Contemporary Engineering Sciences, Vol. 10, 2017, no. 14, 691 - 702
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/ces.2017.7763

Comparative Evaluation of Different Refrigerants on a Vapor Compression Refrigeration System via Exergetic Performance Coefficient Criterion

Guillermo Valencia, Jaison Beltrán, Osvaldo Romero and José Cabrera

Faculty of Engineering
Universidad del Atlántico, km 7 antigua vía Puerto, 081008
Barranquilla, Colombia

Marisol Osorio

Electric and Electronic Engineering Faculty
Universidad Pontificia Bolivariana
Medellín, Colombia

Abstract

Classical study of exergy coefficient, as a measure of the quality of the energy, is based on the coefficient of performance COP. This is a reliable tool, which is related to the thermodynamic second law of efficiency. Some factors such as the evaporator and condenser temperature, pressure drop, and environmental conditions, can affect the refrigerant behavior inside the thermodynamic cycle. This paper presents the behavior of a vapor compression refrigeration simple cycle, taking the Exergy Performance Coefficient (EPC) criterion, Coefficient of Performance (COP), and exergy destroyed as study method, using different refrigerants such as R-12, R-22, R-40, R-134A, and R-410A in the cycle. The refrigerants R-22 and R-40, which are highly flammable and explosive combined with air, presented the highest EPC and COP performance, therefore these are considered ozone depleting substances. On the other hand, the R-410A is not the working fluid with the best performance in terms of thermal capacity, although it preserves the ozone layer; thus this refrigerant might be used as a new alternative in Vapor Compression Refrigeration (VCR) simple cycle.

Keywords: Refrigerating System; coefficient of performance, thermodynamic second law, exergetic performance coefficient, operation condition, R-410A

1 Introduction

A great amount of energy consumption in the world energy matrix is represented by refrigeration and air conditioning systems. Using air as working fluid on the evaporator and condenser heat exchangers instead of water, due to its absence, implies a large different operation temperature between the evaporator and condenser line and lower cooling capacity, which finally leads to require higher compressor energy. The described phenomena may induce a fault in the compressor due to operation during large periods of time under harmful operational conditions so that the desired cooling capacity can be reached [1]. In a wide variety of industries such as pharmaceutical, chemical, and food, cooling systems are of significant application due to the fact that these devices are used for different applications which requires large amount energy consumption as water cooling, air conditioning, and cold rooms; therefore, it is of utmost importance that VCR systems present a good performance in order to avoid unnecessary energy feeding to the compressor. So that to study the efficiency in processes and fault detection in equipment and devices, the exergy analysis is a great thermodynamic tool, which allows us to evaluate and improve the VCR exergy performance [2].

2 Background

2.1 Thermodynamic analysis for vapor compression refrigeration cycle

One of the most common area of application in thermodynamics is the refrigeration and air conditioning, which conducts the heat transfer from the cooled space at lower temperature to a higher temperature environment [3]. The most basic refrigeration basic cycle, known as VCR cycle is commonly integrated by a condenser, a compressor, an evaporator, and an expansion valve device.

The VCR removes heat from the cooled space at low temperature in order to decrease or keep the set low temperature inside the cooled space and reject it to the hot environment as shown in Figure 1, in this cycle the refrigerant fluid enters as saturated vapor to the compressor, therefore increasing its pressure and temperature, thus leaving the compressor as superheated vapor with proper thermal conditions to reject heat to the environment through the condenser where a pressure drop in this device is presented due to roughness and friction of the pipe lines without induce subcooling conditions to the refrigerant fluid. Consequently, the refrigerant passes through the expansion valve as saturated liquid and leaves it as a low pressure mixture with a quality determined by the state point conditions, finally the low pressure mixture removes heat from the cooled space in the evaporator until it get thermal conditions as a low pressure saturated vapor.

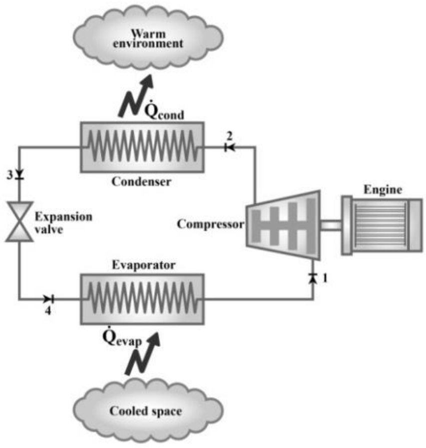

Figure 1. Operation system of vapor compression refrigeration cycle.

The energy balance of any steady flow control volume according to [3], is given as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\theta, \quad (1)$$

where

$$\theta = h + \frac{V^2}{2} + gz. \quad (2)$$

Applying the energy balance using (1) for condenser and evaporator, the rate of heat flow is determined as equations (3) and (4) respectively.

$$\dot{Q}_{cond} = \dot{m}(h_2 - h_3), \quad (3)$$

$$\dot{Q}_{evap} = \dot{m}(h_1 - h_4). \quad (4)$$

Based on (1), the isentropic duty ($\dot{W}_{in,ise}$) for the compressor is estimated as in equation (5)

$$\dot{W}_{in,ise} = \dot{m}(h_{2s} - h_1), \quad (5)$$

As well for the real duty ($\dot{W}_{in,ise}$) is estimated as in equation (6)

$$\dot{W}_{in,real} = \dot{m}(h_2 - h_1) = \frac{\dot{m}(h_{2s} - h_1)}{\eta_{comp.ise}}. \quad (6)$$

From the isentropic duty defined in (5), the compressor electrical power, involving the isentropic, electrical, and mechanical efficiencies becomes

$$\dot{W}_{in,elec} = \frac{\dot{m}(h_{2s} - h_1)}{\eta_{comp,ise}\eta_m\eta_{el}}, \quad (7)$$

as a function of real thermodynamics state is defined by

$$\dot{W}_{in,elec} = \frac{\dot{m}(h_2 - h_1)}{\eta_m \eta_{el}}. \tag{8}$$

The thermal performance for the simple VCR cycle is expressed as *coefficient of performance* COP at classical analysis, which is influenced by the heat removed from the cooled space and the compressor energy consumption. COP is calculated according to the following equation

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{in,elec}}. \tag{9}$$

Complementary formulation based on second law of thermodynamic, such as the exergy analysis, is used to quantify the performance of the VCR cycle. The exergy, which decreases while the thermodynamic irreversibility increases, is the highest useful work obtained from the thermal cycle at a given state in a specified environmental conditions [2]. The specific exergy of a steady flow control volume in VCR cycle expressed as [4]

$$\psi = (h - h_0) - T_0(s - s_0), \tag{10}$$

to exergy rate flow terms

$$\dot{X} = \dot{m}[(h - h_0) - T_0(s - s_0)]. \tag{11}$$

The exergy analysis provides an important method [5] to calculate the availability of energy; otherwise, the general exergy balance can compute the work destroyed due to irreversibility as follows

$$\sum \dot{X}_{in} - \sum \dot{X}_{out} = \sum \dot{X}_{dest}. \tag{12}$$

The general method to analyze the exergy destruction rate for steady flow control is expressed as [2]

$$\dot{X}_{dest,i} = \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{in} - \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{out} + \sum(\dot{W}_{in} - \dot{W}_{out}) + \sum(\dot{X}_{in} - \dot{X}_{out}), \tag{13}$$

where $\dot{X}_{dest,i}$ is the useful work destroyed by the system, the first and second terms on the right hand side $\sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{in} - \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{out}$, represents the net exergy supplied through heat transfer to the systems; likewise, the variation by work and net exergy from the work fluid is represented by the third and fourth terms $\sum(\dot{W}_{in} - \dot{W}_{out}) + \sum(\dot{X}_{in} - \dot{X}_{out})$ respectly.

2.2 Exergy destruction rate in system devices.

From equation (12), the exergy destruction rate for every control volume in a VCR cycle can be written as below,

compressor	condenser	evaporator	expansion valve
$\dot{X}_{dest,comp} = \dot{X}_1 - \dot{X}_2 + \dot{W}_{in,elec}$, (14)	$\dot{X}_{dest,cond} = \dot{X}_2 - \dot{X}_3$, (15)	$\dot{X}_{dest,evap} = \dot{X}_4 - \dot{X}_1 + \dot{X}_{\dot{Q}_{evap}}$, (16)	$\dot{X}_{dest,exva} = \dot{X}_3 - \dot{X}_4$, (17)

Where thermal exergy rate is related with the heat transfer rate as follows

$$\dot{X}_{\dot{Q}_{evap}} = \dot{Q}_{evap}\left[\frac{(T_{cs}-T_0)}{T_{cs}}\right]. \quad (18)$$

The total exergy destruction of the VCR simple cycle is calculated by combining and grouping equations from (14) to (17) as

$$\dot{X}_{dest,total} = \dot{X}_{dest,comp} + \dot{X}_{dest,cond} + \dot{X}_{dest,evap} + \dot{X}_{dest,exva}. \quad (19)$$

2.3 Exergetic performance coefficient.

The COP is known as the classical measure of refrigeration unit or heat pump thermal efficiency [6]; this study introduces a new criterion named *Exergetic Performance Coefficient* EPC, which provides information about the total exergy destructions rate of a VCR cycle, and indicates the magnitude of the output exergy rate. The simple notion of exergetic efficiency or second law thermal efficiency only relates the ratio of the output and input exergy rates as below [3].

$$\eta_X = \frac{\dot{X}_{out}}{\dot{X}_{in}} = 1 - \frac{\dot{X}_{dest}}{\dot{X}_{in}}, \quad (20)$$

where

$$\dot{X}_{in} = \dot{W}_{in,elec}. \quad (21)$$

The output exergy rate of the VCR cycle is associated with exergy loss by heat transfer as below.

$$\dot{X}_{out} = \dot{X}_{\dot{Q}_{evap}}, \quad (22)$$

therefore, the exergetic efficiency is calculated as

$$\eta_X = \frac{\dot{Q}_{evap}\left[\frac{(T_{cs}-T_0)}{T_{cs}}\right]}{\dot{W}_{in,elec}} = COP\left[\frac{(T_{cs}-T_0)}{T_{cs}}\right]. \quad (23)$$

Based on their definition [2], the EPC is the ratio of output exergy rate to the total exergy destroyed as below.

$$EPC = \frac{\dot{X}_{out}}{\dot{X}_{dest}} = \frac{\dot{X}_{out}}{\dot{X}_{dest,total}} = \frac{\dot{X}_{in}}{\dot{X}_{dest,total}} - 1. \quad (24)$$

2.4 Exergetic performance coefficients for VCR cycle devices.

Applying equation (24) to each component, the EPC is defined as [2],

compressor	condenser	evaporator	expansion valve
$EPC_{comp} = \frac{\dot{X}_2}{\dot{X}_1 - \dot{X}_2 + \dot{W}_{in,elec}}$, (25)	$EPC_{cond} = \frac{\dot{X}_3}{\dot{X}_2 - \dot{X}_3}$, (26)	$EPC_{evap} = \frac{\dot{X}_1}{\dot{X}_4 - \dot{X}_1 + \dot{X}_{\dot{Q}_{evap}}}$, (27)	$EPC_{exva} = \frac{\dot{X}_4}{\dot{X}_3 - \dot{X}_4}$. (28)

3. Results and discussion

Recently, the refrigerants are widely used for industrial applications, according to the required or highly desirable characteristics, as, for instance environmental acceptability, chemical stability, materials compatibility, and refrigeration-cycle performance [7]. Ignoring some of them, the EPC analysis is performed to evaluate the effects of the evaporator and condenser temperature, COP, exergy rate destroy to evaporator and condenser temperature, pressure drops and environmental temperature for different refrigerants such as R-12, R-22, R-40, R-134A, R-143A and R-410A on the VCR simple cycle. Some assumptions were taken for the EPC analysis; the VCR cycle devices are on steady state, the kinetic and potential energy associated to mechanical energy were neglected, the heat transfer energy loses into condenser, evaporator, expansion valve and compressor are omitted, as they are considered adiabatic components, the real pressure drops in the pipe nets are neglected and, finally, the process on the expansion valve is considered isenthalpic.

3.1 EPC behavior for VCR cycle

Figure 2a shows the effect of the refrigerants on the EPC criterion for evaporator temperatures in a range from 223K to 273K. It can be seen that EPC increases with increasing evaporator temperature, but after the evaporator temperature range from 243K to 253K the EPC decreases for all refrigerants; therefore, keeping the temperature above that rank will increase the performance of the VCR system regardless which refrigerant is used. On the other hand, analyzing each refrigerant behavior separately, R-40 extremely toxic and flammable; and R-12, harmful for the ozone layer; has got the best EPC. The less harmful refrigerant such as the R-143A presents the lower EPC value. The R-410A, which has zero ozone depletion, has an optimal temperature 244 K. Otherwise if condenser temperature gets higher, the EPC will suffer a decrease as shown in Figure 2b; hence, increases this temperature won't increase EPC and it doesn't have a remarkable mean.

Figure 3(a) shows the EPC for the cycle as a function of the COP, where the EPC begins to decrease while the COP increases until the optimal operation condition, which is around COP=1.54 for all refrigerant studied on this research. Figure 3(a) shows R-40 as the best option between these refrigerants, and R-410A is upon of R-143A. On the other hand, the EPC in function of the thermal exergy rate on the evaporator is shown on Figure 3(b).

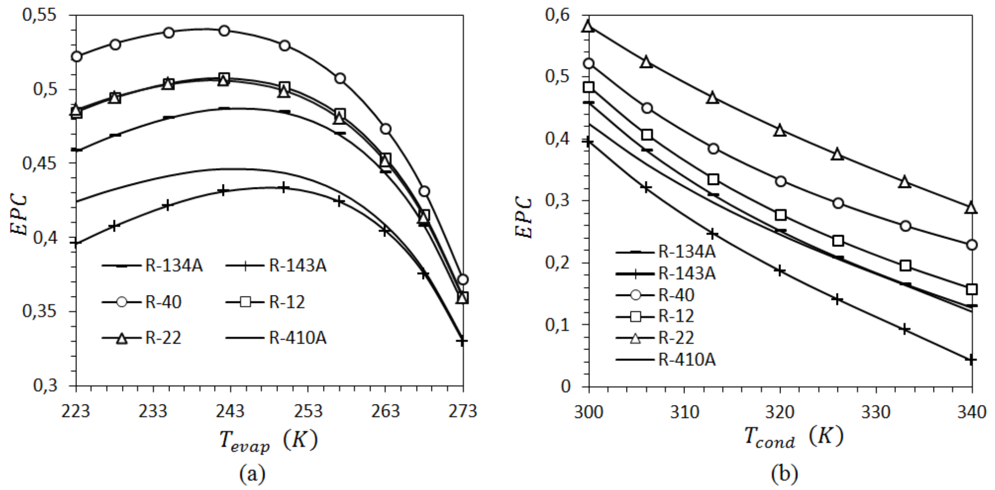

Figure 2. Effect of the refrigerants on the EPC while changing; (a) evaporator temperature, and (b) condenser temperature.

For the R-40, the best performance on EPC and heat exergy rate is obtained on 0.543 and 66.5 kW respectively, which is 20.6% higher than EPC for the R-410a at optimal point. The above results are valid for evaporator temperature ranging from 223K to 273K.

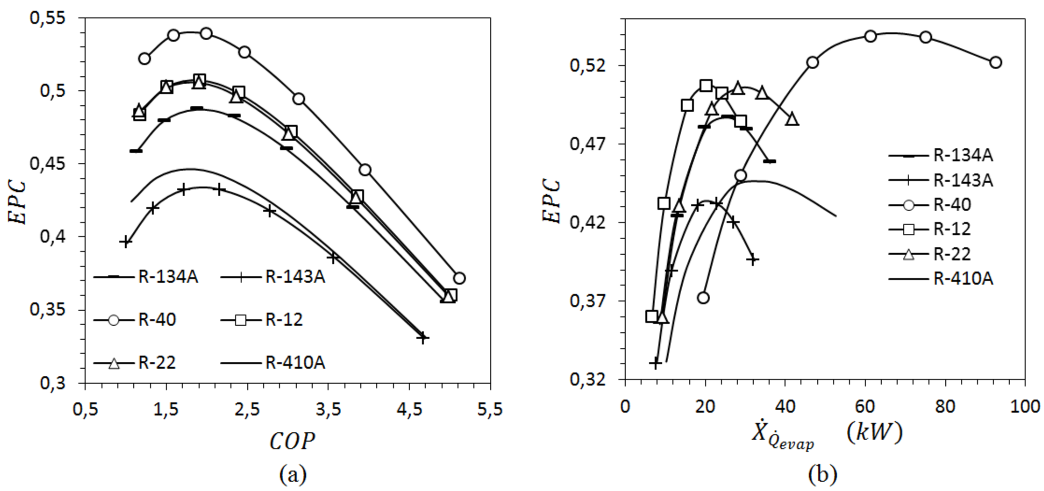

Figure 3. Variation of EPC for different refrigerants in function of; (a) COP, and (b) thermal exergy rate.

3.2 Exergy destruction rate of VCR cycle and its components

Condenser temperature, evaporator temperature, pressure drops, and the environmental temperature, have different effects on exergy destruction for each refrigerant, for present report, R-410A was chosen as based fluid for case studies. As a general remark, the exergy destroyed in compressor is the highest, which represents the majority exergy destroyed among components. This phenomenon is shows in Figure 4(a); 4(b); 5(a) and 5(b).

It is evident a real exergy destruction rate when evaporator temperature goes down on, Figure 4(a) the trend keeps equal for the components; However, in the expansion valve's case, the slope proves that present temperature does not impact its behavior as strongly as the compressor station; consequently, having lower evaporator temperature provides a better performance due to reduction on exergy destroy (destruction). On the opposite case, as condenser temperature goes up, exergy destruction rate goes higher; therefore, the possible variation on a VCR cycle with the last temperature mentioned does not work at positive way, by this characteristic slope to increase energy availability losses, according to Figure 4(b) dates.

Energy loses in pipes used for the trasportation of fluids are esencially due to friction, as well as to the sigularities encounteder, this definition is according to [8]. When a mass flow goes on closed way, inicially this mass have energy and pressure diference between two points, but these points include elements of fluid retention, consenquently pressure goes down [9]. The condenser and evaporator include some of this elements, which results in pressures drops inside of them. The Figure 5(a) represents how this variation of pressures on the mencionated components, only evaporator and expansion valve feel that factor significantly; otherwise, the others device have not a remarkable slope of the exergy rate destruction.

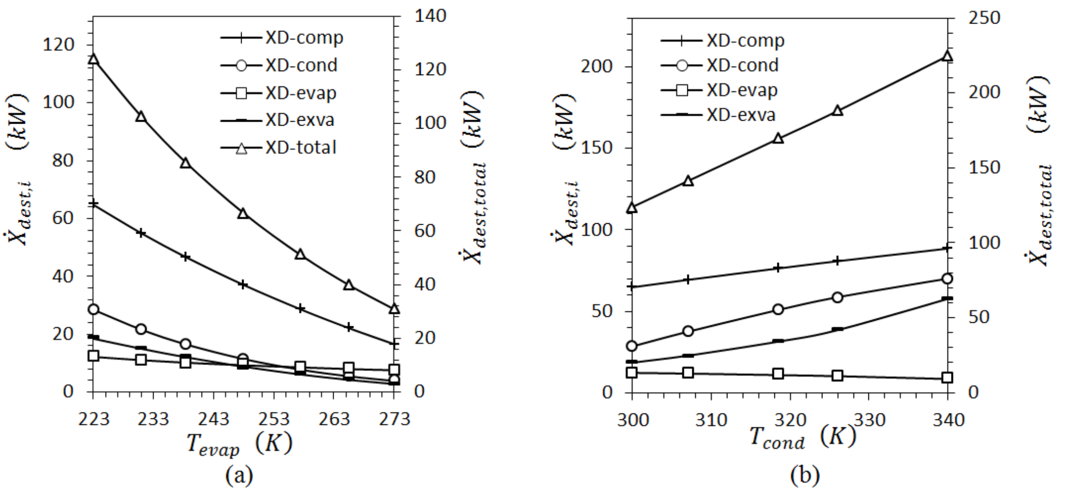

Figure 4. Destroyed Exergy rate of VCR simple cycle to COP for system components. (a) Evaporator temperature; (b) condenser temperature.

The environmental conditions influence on how much exergy could be obtained by a source, being their most important features the temperature and pressure. For this case, Figure 5(b) presents an idea about the behavior of the exergy destroyed on each component when local temperature changes. As a special annotation it is valid to say that Figure 9 range is defined from 295K to 318K due to normal estimated environmental temperatures operation. The exergy rate destruction shows that compressor feels a little increase on this destruction, but with the higher rank; while the condenser, with a lower exergy rate destruction, has a tendency to get lower when environmental temperature goes up.

3.3 EPC behavior of VCR cycle components

In order to analyze the behavior of EPC in the components separately, assuming the same conditions established before on section 3.2; the EPC criterion shows other way to analyze device's performance. Relating Figure 4 with Figure 6, this result shows a decrease on exergy rate destruction and an increase on EPC by components, when evaporator temperature goes up; thus when this temperature is higher, an optimal point operation due to abode can be defined by this increase.

Condenser temperature according to exergy rate destruction has not a remarkable value; however, EPC criteria shows a way to make a definition or select an optimal operation point due to this factor. The Figure 6(a) provides this information; compressor has got a tendency to be increased but with a not notarial slope, and the evaporator has a same behavior; therefore, the main attention for this case depend on high measure of condenser and expansion valve, where both components show a common point, which says that if condenser temperature keeps increasing, expansion valve will decrease its EPC and condenser will increase it.

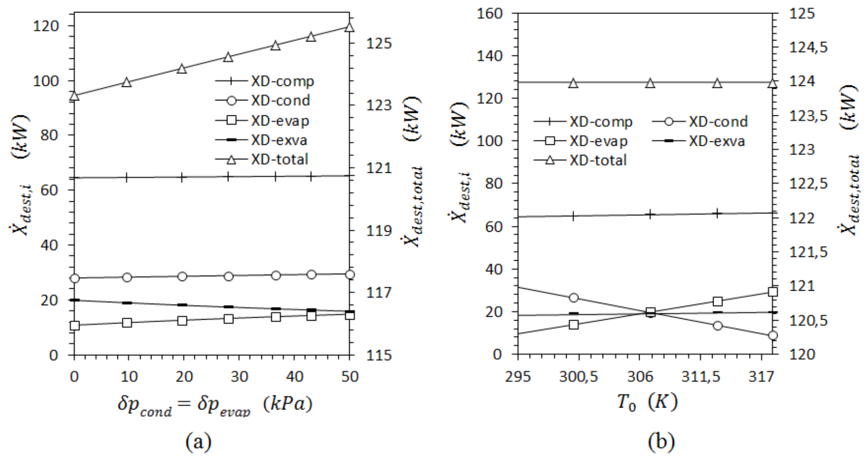

Figure 5. Destroyed Exergy rate of VCR cycle to. (a) drop pressure; (b) enviroment temperature.

The figure 7(a) shows the EPC of the expansion valve as function of the mentioned factor, when it is increased represents a gain, but with condenser and evaporator case, it does not happen in the same way, because their behavior indicates a little negative slope.

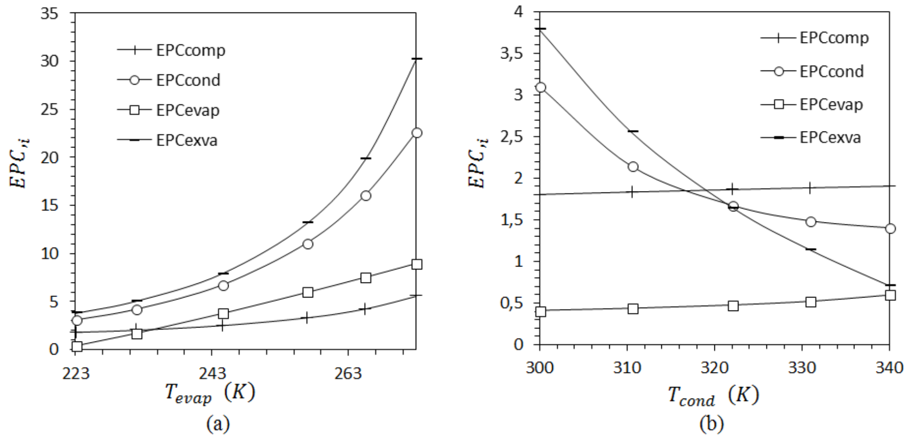

Figure 6. EPC variation of VCR cycle to COP for system components. (a) evaporator temperature; (b)condenser temperature.

For compressor's case, it has a non-notarial slope, but it exists with a very small tendency to go up. The environmental influence through the temperature is shown in Figure 13. The most affected component is the condenser due to its direct relation, which function is reject heat to the environment [10]. On the other hand, compressor, evaporator and expansion valve have a relation with this temperature not easy influent able; however, the evaporator has a notarial tendency to get higher.

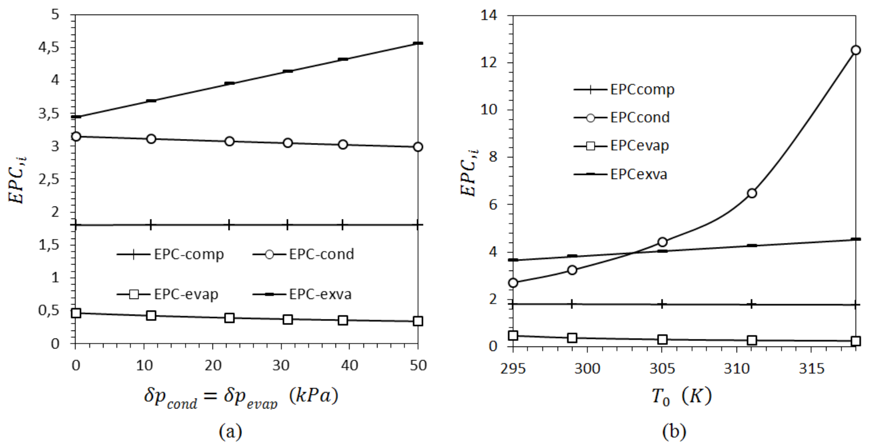

Figure7. EPC variation of VCR cycle to COP for system components. (a) drop pressure; (b) environment temperature.

4 Conclusions

For several industrial applications, many refrigerants have been carried out according the specific request. R-12, R-22, R-40, R-134A, R-143A and R410A were tested on the VCR cycle. The study was focused on EPC criteria as a new way to check the VCR simple cycle and system's components; in order to relate the exergy output to the total exergy destruction rate. The classical study based on COP gives an explanation according to the thermal efficiency; but it is only applied to the complete refrigeration system, while EPC criteria can be used to study the whole VCR cycle and their components too, as performed here.

Recently, the studies on refrigerants are focused on their environment effects and their use on the refrigeration devices; therefore, new alternatives as R-410A provides a guarantee in this skill, but when it is compared to traditional refrigerant such as R-22 or R-40, the performance keeps lower even with R-134A, but goes better than R-143A. On the other hand, R-40 shows the best EPC value for evaporator temperature, COP at maximum conditions and thermal exergy rate; however, at condenser temperature R-22 has the best behavior according to the factor studied.

For R-410A, the exergy destruction is influenced mainly by the evaporator and condenser temperature variations on the compressor; while the evaporator provides the less exergy destruction rate. Otherwise, the EPC criteria applied on VCR cycle system's components shows that best performance is obtained for the expansion valve, condenser, and finally the compressor and evaporator respectly. Finally, the pressure drops has not significant effects on the exergy destruction rate; then, the drop pressure on the condenser or evaporator has not really importance on EPC criterion.

Acknowledgments. This research was supported in part by the Mechanical Engineering Department of Universidad del Atlántico. G. Valencia is supported by the Kai and Dimer Research Group. M. Osorio participation is granted by Automatic and Design (A+D) Group and Escuela de Ingenierías de la Universidad Pontificia Bolivariana.

References

[1] J. Breuker, M.S. Braun, Common faults and their impacts for rooftop air conditioners, *HVACR Research*, **4** (1998), no. 3, 303–318. https://doi.org/10.1080/10789669.1998.10391406

[2] Y. Ust, A. V. Akkaya, A. Safa, Analysis of a vapor compression refrigeration system via exergetic performance coefficient criterion, Journal of *Energy Institute*, **84** (2011), 66–72. https://doi.org/10.1179/014426011x12968328625351

[3] Y. A. Cengel, M.A. Boles *Termodinámica*, 6th Ed., México, McGraw-Hill Companies Inc, 2009.

[4] C. Stanciu, A. Gherghian, D. Stanciu, A. Dobrovicescu, Exergy Analysis and refrigerant effect on the operation and performance limits of a one stage vapor compression refrigeration system, Politeh. Univ., 2011, no. 1, 36–42.

[5] A. Hepbasli, A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future, *Renew. Sustain. Energy Rev.*, **12** (2008), 593–661. https://doi.org/10.1016/j.rser.2006.10.001

[6] S. Islam and I. Dincer, Comparative performance study of an integrated air-cycle refrigeration and power generation system, *Appl. Therm. Eng.*, **106** (2016), 493–505. https://doi.org/10.1016/j.applthermaleng.2016.06.044

[7] Criteria for refrigerant selection.

[8] A. Lahiouel, Y. Haddad, Evaluation of energy losses in pipes, *Proc. 6th Saudi Eng. Conf.*, (2002), 577–589.

[9] R. L. Mott, *Applied Fluid Mechanics*, Prentice Hall Up. Saddle River, 2005.

[10] S.C. Kaushik, V. Siva Reddy, S.K. Tyagi, Energy and exergy analyses of thermal power plants: A review, *Renewable and Sustainable Energy Reviews*, **15** (2011), 1857–1872. https://doi.org/10.1016/j.rser.2010.12.007

Received: August 1, 2017; Published: September 7, 2017