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Parametric Study of Cascade and Multi-Stage Vapor Compressor Refrigeration Systems Using a Matlab Guide

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Abstract

This paper shows the application of a software tool to promote the significant learning in refrigeration cycles in undergraduate engineering students through case studies. To solve the case studies the tool calculates in MATLAB® the thermodynamic states and energy balances of the simple vapor refrigeration cycle, the cascade, multi-stage, and absorption refrigeration cycle. In the case of a simple refrigeration system, a proportional behavior between the COP and the compressor's work was obtained as a function of the outlet temperature of the evaporator for compressor efficiencies of 100%, 80%, and 60%. In the case of the cascade refrigeration system, the behavior of both the energy consumed by the compressor and the thermal efficiency of the cycle is explained by the pressure at the inlet of the high compressor. In the multi-stage refrigeration cycle, the variation in the pressure of the flash chamber and the compressor efficiency did not affect the vapor fraction. Finally, the case studies obtained through the program facilitate the understanding of thermodynamic phenomena in refrigeration systems, which normally in a traditional classroom would require time and educational resources for their learning.

Keywords: Refrigeration cycle, MATLAB®, COP, energy balances

1. Introduction

It is a great challenge for teachers to achieve the learning expected of their students. This is why it is important to look for methods or tools that allow students to learn and acquire skills in different areas including thermodynamics which is the main focus of this article. These tools should be structured in such a way that learners can progress according to their level of learning, receive feedback and appropriate counseling, and have their say during this process until they are fully proficient [1]. Computer-based educational materials, known as educational software, complement the teaching-learning process in the classroom by creating computer-based learning environments based on information technology [2]. The computer has been used as a mechanism to reinforce, in some cases, the subjects that are catalogued with a medium high degree of complexity [3]. For this reason, some software has been created to meet the requirements that help the educational process of engineering students [4], some of which are aimed at the student experiencing the decision-making process according to the options or resources available [5, 6]. On the other hand, the creation of software for engineering education has recently been based on didactic and pedagogical aspects, which facilitate and guarantee the satisfaction of educational needs [5], where primordial aspects such as quality, functionality, usability, and reliability have been considered [7]. Research on the use of software in education has shown that a high degree of student learning of the contents is achieved, which is very beneficial for higher education institutions [8]. This kind of software relates situations of technical problems, their causes and possible solutions, allowing students to make decisions based on their application generating the best results [9]. In this way, software was created focused on teaching refrigeration cycles in thermodynamics [10], and the improvement of critical thinking in students was evaluated in terms of clarity, precision and relevance in students [11, 12].

The main contribution of this article is to present the results of three case studies with the help of an educational software created in MATLAB® to work on the cycles of simple refrigeration, cascade refrigeration, multi-stage refrigeration, and absorption refrigeration. It lets to improve the learning process of the given student in an automatic graphical process and calculation of the properties of each state in the cycle, besides the thermal performance of these.

2. Methodology

2.1 General purpose of the software

It was used an innovative software application designed to perform the analysis and solve real process problems related to Matlab® cooling cycles, such as simple cooling cycle, cascade cooling, multi-stage cooling, absorption cooling. It is done calculating the heat removed, the heat delivered to the environment, the work performed by the compressors, the mass flow of the refrigerant in some cases and the thermal performance. The software is aimed at engineering students as a support tool in the process of learning thermodynamics, with the main advantage of presenting the results in the tabular and graphical form of the thermodynamic properties, component energies, and system performance [13].

2.2 Fundamental Equations

The fundamental equations used in the software have been widely studied in literature and are available in the basic books on thermodynamics [14]. In the case of the simple refrigeration system, the performance coefficient (COP) is defined as the quotient between the heat removed from the enclosure ($\dot{Q}_L$) and the compressor work ($W_{compressor}$), as shown in equation (1).

$$\mathrm{COP} = \frac{\dot{Q}_L}{\dot{W}_{compressor}} \quad (1)$$

In the case of the Cascade cooling system, where a heat exchanger is used in which cycle A and B are joined together, the low compressor discharge temperature is lowered, and the efficiency is increased, which is calculated as shown in equation (2).

$$COP = \frac{\dot{Q}_L}{\dot{W}_{compressor\ A} + \dot{W}_{compressor\ B}} \ , \quad (2)$$

where $W_{compressor\ A}$ and $W_{compressor\ B}$ represent the energies consumed by the low and high compressor respectively. The energy conservation equation for the heat exchanger as a function of the mass flows is as shown in equation (3).

$$\frac{\dot{m}_A}{\dot{m}_B} = \frac{(h_5 - h_8)}{(h_2 - h_3)} \quad (3)$$

Finally, in the case of the multi-stage cooling system, it is necessary to estimate the vapor mass fraction *(x)* as shown in equation (4).

$$x_6 = \frac{h_6 - h_f}{h_{fg}}, \quad (4)$$

where *hf* and *hfg* are enthalpies of saturated liquid and latent heat of vaporization, respectively. For this system, the heat removal q_L is represented as shown in equation (5).

$$q_L = (1 - x_6)(h_1 - h_8). \quad (5)$$

Therefore, the performance coefficient of this COP cooling cycle and the energy consumed by the compressor W in to the cycle is estimated as shown in equation (6) and equation (7).

$$\mathrm{w_{in}} = (1 + x_6)(h_2 - h_1) \ + \ (1)(h_4 - h_9) \quad (6)$$

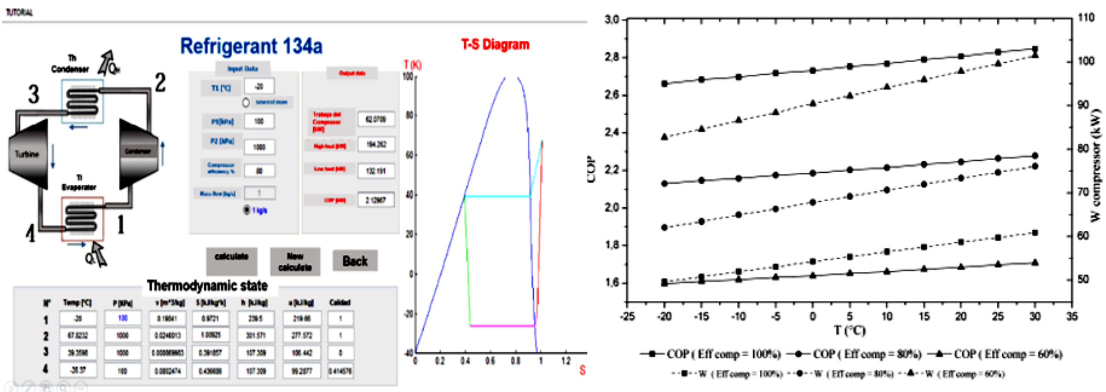
$$COP = \frac{q_L}{w_{in}}. \tag{7}$$

3. Results and discussion

Below are the results of three case studies for single compression, cascade, and multi-stage cooling systems.

3.1 Case study: simple compression cooling system.

To study the behavior of the coefficient of performance (COP) and the energy consumed by the compressor (W compressor) as a function of the temperature variation at the compressor inlet in a single vapor compression refrigeration system, the initial conditions were defined. For pressure at the compressor outlet (P_2=1000 kPa), pressure at the compressor inlet (P_1=100 kPa), and finally the refrigerant mass flow of 1 kg/s as shown in Figure 1a. The compressor efficiency was varied for 60%, 80% and 100% and the temperatures at the compressor inlet T_1 between -20°C and 30°C, obtaining the results shown in Figure 1b.



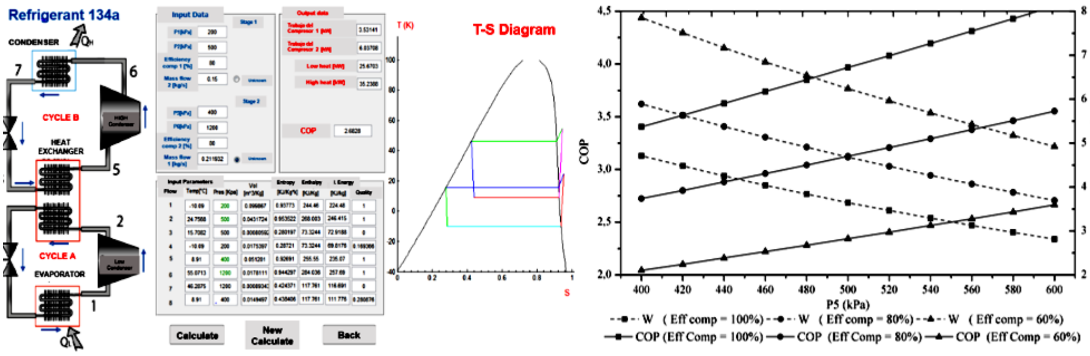
(a) (b)

Figure 1. Simple compression cooling system, a) Software results, b) COP and $W_{compressor}$

The results obtained show a proportional behavior between the COP and the compressor work as a function of the temperature at the evaporator outlet for the three evaluated compressor efficiencies. It can be seen that an increase in temperature from -20°C to 30°C causes an increase in the heat removed from the evaporator. It causes as well an increase in the COP of 7.4%, and 6.76% for the case of compressor efficiencies of 60% and 100%. Regarding the behavior of the compressor work for the three efficiencies studied, a percentage increase about 22.6% was obtained since the compressor pressure ratio remained fixed at 10. It makes the temperature to affect directly the thermal load removed by the system and the thermal performance.

3.2 Case study: Cascade cooling system case study.

In order to study the behaviour of the COP and Wcompressor, the following operating conditions were used, the pressure at the inlet of the high-pressure compressor of a cascade refrigeration system (P_5) ranged from 400 kPa to 900 kPa every 50 kPa, maintaining constant the initial pressure conditions at the outlet of the low pressure compressor (P_2=500 kPa), a low compressor inlet pressure (P_1=200 kPa), a high compressor outlet pressure (P_6 = 1200 kPa), and a refrigerant mass flow of 0.15 kg/s, as shown in Figure 2a. Figure 2 shows the results obtained for compressor efficiencies of 60%, 80%, and 100%.



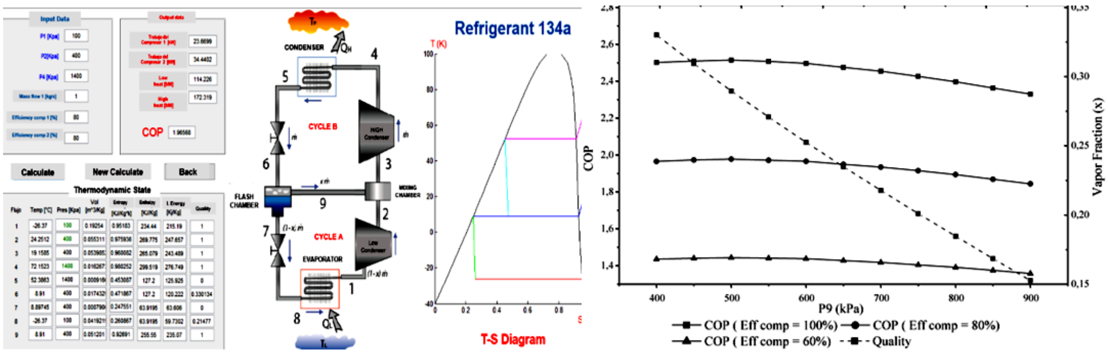
(a) (b)

Figure 2. Cascade cooling system, a) Refri-Term V.2.0 results, b) COP and $W_{compressor}$

The linear behavior between the high $W_{compressor}$ and the COP in relation to the P_5 was confirmed by a statistical analysis of the results, obtaining an average R^2 of 0.99 for both correlations. It indicates that the variance of both, the energy consumed by the compressor and the COP are fully explained by the P_5 given the constant parameters that were assumed in the study. Also, there is also an inversely proportional behavior in the variations of the high $W_{compressor}$ with respect to P_5, given that for every 20 kPa of pressure increase there was a percentage decrease in the $W_{compressor}$ of 40.27%. It happens because the working fluid requires less energy to compress itself and reach the operating discharge pressure of the cycle.

3.3 Case study: Multi-stage refrigeration system.

For the analysis of the behavior of the vapor fraction *(x)* and the COP with respect to the variation of the pressure at the inlet of the mixing chamber (P_9) between 400 kPa to 900 kPa of a multi-stage cooling system, it was given the initial pressure conditions at the low compressor outlet (P_2=400 kPa), the low compressor inlet pressure (P_1=100 kPa), the condenser inlet pressure (P_4=1400 kPa), and a refrigerant mass flow of 1 kg/s, as shown in Figure 3a.



(a) (b)

Figure 3. Cascade cooling system, a) Software results, b) COP and $W_{compressor}$

Figure 3b shows the results of x and COP as a function of P_9 for compressor efficiency values of 60%, 80%, and 100%. It was obtained that as the pressure in the self-evaporating chamber varied and the percentage of compressor efficiency remained constant in the vapor fraction. It happens because this is only a function of the pressure at the compressor discharge when there is no pressure drop in the condenser and the refrigerant phase is strictly saturated liquid at the outlet of the condenser. Additionally, when studying the influence of P_9 on compressor efficiencies of 100%, 80% and 60%, a decrease of 6.86%, 6.18% and 5.43% in COP was observed, respectively. Given that the low compressor consumes more energy by operating at higher pressure limits and higher refrigerant quantity due to the decrease in mass fraction, the cycle tends to have similar efficiency to the single cycle obtained in case study 3.1.

4. Conclusions

The case studies developed with the computational tool allowed thermodynamically studying the simple refrigeration cycle, cascade cooling, and the multi-stage refrigeration cycle, as well as the behavior of operational variables such as the evaporator heat, the energy consumed by the compressors, the mass flow of the refrigerant in some cases and the thermal performance. For the simple compression refrigeration cycle, a linear behavior was obtained between the COP and the compressor work for different compressor efficiencies, with an equal proportional increase for the energy consumed by the compressor independent of the compressor efficiency, since this only affects the thermal load on the evaporator and the thermal performance of the system. The linear behavior also occurred between the energy consumed by the compressor and the thermal efficiency for the cascade cooling system as a function of pressure at the inlet of the high compressor, since the working fluid requires less energy to compress and the system has a higher efficiency. Finally, in a multi-stage cycle, the variation in pressure in the flash chamber and the compressor efficiency does not change in the vapor fraction, causing a decrease in the performance coefficient independent of the compressor efficiency.

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