Engineering design experience of an undergraduate thermodynamics course

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ABSTRACT: One important educational outcome required of any engineering programme, as per ABET 2000 Criteria 3, is the ability of engineering graduates to design a component or a system. Engineering design is an integral part of several mechanical engineering courses throughout the curriculum at King Faisal University (KFU). Presented in this article is an example of engineering design experience in an undergraduate first thermodynamics course. It presents a thermodynamics initial design of a refrigeration system that meets desired needs. Basic thermodynamics principles such as the first and second laws, isentropic efficiency, and coefficient of performance (COP) were employed in the analysis, leading to the initial design of this refrigeration system.This kind of experience serves to enhance the understanding of the various thermodynamics concepts and principles.

INTRODUCTION

For an engineering curriculum to be successful, it must provide students with the opportunity to be exposed to engineering design. In addition, ABET 2000 Criteria 3 requires that for an engineering programme to be accredited, it must demonstrate that appropriate educational programme outcomes are met. According to these criteria, all undergraduate engineering programmes need to provide for design experience. This fact is stated in outcome c): *an ability to design a system, component, or process to meet desired needs* [1]. To meet the requirements of the ABET accreditation criteria, the mechanical engineering academic staff at KFU have integrated engineering design throughout the curriculum, spanning freshman, sophomore, junior and senior level courses.

Thermodynamics is a very important subject and has long been an essential part of mechanical engineering curricula all over the world. Thermodynamics is encountered in a wide variety of engineering applications where heating, cooling and refrigeration is required. Thermodynamics plays an important role in the design of many devices, such as radiators, heating and air conditioning systems, refrigerators, power plants and many others.

Objective

Discussed in this article is a design project set for students of Mechanical Engineering at KFU. The objective of this project is to obtain an initial design of a refrigeration system. This project is one of the requirements of the Thermodynamics I class. Thermodynamics I is a mechanical engineering sophomore level course. This project is very comprehensive and requires the understanding of most thermodynamics concepts that were covered in the course in order to obtain a successful design [2-4]. The following is the problem statement of the design project that was given to the students.

Problem Statement

A refrigeration system is to be designed to maintain the temperature in the range -15°C to -5°C, while the outside temperature varies from 15°C to 25°C. The total thermal load on the storage unit is given as 20 kW. Obtain an initial design for the vapour compression refrigeration system shown in Figure 1. Choose a safe and suitable refrigerant. For safe operation and other factors, such as additional energy transfer, design the system using a safety factor of 1.3. The compressor efficiency could range from 60 to 80 percent.

Need to specify or/and determine the temperatures and pressures at the different states and show the cycle with the vapour dome on a temperature entropy (T-s) diagram. Also, need to determine the coefficient of performance value and the mass flow rate of the working fluid.

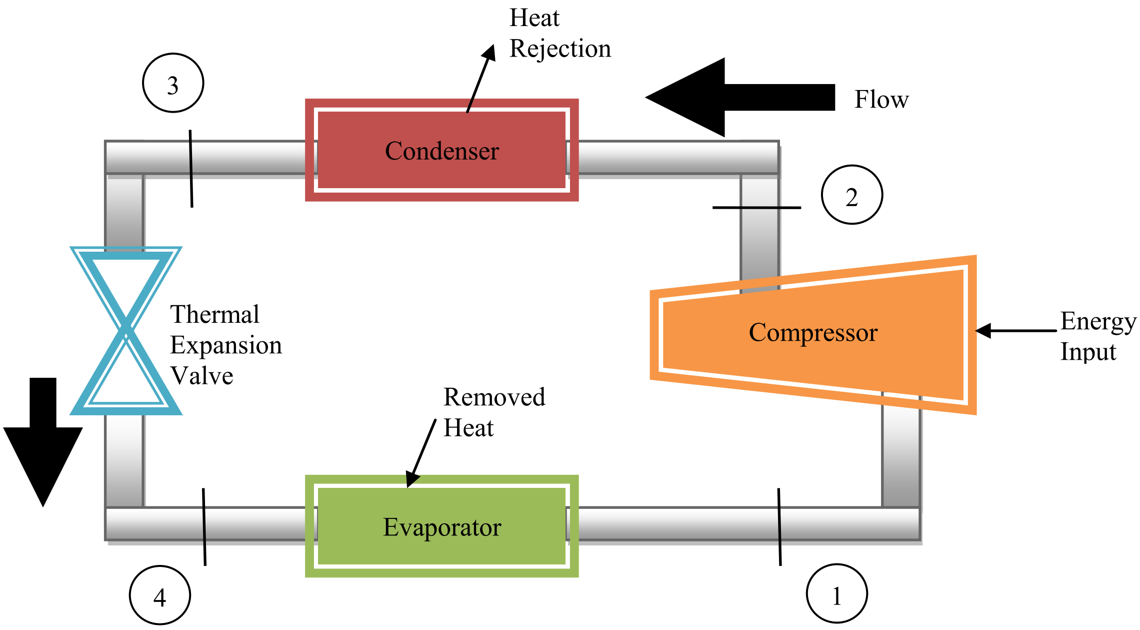

Figure 1: Vapour compression refrigeration cycle.

Background

Refrigeration Cycle

A basic refrigeration cycle consists of four major components: a compressor, a condenser, a thermal expansion valve and an evaporator [3]. As a refrigerant passes through a cycle containing these four elements, air conditioning occurs. The cycle starts when refrigerant enters the compressor at low pressure, low temperature and in a gaseous form. The refrigerant is compressed by the compressor to a high pressure and temperature gaseous state. The high pressure and temperature gas then enters the condenser. The condenser precipitates the high pressure and temperature gas to a high temperature liquid by transferring heat to a lower temperature medium, usually ambient air. The high temperature liquid then enters the expansion valve where the TX valve allows a portion of the refrigerant to enter the evaporator. In order for the higher temperature fluid to cool, the flow must be limited into the evaporator to keep the pressure low and allow expansion back into the gas phase.

Compressor

This component is a compression device that requires input of power to increase the pressure of a gas. It cannot operate on liquids or two-phase. Therefore, the working fluid such as the refrigerant must leave the evaporator and enter the compressor at least as saturated vapour.

Condenser and Evaporator

These devices are heat exchange devices [5][6]. They are used to transfer heat between two different fluids. The evaporator is used to remove heat from the interior of the refrigerator compartment by exchanging heat between the air inside the refrigerator and the refrigerant passing through the tubes of the evaporator. The condenser is used to remove the heat from the refrigerant gained through the evaporator and the compressor. This is done by transferring the heat to the ambient air, which must be at a lower temperature than that of the refrigerant exiting the condenser.

Thermal Expansion Valve

A thermal expansion valve (TEV) is a component in refrigeration and air conditioning systems that controls the amount of refrigerant flow into the evaporator, thereby, controlling the superheating at the outlet of the evaporator.

DESIGN METHODOLOGY

Assumptions

To obtain an initial design of a refrigeration system as requested by the problem statement, the following assumptions are made:

- The four components (compressor, condenser, evaporator, thermal expansion valve) of the thermodynamics cycle are modelled as open systems.

- The four components (devices) operate under steady-state, steady-flow process.
- The changes in kinetic and potential energies across each device are negligible.
- Both the compressor and the expansion device are considered adiabatic (i.e. the heat transfer from these devices is negligible).
- Both the evaporator and the condenser are considered constant pressure devices.

Thermodynamics Modelling

The basic concept of this design is to use a vapour compression cycle. Utilising the first and second laws of thermodynamics [3] along with the above mentioned assumptions, a thermodynamics model for the refrigeration system can be developed as follows:

Compressor: $$\dot{W} = \dot{m}\,(h_1 - h_2) \quad (1)$$

Condenser: $$\dot{Q}_{out} = \dot{m}\,(h_3 - h_2) \quad (2)$$

Evaporator: $$\dot{Q}_{in} = \dot{m}\,(h_1 - h_4) \quad (3)$$

Expansion Valve: $h_3 = h_4$ throttling process (4)

Where $\dot{W}$ is the power input to the compressor, $\dot{m}$ is the mass flow of the refrigerant, $\dot{Q}_{in}$ is the heat absorbed by the evaporator, $\dot{Q}_{out}$ is the heat rejected by the condenser and h is the enthalpy. In these relations the number refers to the state of the refrigerant as indicated in Figure 1.

The isentropic efficiency of the compressor, η, is defined as the ratio of the isentropic (ideal) work input required to the actual work input required for the same inlet state and the same exit pressure [3]:

$$\eta = \frac{h_1 - h_{2s}}{h_1 - h_{2a}} \quad (5)$$

The coefficient of performance (COP) for the refrigeration system is given by [3]:

$$COP = \frac{Q_{in}}{W} \quad (6)$$

Analysis

Refrigerant Selection

For an effective system, a refrigerant should be used to ensure necessary thermodynamics properties at the temperatures and conditions the system will be operating at, and to ensure increased efficiency. To determine which refrigerant to use, several factors should be considered. The refrigerant should not be toxic, it should not be flammable at the operating pressures and temperatures, it should be minimally environmentally degrading, and in general, it should not be harmful to humans.

Based on an intensive review and search of several refrigerants such as R-12, R-22, R-134a, R-410a, and ammonia, it was found that R-134a is a safe, no toxic refrigerant that is easy to obtain. Thus, it was selected to be the working fluid for this refrigeration system.

Design Parameters

To ensure that the system will operate over the entire temperature ranges stated in the problem statement, the refrigeration system was designed for the extreme conditions (i.e. -15^{o}C for the inside and 25^{o}C for the ambient). On top of that, a safety factor of 1.3 was also used as suggested by the design project statement. The isentropic efficiency of the turbine was selected to be 75%.

Design Procedure and Calculations

There are several thermodynamics and heat transfer facts that must be satisfied while deciding on the design [7][8]:

1. From basic physics, heat always flows in the direction of decreasing temperature and in order to have heat transfer there must be a temperature difference. Therefore, the temperature of the refrigerant in the evaporator tubes must be less than the air temperature inside the refrigerator and the temperature of the refrigerant at the exit of the condenser is higher than the outside ambient air.

To satisfy this, temperature of the refrigerant in the evaporator was selected to be -20°C (less than -15°C) and the temperature of the refrigerant at the exit of the condenser was selected to be 40°C (higher than 25°C).

2. As mentioned earlier, the compressor operates only on gases (not liquids or two-phase). Therefore, the exit of the evaporator must be at least saturated vapour ($x_1 = 1$).
3. The exit of the condenser must be at least saturated liquid ($x_3 = 0$).

Based on the above three facts, a thermodynamics model can be constructed and an initial design of a refrigeration system that satisfies the stated requirements can be obtained.

RESULTS

Detailed calculations were carried out utilising the relations and the thermodynamics model outlined in the above to obtain an initial design of a refrigeration system that meets the stated requirement. Table 1 includes the relevant thermodynamics properties at the inlets and outlets of the four components (devices) that comprise the vapour compression cycle of the refrigeration system. These properties are needed to determine the heat input to the evaporator, the heat rejected from the condenser, the work input to the compressor, the refrigerant mass flow rate and the coefficient of performance of the system. Table 2 is a summary of the initial design values of the refrigeration system that meets the specified requirements.

Figure 2 shows the vapour compression cycle of the designed refrigeration system on T-s phase diagram (temperature - entropy phase diagram) along with the vapour dome. Also, the figure shows both the actual and isentropic (ideal) compression of the refrigerant through the compressor.

Table 1: Thermodynamics properties at the relevant states.

State	T (°C)	P (KPa)	h (kJ/kg)	s (kJ/kg. K)	x
1	-20	132.8	238.4	0.94564	1
2s	48	1000	280.55	0.94564	N/A
2a	61.17	1000	294.6	0.98861	N/A
3	40	1000	107.32	0.39189	0
4	-20	132.8	107.32	0.4279	0.384

Table 2: Initial design values.

$\dot{Q}_{in}$ (W)	26
$\dot{Q}_{out}$ (W)	34.46
$\dot{W}_{comp}$ (W)	8.46
$\dot{m}$ (kg/s)	0.1895
COP	3.07

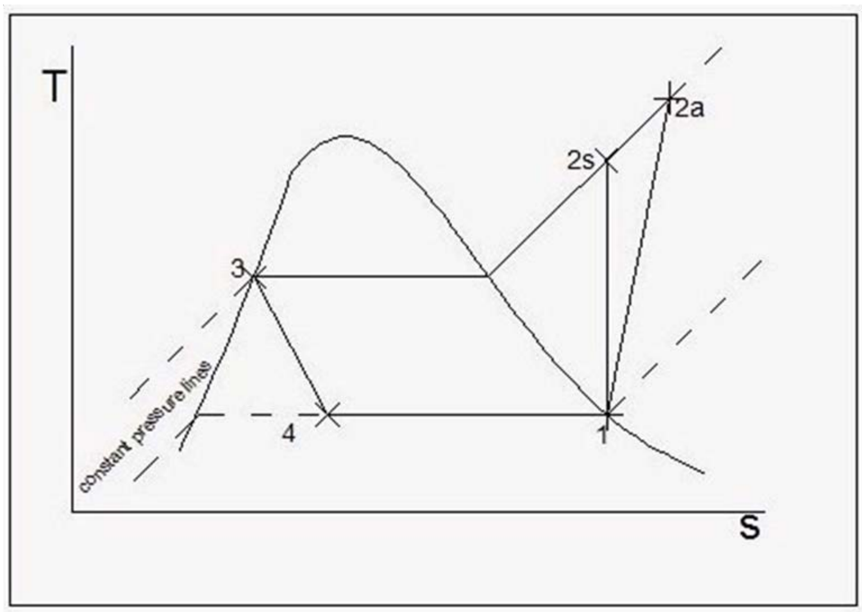

Figure 2: Vapour compression cycle on T-s phase diagram.

CONCLUSIONS AND RECOMMENDATIONS

A practical example of an engineering design project in the area of thermodynamics is presented in detail. The project involves an initial design of a refrigeration system based on a vapour compression cycle that meets specified requirements.

This type of design project can be used as a measure of students' understanding of the various thermodynamics concepts and principles normally covered in the undergraduate first thermodynamics course. Feedback from the students was very positive.

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