originally, labs were not well-developed and were very basic throughout the first year that the course was offered. In 2016, more emphasis was given to the lab experience, using just-in-time instruction to address key concepts and topics, given the breadth of the material. Students were required to complete exercises that reinforced material from the lectures and instructors gave them a demonstration of a solution as a preview of the actual lab activity. This sequence was repeated for each lab, which strengthened their understanding of the material and helped make demonstrations go smoothly on lab day.

This course originally attempted to cover a wide range of topics with minimal deep learning from labs or hands on material. Caudron [6] suggested that educators consider the following five areas when teaching students, and many of these strategies are exemplified in the improvement of this class:

(1) Make learning experiential by engaging students in cooperative learning experiences.
(2) Give students control of their learning.
(3) Highlight key points since new learners are surfers and scanners rather than readers and viewers.
(4) Motivate learning by engaging students in their own learning environment.
(5) Challenge students to construct knowledge from their experiences.

In thermal/fluids courses, a refrigeration lab is usually a standard activity. While costs of refrigeration training systems vary based on features and quantity purchased, most standard systems are well over $10,000. This alone can be a burdensome up-front cost, but there are also maintenance costs over the life cycle of the unit(s) along with difficulty finding suitable storage locations. In this paper, a refrigeration lab is proposed that costs less than $300, and yet may be a more useful activity for students than expensive and bulky training systems. The structure of the paper is as follows. First, basic vapor compression cycles are reviewed, followed by a description of the lab equipment and exercise. Next, sample results are provided, and finally, potential mappings of this lab experiment to ABET student outcomes are given.

Vapor Compression System Analysis

Prior to the lab exercise, it is highly recommended that students have learned the ideal and actual vapor compression system cycles. This is standard material in any undergraduate thermodynamics textbook, e.g. Cengel and Boles [7] or Moran et al. [8]. The ideal cycle is depicted in Fig. 1 schematically and on a T-s diagram. States 1, 2, and 4 are replaced by 1a, 1b, 2a, 2b, 4a, and 4b for measurement purposes discussed later in the paper. In the ideal cycle, state 1 lies on the saturated vapor line. The refrigerant is compressed isentropically to superheated vapor at state 2. The refrigerant condenses at constant pressure to state 3, and enthalpy is assumed to remain constant through the expansion valve before the refrigerant returns through the evaporator to state 1 at constant pressure.

Knowledge of two thermodynamic state variables enables all other variables at that state to be obtained. For example, if the pressure and entropy are known at state 2, then the enthalpy and temperature could be determined from charts or tables for the refrigerant. Once all of the enthalpies are known, quantities such as work input to the compressor and heat removed can be determined using Eqs. 1 and 2. The ratio of these quantities gives the coefficient of performance as in Eq. 3.

$$\dot{Q}_{\mathrm{in}} = h_1 - h_4 \tag{1}$$

$$\dot{W}_{\mathrm{in}} = h_2 - h_1 \tag{2}$$

$$\mathrm{COP}_{\mathrm{R}} = \frac{\dot{Q}_{\mathrm{in}}}{\dot{W}_{\mathrm{in}}} = \frac{h_1 - h_4}{h_2 - h_1} \tag{3}$$

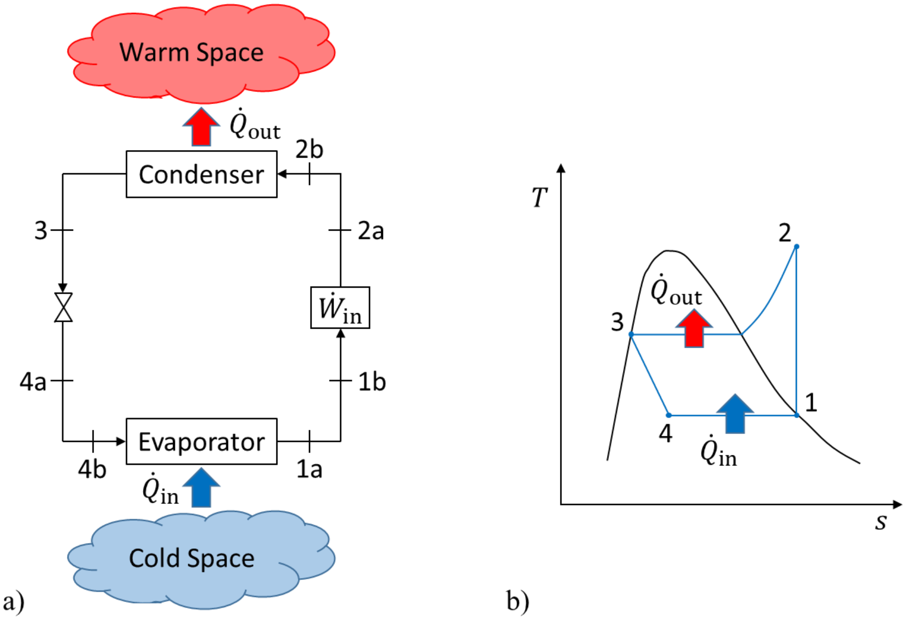

Fig. 1: a) Schematic and b) T-s diagram for an ideal vapor-compression refrigeration cycle.

The actual vapor compression cycle is an alteration from the ideal cycle due to irreversibilities and smart planning by engineers to protect the system components. At the inlet to the compressor, the refrigerant is slightly superheated to ensure that no liquid enters the compressor. The actual compression is not reversible or adiabatic so it is not isentropic. State 3 is slightly subcooled to ensure pure liquid enters the throttling valve. A T-s diagram more representative of an actual refrigeration cycle is given in Fig. 2.

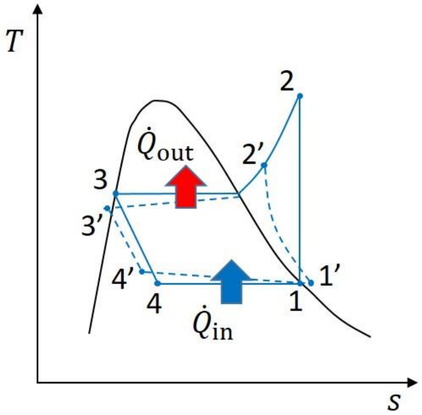

Fig. 2: T-s diagram for an actual refrigeration cycle. The solid line represents the ideal cycle and the dashed the actual cycle. The altered states are denoted by a prime, e.g. 2'.

Experiment Description

The equipment required for the experiment can be purchased at low cost and easily stored. Approximate costs for the required laboratory components are provided in Table 1. The total cost per laboratory kit is under $300, and each kit can be stored in under one cubic foot of space.

Table 1: Refrigeration Laboratory Kit Costs

Item	Cost
Magic Chef ® 27-Lb. Countertop Ice Maker	$130
Type K Thermocouple (Multimeter included)	$150

During the lab, students are given an ice maker with the back panel removed and a type-K thermocouple with a multimeter. They are tasked with determining the coefficient of performance of the unit. It is at the discretion of the instructor on how much information to provide students with respect to identifying components. At the very least, the instructor may want to warn students that properties change along the length of tubing, and they ought to consider measuring immediately before and after each component to obtain the best data on performance. Figure 3 shows each of the four main components on the ice maker. Rather than passively receiving an abstract description of the processes, students are able to test the equations on real equipment, learn the limitations of the analysis and data acquired, and improve their overall understanding of the material.

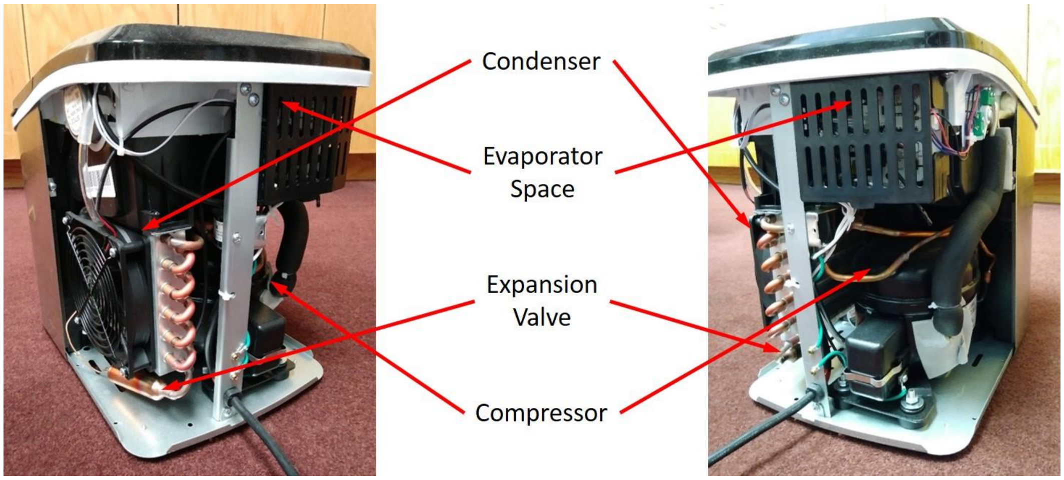

Fig. 3: Ice maker with back plate removed to expose refrigeration components. Main components are labeled.

Sample Results

The properties of R-134a (refrigerant for this particular unit) can be determined by temperature measurements only if the ideal cycle is assumed. As mentioned previously, state 1 in an actual vapor compression system is slightly in the superheated region to ensure the refrigerant is completely vaporized before entering the compressor. However, with no means of determining pressure without tapping the lines, it is assumed state 1 is at saturated vapor conditions. In going from state 1 to 2, there may be an increase or decrease in entropy, but an isentropic assumption is necessary. The refrigerant will experience some pressure drop through the condenser, and actual systems operate with the refrigerant subcooled at state 3 to ensure a completely condensed liquid prior to the throttling valve. Again, with no means to determine pressure, the ideal cycle with equal pressures at state 2 and 3 is required. Finally, there is a small drop in pressure from state 4 back to state 1, but constant pressure must be assumed here as well. Table 2 provides sample measurements and properties from the ice maker. Whenever possible, measurements were taken immediately before or after each component (hence states 1a and 1b, etc. as in Fig. 1a)

Table 2: Temperature Measurements and R-134a Properties[*]

State	T, °C	p, kPa	h, kJ/kg	s, kJ/kg-K
1a	-10.8	192.29	244.03	0.9385
1b	-4.8	245.49	247.62	0.9342
2a	38.9	704.5	287.43	0.9920
2b	31.5	704.5	280.06	0.9688
3	26.9	704.5	89.12	0.3333
4a	27.7	192.29	89.12	-
4b	16.1	192.29	89.12	-

[*] Assumes saturated states at 1 and 3 and constant pressures across the evaporator and condenser

Using the data in Table 2, Eqs. 1-3 can be applied to determine the specific work of the compressor, specific heat transfer in the evaporator, and the coefficient of performance. These values are given in Table 3. The mass flow rate of the refrigerant would need to be known to compute actual work and heat transfer. If these quantities were known, the work could be compared to the listed product specifications for the compressor.

Table 3: Calculated Values

$\dot{W}_{\text{in}}$, kJ/kg	$\dot{Q}_{\text{in}}$, kJ/kg	COP_{R}
39.81	154.91	3.89

The accuracy of the thermodynamic properties could be improved if pressures were determined by tapping the lines. Mass flow rates could be found similarly, and this would enable work comparisons with listed specifications. While most universities have certified maintenance staff that could perform these modifications, they are probably not worth the extra expense and risk. For example, a mass flow meter and pressure gauge would both cost on the order of hundreds of dollars. Additionally, a certified refrigeration technician would also cost on the order of hundreds of dollars per hour. The modifications would easily cost more than the entire unit itself. There is the risk that the unit may not function properly after the modifications as well. Additionally, this device is used just several times each year and remains in storage most of the time. Once the system is "opened" for meter and gauge installation, there are the concerns for refrigerant leaks and additional humidity. The authors feel these concerns do not outweigh the benefits of having a readily available refrigeration apparatus. Students can obtain reasonable values for enthalpy and overall coefficient of performance from temperature measurements alone. The hands-on process of identifying components and direction of refrigerant flow is the invaluable portion of the exercise, and this is not compromised by missing flow rates or pressures. Additionally, students can be asked to estimate the impact of their idealized numbers on their results.

Mapping to ABET Student Outcomes

Laboratory exercises in engineering are typically mapped to one of two ABET [9] student outcomes: (b) *an ability to design and conduct experiments, as well as to analyze and interpret data* or (g) *an ability to communicate effectively*. This exercise is no exception as the data collection and analysis phase easily maps to outcome (b) and any formally submitted documentation of the exercise maps to (g).

However, this exercise also tests outcome (a) *an ability to apply knowledge of mathematics, science and engineering*, especially if students are required to explain how their results might differ if they had the ability to determine pressure at various points in the unit. The lab can alternatively be mapped to outcome (k) *an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice* as well. Thermodynamics property tables are now accessible from MATLAB, C++, or nearly any other language. Students could be required to perform their analyses in a computer program that uses calls to thermodynamics databases to determine properties.

Assessment of Student Learning

The lab exercise was conducted for the first time in the current academic year. Thus, at the time of writing this paper, the authors have an incomplete picture on student learning. In terms of immediate results, approximately 40% of students were able to obtain COP values within 20% of values obtained by the instructors. One of the biggest mistakes students made was incorrectly reading the refrigerant tables in determining their enthalpy values. Approximately 78% of students obtained COP values that could be considered reasonable.

To assess long-term impact of the activity, the change in student performance on the refrigeration problem on the final exam for the course will be monitored. These exams are not returned to students and remain largely unchanged from year to year so this will serve as an outstanding historical gauge. An exam question may also be added where students must identify various parts from a photo of an actual refrigerator. This will demonstrate students' ability to move beyond textbook schematics of refrigeration systems to actual systems. Despite the incomplete picture on assessment, the authors can report that students were generally enthusiastic about the lab activity. In particular, students like the open-ended nature of the lab rather than following a prescriptive set of instructions. Due to the positive response, the lab is scheduled to move forward next year with additional refrigeration units and instructor checks in place to ensure students use the refrigerant table properly. This lab was not an embedded indicator for the program's student outcomes (ABET a-k) this year due to its first use. However, the awareness gained from it scaffolds future knowledge and contributes to some ABET outcomes. The engineering program will consider this lab as an embedded indicator when it remaps to new student outcomes after this academic year (ABET 1-7).

Summary

This paper describes recent development of a hands-on, laboratory exercise in a Thermo-fluids course. The benefits of using real world equipment for the lab provide curiosity among students and enthusiasm among faculty. As students were able to measure physical parameters on a real world device, they began to see utility in their lab experience. This drives student engagement, as they become invested in the lab, and the open-ended nature of the problem promotes the idea that students must continually strive to update their skills throughout their careers. The short term goals are to evaluate existing coursework and integrate more applications and labs that could make an impact on the students' learning. There are many opportunities to improve the course, but initially focusing on the lab exercises has shown that teaching effectiveness can be improved. The careful selection of the lab and requirements promoted depth of student understanding and engagement that would not have been possible with a lecture.

A low-cost and portable alternative to large refrigeration training systems has been described. All equipment for the lab exercise can be purchased for under $300. In order to determine the coefficient of performance for the unit, students must identify individual parts of the refrigerator, take temperature measurements, and then determine thermodynamic properties from tables. The sample results show that the apparatus is well designed for its intended purpose of demonstrating basic thermodynamics processes and principles. The lab can be mapped to several ABET student outcomes.

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