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Application of a Genetic Algorithm to Optimize the Exergy Performance of a Vapor Compression Refrigeration System

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Abstract

This paper presents a theoretical performance study of a vapour compression refrigeration (VCR) system using R134a, R22, R32, and R40. The VCR system was modeled and simulated in Aspen HYSYS® through the selection of the proper fluid package to compare the Coefficient of Performance (COP) and the exergy of four different conventional refrigerants against different temperatures values. The results obtained have been compared through graphics that allow to identify the most proper refrigerant for the VCR. Finally, the use of genetic algorithm allowed to obtained the optimal operational condition.

Keywords: COP, exergy, vapour compression, refrigeration system

1. Introduction

Cooling systems are one of the main areas of application of thermodynamics, these systems can be defined as the heat transfer from a lower to a higher temperature zone, this process is determined as cooling cycles [1]. The focus of this paper is about one of the most used cooling cycle, which is the vapour compression cycle or VCR [2]. For the refrigeration systems use conventional refrigerants, which are one of the responsible of the depletion of the ozone layer, the Montreal protocol (UNEP, 1997) wants to eliminate all the conventional refrigerant which are considered ozone depleting substances within CFCs and HCFCs

[3]. Even the Kyoto protocol encourage the use of alternative refrigerants that reduce the emission of CFCs [6].

The R22 is the first refrigerant used for the simulations. The R22 was widely used in refrigeration and air conditioning. This refrigerant is within the (HCFCs), compounds that damage the ozone layer. For this reason, the European Union, by Regulation 1005/2009 on ozone depleting substances, has established a timetable for the total elimination of refrigerant R22 in 2015 [4]. Due to the use of refrigerants such as R22, in recent years the performance and characteristics of operating system with environmental friendly alternative refrigerants that replace the use of CFC and HCFC have been investigated on experimental and theoretical bases for refrigeration systems [5]. Exergy analysis has showed a great relevancy in recently due to the fact that it combines the application of the first and the second law of thermodynamic. This analysis helps to understand irreversibility in thermodynamic process. It allowed to identify and calculate the exergy losses in different components, hence leads to improve thermodynamic efficiency [6]. Exergy analysis is commonly used as a tool in obtaining an improved understanding of the overall system and system components through to the quantification of inefficiency sources and distinguishing energy refrigerant R12. Moreover, by its nature, does not deplete the ozone layer, R134a is not considered a hazardous waste component as defined by the Act of Resource Conservation and Recovery of the United States 1976 [7].

The objective of this study is to introduce an exergy analysis on VCR system in order to compare the performance between different case studies using 4 different refrigerants, such as R-134a, R-22, R-32, and R-40. The analytical results obtained from Aspen HYSYS® will compare each other and displayed in graphics which will allow to identify the performance on each refrigerant with respect to variations on the temperature for the evaporator and the condenser.

2. Methodology

Refrigeration cycles conduct a heat transfer process from a low temperature source to a higher temperature source which may be nearby [8]. The VCR cycle will be taken as case study, which operates between 2 sources of temperature as shown in the t-s diagram as in Figure 1, for this system, the refrigerant fluid in the state enters the compressor as saturated steam, as a result of mechanical compression increases, the compressor increases the temperature and pressure of the refrigerant as superheated steam. Afterwards the fluid enters in the condenser to exchange heat with the surrounding area and reduce the temperature of the fluid, at the exit of the condenser, the fluid has got saturated liquid properties. The refrigerant passes through the expansion valve to lower its pressure through an isenthalpic process; finally, with these conditions, the fluid enters the evaporator to extract heat from the cooled space and repeat the cycle. As the *evaporator extracts more heat from the cooled space, it will have higher refrigeration capacity.*

It means that the refrigeration system will be able to reduce the temperature as low as demanded, using the same energy requirement on the compressor.

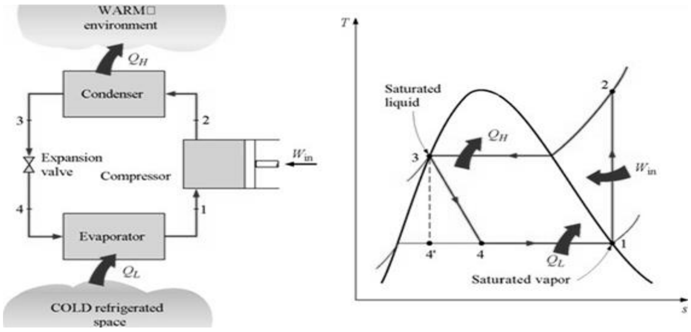

Figure 1. Vapor compression refrigeration system and cycle t-s diagram

2.2 Energy and exergy analysis

The analysis of the case study is carried out under the following considerations, all the components operate in steady state and the kinetic and potential energy and the kinetic and potential exergy of the components are omitted for calculations. The heat flow from the heat source to the evaporator $\dot{Q}_{eva}$ and the heat flow from the condenser to the heat sink $\dot{Q}_{cond}$ can be expressed as in equation (1) and (2) respectively, The real power in the compressor is given as in equation (3) And the electrical power input for the compressor is determined as in equation (4), as shown in Table 1.

Table 1. Equations that describe the process in components.

Component	Equations
Evaporator	$\dot{Q}_{eva} = \dot{m}(h_1 - h_4)$ (1)
Condenser	$\dot{Q}_{cond} = \dot{m}(h_2 - h_3)$ (2)
Compressor	$\dot{W}_{comp} = \dot{m}(h_{2r} - h_1)$ (3)
Compressor power	$\dot{W}_{in,el} = \frac{\dot{m}(h_{2r} - h_1)}{\eta_m \eta_e}$ (4)

In the classical performance analysis of refrigeration systems, the COP is used as a main performance indicator. The COP provides information about the required electrical power input in order to produce a certain amount of cooling load [9]. From the first law of thermodynamics, the COP is defined as the ratio of cooling load and the electrical power input for VCR cycle, expressed as in equation (5).

$$\text{COP} = \frac{\dot{Q}_{eva}}{\dot{W}_{in,el}} \qquad (5)$$

The exergy loss rate in each component of the VCR system is obtained as in equation (6) [10]:

$$\dot{X}_{in} = \dot{X}_{out} + \dot{X}_D \tag{6}$$

The input electrical power in the system enters through the compressor, therefore, the exergy loss rate in the compressor is defined as in equations (7) and (8). The condenser exchanges heat with the environment, so the exergy loss rate for the condenser is given as in equation (10). Similar to the condenser, the evaporator exchanges heat with the cooler space, therefore, the exergy loss rate for the evaporator is described as in equation (14), as shown in Table 2.

Table 2. Equations that describe the exergy lost rate in components.

Exergy lost rate in components	Equations
Compressor	$\dot{X}_{Dcomp} = \dot{X}_1 + \dot{W}_{in,el} - \dot{X}_2$ (7) $\dot{X}_{Dcomp} = (h_1 - h_2) + \dot{W}_{in.el} - T_0(s_1 - s_{2r})$ (8)
Condenser	$\dot{X}_{Dcond} = \dot{X}_2 - X\dot{Q}_{con} - \dot{X}_3$ (9) $\dot{X}_{Dcomp} = (h_2 - h_3) - T_0(s_1 - s_{2r}) - \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_{cond}$ (10)
Expansion valve	$\dot{X}_{Dex.val} = \dot{X}_3 - \dot{X}_4$ (11) $\dot{X}_{Dex.val} = (h_3 - h_4) - T_0(s_3 - s_4)$ (12)
Evaporator	$\dot{X}_{Deva} = \dot{X}_4 + X\dot{Q}_{eva} - \dot{X}_1$ (13) $\dot{X}_{Dcomp} = (h_4 - h_1) - T_0(s_4 - s_1) + \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_{eva}$ (14)

Finally, the main function of a cooling unit is the heat extraction form a cooled space in order to achieve a low temperature through the utilization of mechanical devices that represent power consumption for the system [1]. When the heat is extracted from a reservoir, it is able to allow the production of work by a reversible thermal machine that receives heat from the environment and discharge into the tank; then, the exergy efficiency is described as in equation (15):

$$\eta_X = \frac{\left|\dot{Q}_{eva}[(T_{cs} - T_0)]\right|}{\dot{W}_{in,el}} \tag{15}$$

3. Results And Discussions

The results of the steady state properties for every state are shown in the Table 3. The exergy analysis is an extremely relevant tool, since it allows to calculate the input and output power in addition to the inlet and outlet material and heat streams, furthermore, it allows determinate the quality of the energy and the magnitude of irreversibility losses in the process.

Table 3. Results of the properties at each state

State	***T*** **(K)**	***P*** **(kPa)**	***h*** **(kJ/kg)**	***s*** **(kJ/kg K)**	$phase$
1	223	29.406	219.80	0.986	VS $x = 1$
2s	321.00	721.68	286.20	0.986	VSC
2r	343.220	721.68	308.33	1.052	VSC
3	300	706.68	88.65	0.331	LS $x = 0$
4	230	44.40	88.65	0.385	$x = 0.40$

The results of the exergy destruction in each component are in the Table 4.

Table 4. Results of the properties at each state

Component	Compressor	Condenser	Valve	Evaporator	System
Exergy loss rate (kW)	46.89	3.56	15.85	11.35	77.65
Exergy loss ratio (%)	60.39	4.58	20.41	14.62	100

It was possible to notice that the results calculated for exergy loss in each component in Aspen HYSYS®, are similar to the results calculated with thermodynamic tables in the Table III. The results for the COP, η_X and $\dot{W}_{in,el}$ have been calculated in Aspen HYSYS® using (8), (15) and (7) respectively. According to the results obtained in Aspen Hysys®, it is possible to validate the procedure used in this paper to calculate the COP and the exergy efficiency. The performance of the different refrigerants used in our case study with respect to different condensing temperature within 40 - 60°C, includes the variation of the COP and exergy efficiency of each refrigerant fluid as shown in Figure *2*a.

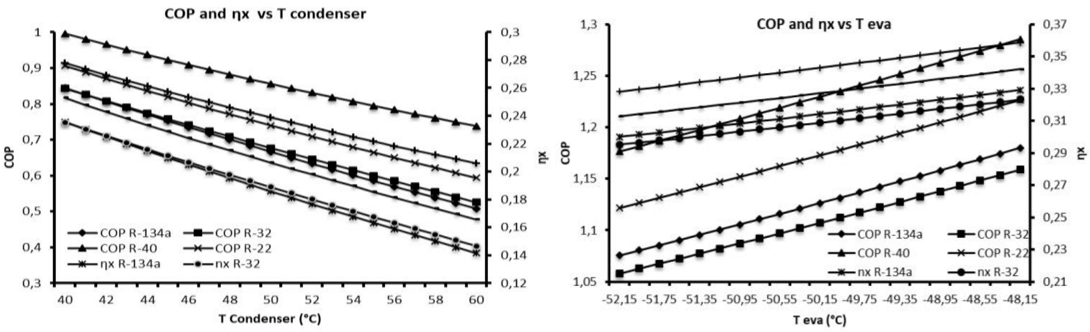

Figure 2. COP and exergy efficiency as function of a) condensing temperature, b) evaporating temperature

The performance of the different refrigerants used in our case study with respect to different evaporating temperature within -52,15 - -48,15°C, includes the variation of the COP and exergy efficiency of each refrigerant fluid as shown in Figure *2*b.

In the Figure *2* it is possible to observe that the COP and the power supplied by the refrigerant (R-40, R32, R134A and R22) in the compressor and the evaporator, taking into account the condensing and evaporating temperatures; with noticeable result that the R-40 showed higher values of COP and power for use in compressor and evaporator with respect to the variation of condensing and evaporating temperatures. After the exergy analysis with the 4 different refrigerants used in this research, it noticeable that the performance of the system is directly related to the thermodynamic properties of the refrigerant and its behavior with respect to the device and the condensing and evaporating temperature. Therefore, it is considered necessary to conduct an optimization process to determine the proper refrigerant fluid to work in a conventional VCR. In this study, a parameter optimization is achieved through the utilization of genetic algorithm and artificial intelligence in order to achieve the maximum exergy efficiency without overloading the VCR to overcritical conditions, so that to avoid and prevent failures in the system [11]. The optimization in this is study was calculated based one the initial parameters, which give us an idea, where to change certain parameters, the parameters for the optimization and the results of are in Table 5 and Table 6.

Table 5. Parameters constants in the optimization

Environment temperature (K)	Enviroment pressure (kPa)	Mass flow (kg/s)	Pressure drop in components (kPa)	Mechanical efficiency (%)	Electrical efficiency (%)	Isentropic efficiency (%)
298	101.325	1	15	85	90	75

Table 6. The optimization results of the parameters for the combined cycle

T evaporator (K)	T condenser (K)	Q evaporator (kW)	Q condenser (kW)	W compressor (kW)	W electrical in (kW)	COP	Exergy efficiency (%)
231	298.12	139.2	212.6	73.42	95.98	1.45	40.46

4. Conclusions

After conducting the theoretical and computational analysis of the VCR system, it is possible to observe the performance and efficiency of the different refrigerants (R134a, R22, R-32 and R-40), through the results it was possible to get some conclusions such as the refrigerant fluid R-40 provides a higher COP and a greater cooling in the compressor and the evaporator, with respect to the evaporation and condensing temperatures in this research, the total exergy loss rate is inversely proportional to the T_{evap} and T_0, and it is directly related to the T_{cond} and $\delta P_{evap} = \delta P_{cond}$. In additions, the refrigerant R-134A shows a higher percentage of exergy loss ratio in the devices of the system with respect to the other refrigerant fluids, and the pressure drops in the evaporator and condenser does not have a high influence on the exergy loss rate of the devices. Finally, the method proposed in this paper can also be applied to other refrigerants and currently used cycles, where the variation on the temperature improves the COP, with exemption to the electrical power.

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