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EXPERIMENTAL EVALUATION OF REFRIGERANT R290 IN A SMALL REFRIGERATION SYSTEM ORIGINALLY DESIGNED FOR R134a

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Abstract. *The present paper focuses on the performance of the hydrocarbon (HC) R290 used to replace the hydrofluorocarbon (HFC) R134a for a small capacity refrigeration application. The original system provides nominal refrigerating capacity of 0,25 kW. The condition of replacement of R134a by the alternative fluid (R290) represented a drop-in operation; there were no changes in the basic cycle components during the tests. The tests were performed using a water evaporator, at controlled temperatures of 3, 5 and 7 ºC, in steady state condition and for different levels of modulation of expansion valve (EEV), thus enabling the realization of a complete thermodynamic analysis. The use of the hydrocarbon, which has a low global warming potential (GWP) and zero ozone-depleting potential (ODP) guaranteed an acceptable operation of the refrigeration system with a refrigeration capacity higher than original system with R134a. On the other hand, for the application range analyzed the compressor required higher power with R290. Finally, the use of the refrigerant R290 resulted in the maximum values for the coefficient of performance, COP, compared to the original system with R134a, indicating that this hydrocarbon has potential to replace R134a in some applications.*

Keywords: *refrigeration, R290, R134a, COP, drop-in and GWP.*

1. INTRODUCTION

Since the 1930s, clorofluorocarbons (CFCs) and hydrocloroflourocarbons (HCFCs) have been widely used in refrigeration because of their good thermodynamic properties and not being toxic and flammable as other gases used in a vapour compression system. However, it has been proven that this class of gases have high ODP (ozone depletion potential), that is the measure of its relative ability to destroy stratospheric ozone. The Montreal (1987) and Kyoto (1997) protocols set targets for the extinction of these gases.

Some fluids emerged as candidates to replace CFCs, like Hydrofluorocarbons (HFCs) and some HCFCs. These fluids are characterized by the total replacement of chlorine atoms by hydrogen, kept the good thermodynamic properties, low flammability and toxicity and made them less damaging to the ozone depletion. However, some researches related that HFCs refrigerants, like R134a, have high GWP (Global Warming Potential), index that reveals how much the gas intensifies the greenhouse effect. A new generation of refrigerants emerged in last years to eliminate also fluids with high GWP. R290, R600a, R1234yf and R513a are examples of fluids that can replace R134a (HFC) in some applications. Current research and industry trends show that HCFCs and HFCs will be gradually replaced by HFC blends or by natural refrigerants (Mohanraj et al, 2009).

The fluorine gas (F-gas) regulation and the mobile air conditioning (MAC) directive of the European Union supported the development of low GWP refrigerants (Grof, 2009). The new non-ozone-depleting low-GWP refrigerants have a maximum value of 150 for the GWP/100-year time horizon. Some of these will have the potential for broader applications, however they present relative lower efficiency inside the existing systems and they have high costs. In general, natural fluids such as water, hydrocarbons (HCs), ammonia (R717) and carbon dioxide (R744) are refrigerants that have zero ODP and also have a very low GWP. Furthermore, these natural substances are found abundantly in nature, cooperating to ensure their competitiveness in the global market. Hydrocarbons tend to be less widely available and ammonia is sourced from specialist suppliers. During the last years, studies comparing the performance of synthetics and natural refrigerants in various applications were published. In spite of considerable efforts to improve the thermal properties of the alternative fluids and to develop new designs or control strategies for the systems, in some cases, inconsistent experimental results can be found (Domanski and Yashar, 2006).

Mohanraj et al. (2009) evaluated a mixture R290/R600a as substitute for R134a in a domestic refrigerator. It was observed a consumption reduction up to 13,2% with an increase of 3,6% in the coefficient of performance (COP), concluding that the hydrocarbons can be a long-term replacement for R134a. Yu and Teng (2014) replaced R134a in a refrigerator using different mixtures of hydrocarbons R290 and R600a. They concluded that the ideal mass charge in the system is 40% of mass charge with R134a. The freezer temperatures significantly increased using the hydrocarbons (using capillary tube lengths different of original system). The electrical consumption with hydrocarbons was lower than that of R134a, and the energy factors of hydrocarbons were higher than R134a. Abas et al (2018) studied the properties of main refrigerants candidates to substitute halogenated hydrocarbons. Based on efficiency, safety and environmental impact, the naturals (CO_2, HCs) and a few synthetic (R152a, R1234yf) refrigerants can be optimal options to this substitution. Hernandez et. al (2019) replaced R134a by R1234yf in a domestic refrigerator, evaluating the performance in terms of energy and exergy. The exergy destruction of the system with R134a is smaller than R1234yf. The optimization study showed a cost economy of 9,8% using R134a and 6,5% using R1234yf. Yang et al (2019) compared R134a and its replacement by R513A in a domestic refrigerator. The freezing capacity obtained with R513A was higher than R134a, with a mass charge 5,9% lower. The discharge temperature and compressor pressure ratio of the system with R513A was lower than R134a. Gómez and Cascales (2019) studied the use of R1234yf as a drop-in replacement for R134a in a refrigeration system used to produce cool water. The refrigerant R1234yf obtained global efficiency 25% lower compared to R134a, due to its lower isentropic and volumetric efficiency. In spite of highly flammable characteristics, the hydrocarbons offer proper alternatives to the halogenated refrigerants in terms of environment impact, energy efficiency, refrigerant mass and compressor discharge temperatures (Harby, 2017).

The present work aims to contribute to knowledge about using alternative refrigerants. First was used the fluid R134a as working fluid, and then HFC was replaced by refrigerant R290 in the system. The experimental facility provides instrumentation and control strategies to evaluate behavior of the system operating with both fluids in terms of refrigerant capacity and COP.

2. MATERIAL AND METHODS

The basic equipment, visualized in the scheme of the Fig. 1, was located at the Energy and Transport Phenomena Laboratory of the Federal University of Triângulo Mineiro (LEFT/Mechanical Engineering/UFTM). Preview knowledge about operation limits of the experimental facility was a factor considered before apply the drop-in methodology. The experimental bench is equipped to support different refrigerant fluids and instrumented for the determination of the cooling capacity and efficiency in different conditions.

2.1 Experimental facility

The experimental facility consists of an alternative compressor, an air-cooled condenser, an evaporator that consists in an insulated thermal reservoir where the refrigerant pipe is immerged, an Electronic expansion valve (EEV) and all appropriate instrumentation: it were measured the temperatures and pressures of four main points of the cycle, the power consumption of compressor and the power of electrical resistor.

Pressure and temperature data were monitored and managed. The fixed mass of secondary fluid, which is the water inside the reservoir, is maintained at constant temperature (T_R). Moreover, the heat transfer in the evaporator is accomplished using a thermal storage tank that simulates a thermal load through an electrical resistance, with the function of maintaining stable the desired water temperature in the thermal reservoir.

The refrigeration capacity was calculated by the energy balance on the thermal reservoir/evaporator. The first step was applying the First Law of Thermodynamics, Eq. (1), for steady state condition, based on the consideration that the thermal reservoir is a system with a constant mass of liquid water. As the reservoir is insulated, thermal losses were neglected and the refrigeration capacity is equivalent to the electric work of the resistor:

$$\dot{Q}_{EV} = \dot{W}_{EL} = U_{RES}.\,i_{RES} \tag{1}$$

In the equation (1), $\dot{Q}_{REF}$ represents the cooling capacity (kW), U_{RES} (kV) and i_{RES} (A) are the electric tension and current measured at the resistor.

The power consumption in the compressor was measured in the same way, and calculated as follows:

$$\dot{W}_{CP} = U_{CP}.\,i_{CP} \tag{2}$$

Where $\dot{W}_{CP}$ represents the power consumption (kW), U_{CP} (kV) and i_{CP} (A) are the electric tension and current measured at the compressor.

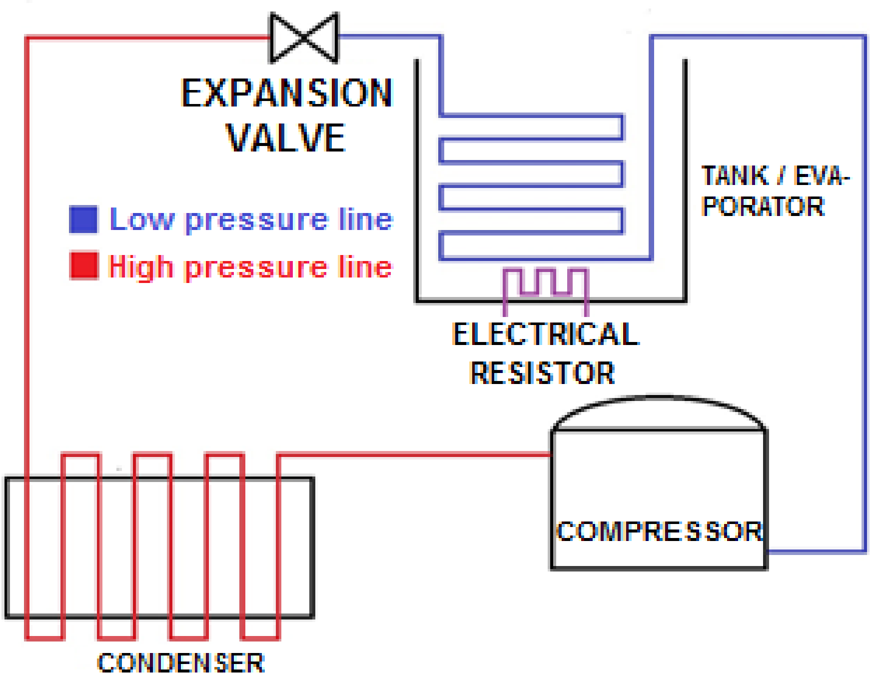

Figure 1. Schematic of the experimental facility

The coefficient of performance (COP) was calculated as the ratio between refrigeration capacity and required power in the compressor (Eq. 3):

$$COP = \frac{\dot{Q}_{EV}}{\dot{W}_{CP}} \quad (3)$$

Ratiometric pressure transducers (with measured uncertainty of 2.50 kPa) and resistance temperature detectors PT-100 (with measured uncertainty of 0.15°C) were used to measure pressures and temperatures, thus enabling the determination of the thermodynamic state of the refrigerant at each point of interest from the vapor compression cycle. The power consumption of the compressor was measured with uncertainty of 0.005 kW.

The mass charge of R134a used for all tests was 0,17 kg. This mass implies in best conditions of the system with R134a. The experimental facility operated originally with the R134a for residential refrigeration applications. It was considered the effects of the increment opening of electronic expansion valve in terms of evaporation temperature and temperature of thermal reservoir.

After the drop in, R290 was used in a smaller amount compared to R134a. It was not necessary to change the oil of compressor. The mass charge of the system with R290 was 0,065 kg (about 40% of R134a charge). During the tests, the parameters responsible for the simulation of thermal load were kept constant for all refrigerants, i.e. water temperature and valve opening were maintained constants at desired values.

2.2 Analyzed refrigerants

The analyzed refrigerants were R134a and R290. The R134a is the ideal fluid to substitute the R12, due to its similar properties, especially critical temperature. For this reason, it is widely used in residential refrigeration. The main advantage of R134a compared to R12 is that R134a has ODP zero. On the other hand, the efficiency of R134a is slightly lower than R12, due to its specific heat (Mc Linden, 1988).

Propane (R290) is a hydrocarbon (HC) that can be used both for refrigerating and for deep-freezing applications. It is also proposed and actually used in small heat pump and refrigeration systems (Palm, 2008). The main advantage of R290 compared to R134a is the reduced mass charge of the system, which can be 55% of mass charge with R134a or even lower, due to R290 high specific volume.

The Tab. 1 shows a comparison between R134a and R290 properties. It can be observed that both fluids have ODP zero, but R134a has GWP much higher than R290, indicating a strong warming potential. On the other hand, R290 is extremely flammable in presence of open flames, sparks and static discharge of oxidizing materials. The safety classification of R134a and R290 are A1 and A3, respectively, according to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The classification A1 indicates non-toxic and non-flammable fluid, while A3 indicates non-toxic and flammable fluid.

Table 1 – R134a and R290 properties

REFRIGERANT	R134a	R290
Chemical formula	CH_2FCF_3	$CH_3CH_2CH_3$
Normal boiling point (ºC)	-26	-42
Safety Group (ASHRAE)	A1	A3
Flashpoint (ºC)	non-flammable	-104
Autoignition point (ºC)	non-flammable	468
ODP	0	0
GWP	1430	3

The Fig. 2 shows a comparison of thermodynamic properties of the refrigerants used in this work, in terms of pressure-enthalpy diagram, based on the ASHRAE reference state, which the values of specific enthalpy and specific entropy are each set to 0 for saturated liquid at -40°C. It can be observed that both fluids have similar range of application, and the R290 has higher pressures for similar evaporation temperatures. Also, can be seen that for similar conditions, the R290 has higher latent heat than R134a, indication a potential heat transfer that can improve efficiency of the thermal systems where this refrigerant can be applied.

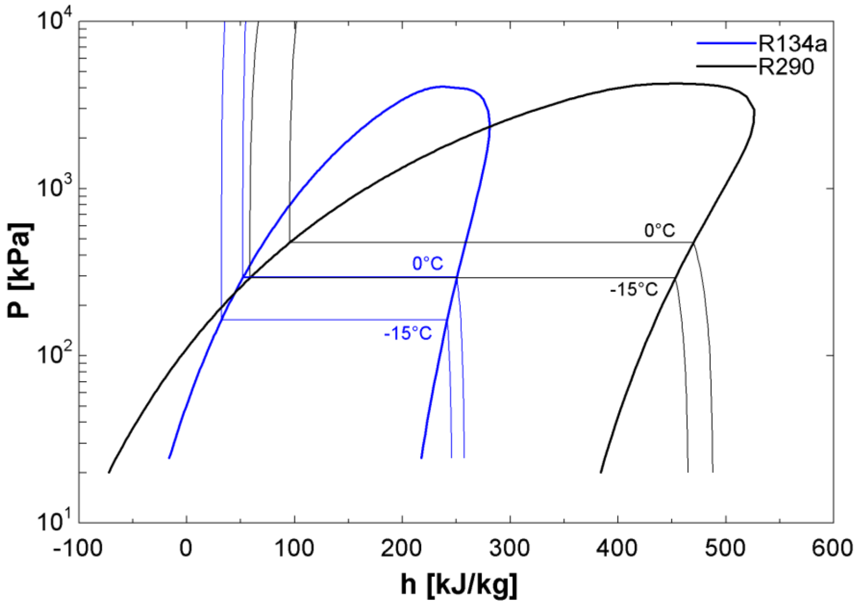

Figure 2. Pressure-enthalpy diagram comparing the refrigerants R134a and R290.

3. RESULTS AND DISCUSSION

The first experimental phase was represented by 9 tests for the system with R134a. The objective was to explore different thermal load conditions for residential applications, proven by evaporation temperatures in Table 2. Therefore, it was necessary to maintain different temperatures in the reservoir (T_R) during the tests and to modulate the electronic valve in different opening conditions. Then the refrigerant in the system was replaced by R290 and the tests were performed in the same levels of reservoir temperature and valve opening. The experimental designs also objectified to prove that the system with R290 can also operate in a similar way to the original system, however the T_{EV} column has higher values, which occurs due to the variation of the volumetric capacity to the evaporation temperature for the studied fluids. According to Antunes and Bandarra Filho (2016), this parameter is a measure of the cooling capacity per volume of refrigerant displaced by the compressor unit. It is a property of the refrigerant and the system operating point. The volumetric capacity decreases with the reduction of evaporation temperature. This is mainly due to the decrease of vapor density at lower temperatures. Moreover, the compressor required for a system operating with R290 must be smaller than the R134a compressor.

In this work, tests with both fluids were performed with the same valve openings, if were tested smaller valve openings, lower TEV values could be obtained for R290. The mass charge could also be reduced to achieve lower evaporation temperatures.

The levels values of reservoir temperature (T_R) and evaporation temperature (T_{EV}) are showed in table 2:

Table 2. Level values of the experiments.

Fluid	Test number	T_R (ºC)	T_{EV} (ºC)	Fluid	Test number	T_R (ºC)	T_{EV} (ºC)
R134a	1	7.0	-12.5	R290	10	7.0	0.5
	2	5.0	-11.1		11	5.0	-0.9
	3	5.0	-9.8		12	7.8	0.5
	4	7.8	-15.3		13	2.2	-3.8
	5	2.2	-12.5		14	7.0	-0.9
	6	7.0	-13.9		15	5.0	-1.6
	7	3.0	-9.8		16	3.0	-1.6
	8	3.0	-13.9		17	3.0	-4.6
	9	5.0	-12.5		18	5.0	-4.6

The Fig. 3 shows the application range of each refrigerant tested in the experimental facility. It can be observed that the evaporation temperatures with R290 were higher than R134a at tested conditions. In the case of R134a, the evaporation temperature is closer to domestic refrigerators evaporation temperature. The condensation temperature for R290 is also higher than that of R134a, indicating that the operation with R290 is near the operational limits of the experimental facility.

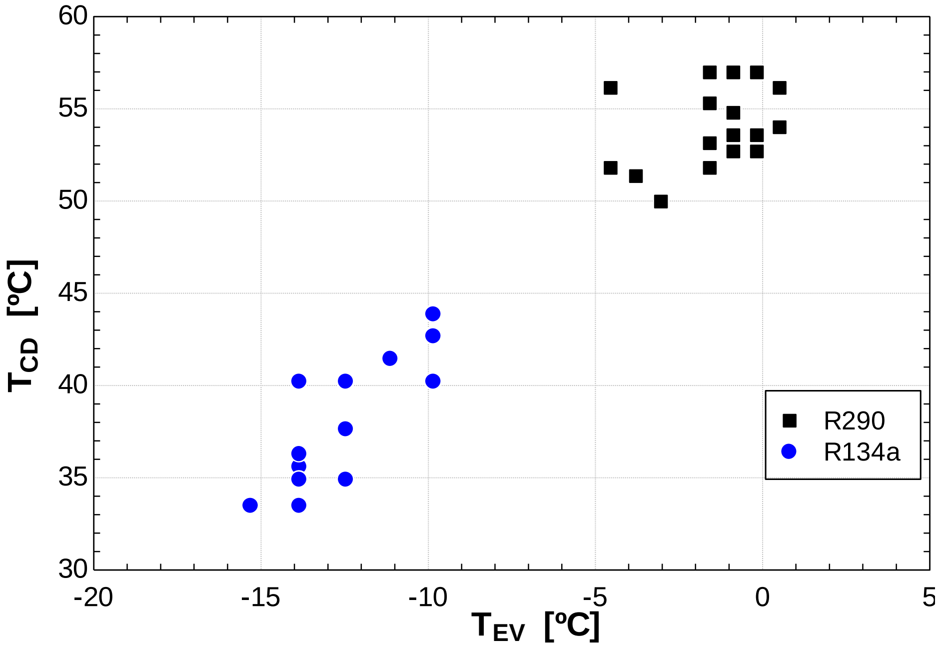

Figure 3. Application range (evaporation and condensation temperature) for tested refrigerants

The response surface in Fig. 4 shows the behavior of the refrigeration capacity according to variation of both factors (T_{EV} and T_R) for the system with R134a and R290. In Figs. 4, 5 and 7, points 1 to 9 indicates tests performed with R134a and points 10 to 18 indicates tests performed with R290. It is noted that the reservoir water temperature has a strong effect in the refrigeration capacity for both fluids. This occurs due to the geometry of the heat exchanger (evaporator), that provides constant temperature in the extern wall. Also, the thermal load is transferred to refrigerant by water, which have higher thermal conductivity than air. It can be observed that in this application range, the refrigeration capacity increases with evaporation temperature, indicating a flexibility of the refrigeration system. It is noted that the refrigeration capacity (Q_{EV}) of the system with R290 is significantly higher than R134a, which can be explained by the higher latent heat of R290 and higher evaporation temperature (T_{EV}) of R290 in the conditions analyzed. The maximum and minimum refrigeration capacity obtained with R134a were 0.41 and 0.15 kW, respectively. For the refrigerant R290, the maximum and minimum capacity were 0.66 and 0.40 kW.

The response surface in Fig. 5 shows the required power compressor. It can be observed a significantly higher consumption for the system with R290 in the range analyzed. The maximum and minimum power required with R290 were 0.363 and 0.298 kW, while the consumption with R134a varied between 0.218 and 0.244 kW. This higher consumption can be explained by the higher system pressure operating with R290 compared to R134a. The Fig. 6 shows a pressure-enthalpy diagram for the refrigeration cycle with both fluids for the test with reservoir temperature 5ºC and same valve opening. It can be observed that the evaporation pressure for R290 is about 450 kPa while for R134a the evaporation pressure is about 200 kPa, and this enhanced pressure implies a higher power required. For both fluids, the evaporation temperature has a stronger effect on power required than reservoir temperature, highlighting that in the drop-in process is extremely important adequate the expansion process (capillary length or valve opening), in order to maintain the energy consumption in the same level.

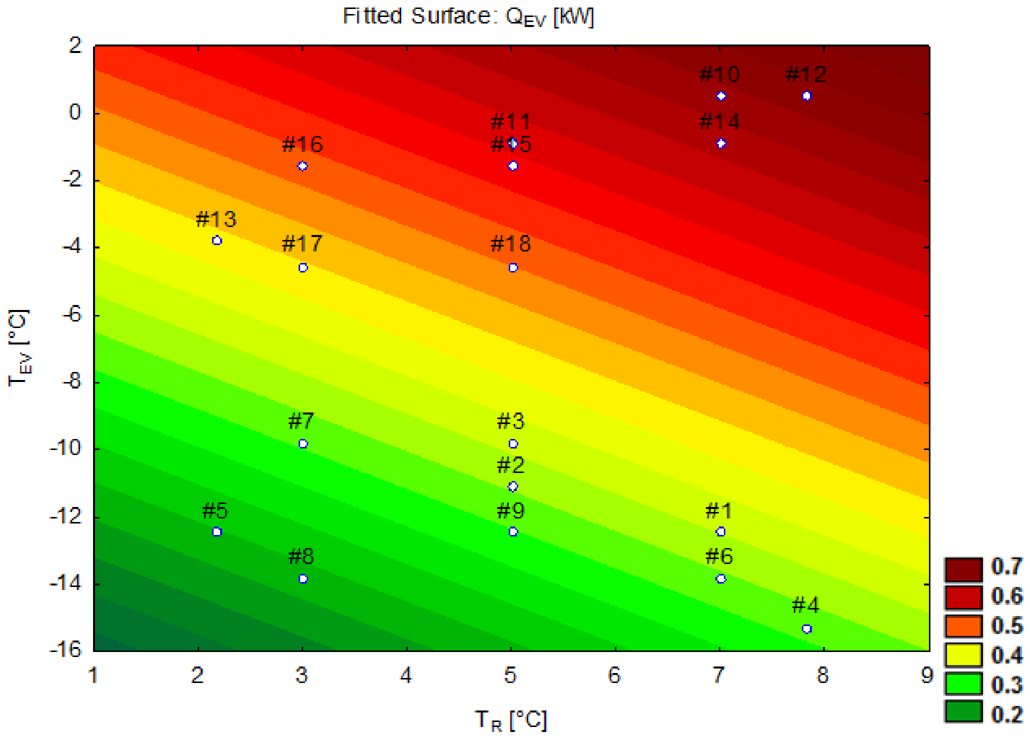

Figure 4. Response Surface for the Refrigeration Capacity. R290 (a) and R134a (b)

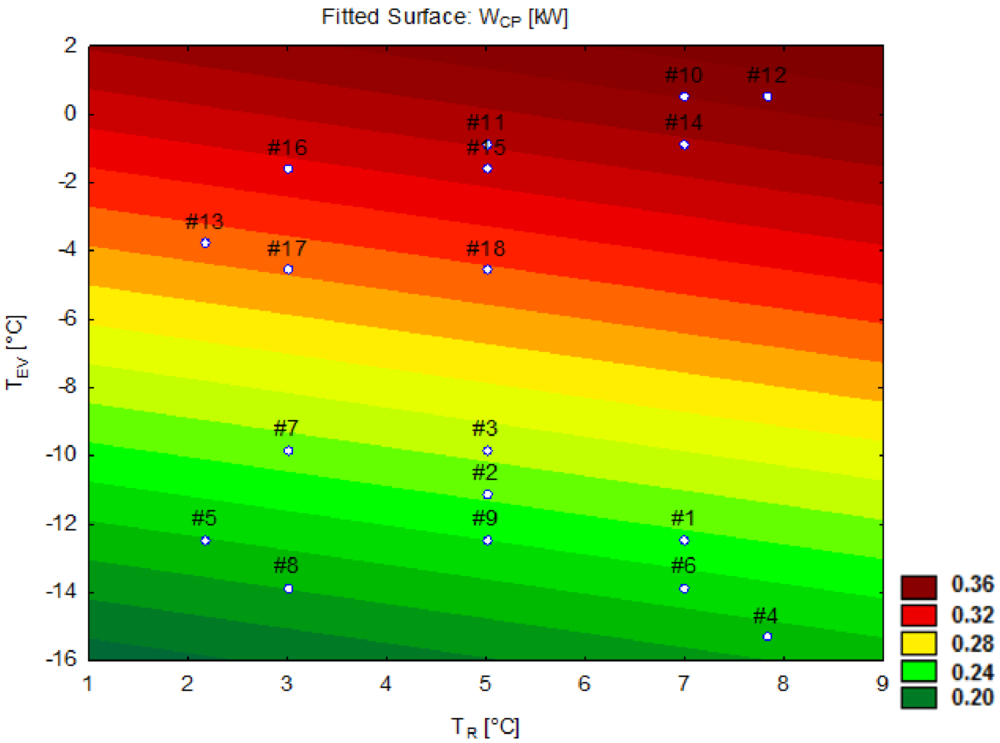

Figure 5. Response surface for the required power of the system with R290 and R134a

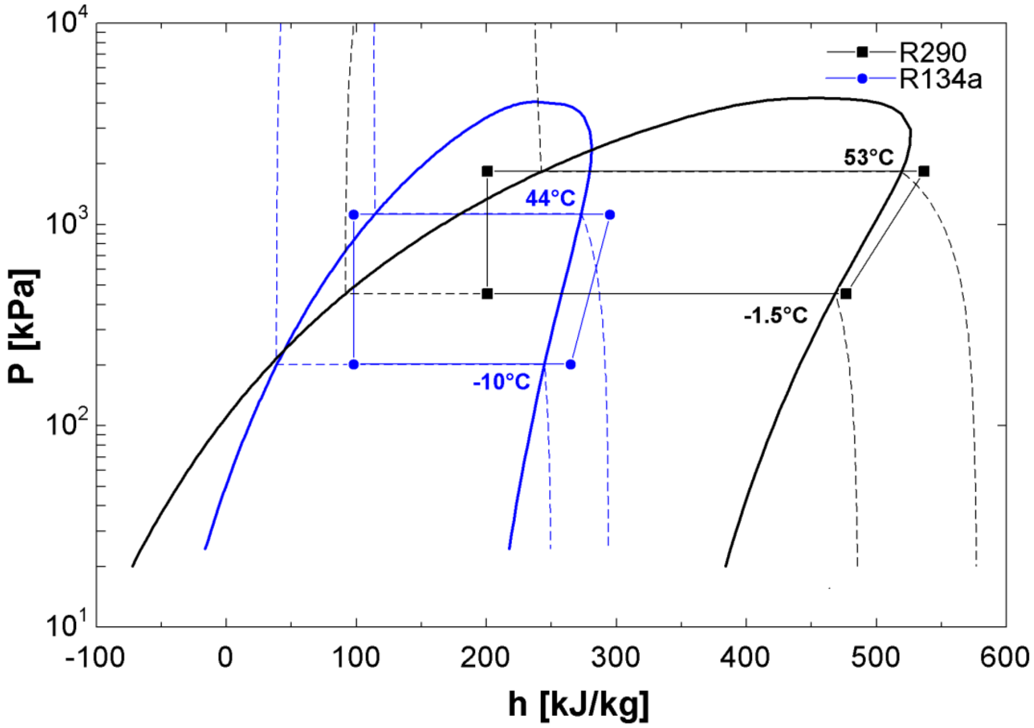

Figure 6. Pressure-enthalpy diagram for the cycles with R134a and R290

The response surface in Fig. 7 shows the efficiency (COP) according to variation of both factors for the system with R134a and R290. It can be observed a linear behavior of COP with the reservoir temperature and valve opening. For both fluids, COP increases with thermal load and evaporation temperature. The values of COP obtained for R290 (from 1.33 to 1.86) were higher than R134a (from 1.11 to 1.45). Even with a higher energy consumption, the higher refrigeration capacity implies an increase in system efficiency, indicating an application range that R290 has potential to replace R134a with energy saving.

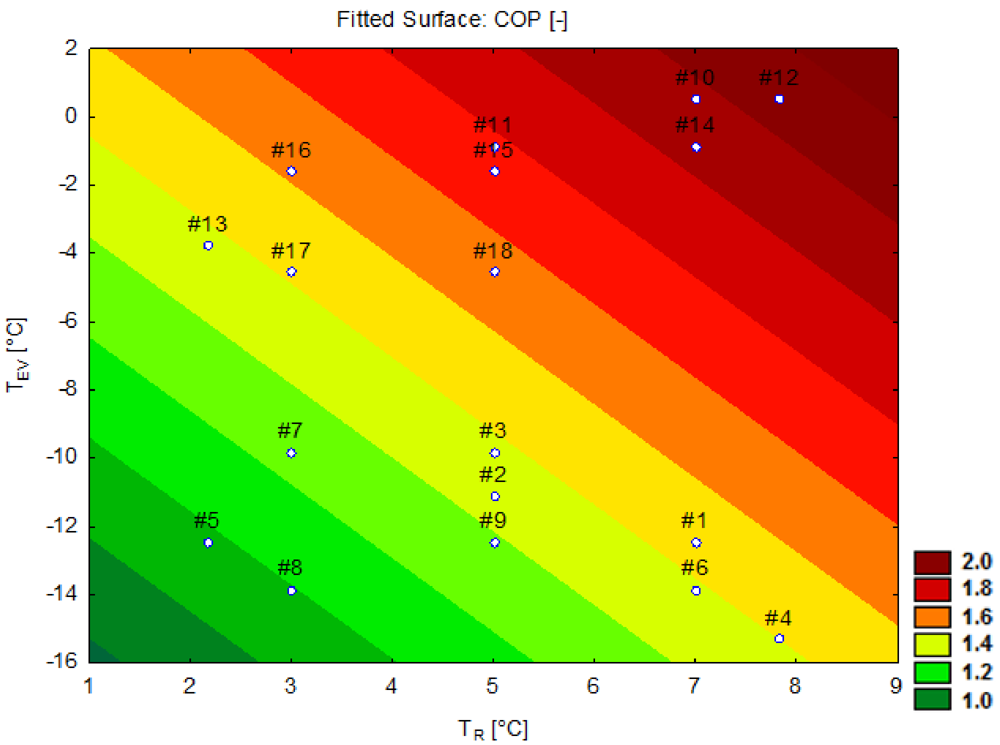

Figure 7. Response surface for the coefficient of performance (COP)

4. CONCLUSION

It was analyzed the possibility of drop in of R134a with R290 in a small refrigeration system, that represents an application in domestic refrigerator. The refrigeration system has operated with R134a and R290 in a flexible way with a well range of application. The results showed that the thermal load have a strong effect in the refrigeration capacity and COP. For higher temperatures of the thermal reservoir, the refrigeration capacity increases, due to the higher evaporation temperature that improves the total heat transfer.

The refrigeration capacity (Q_{EV}) of system with R290 was much higher R134a, which can be explained by the higher latent heat of R290 in the application range and higher evaporation temperature (T_{EV}) obtained for R290 with the same valve opening. The power required in the compressor is higher for R290. This occurs due to higher system pressure operating with R290 in the analyzed range. The effect on the refrigeration capacity was stronger than effect on energy consumption. This is evidenced by the higher efficiency (COP) of system with R290.

In general, results show that R290 has potential to replace R134a in small capacity application and the system refrigeration capacity can increase with this hydrocarbon.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Abas, N., Raza Kalair, A., Khan, N., Haider, A., Saleem, Z, Saleem, M.S., “Natural and synthetic refrigerants, global warming: A review”, Renewable and Sustainable Energy Reviews 90 (2018) pp557–569.

Antunes, A.H.P., Bandarra Filho, E.P., “Experimental investigation on the performance and global environmental impact of a refrigeration system retrofitted with alternative refrigerants”, International Journal of Refrigeration 70 (2016), 119–127.

Domanski, P.A., Yashar, D., “Comparable Performance Evaluation of HC and HFC Refrigerants in an Optimized System”. IIR Gustav Lorentzen Conference on Natural Working Fluids, 7th. Proceedings. May 28-31, 2006, Tondheim, Norway, 2006.

Grof, Tamas, “Preparing for HCFC phase-out: Fundamentals of uses, alternatives, implications and funding for” Article 5 countries. Grof, UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, Vienna, 2009.

Harby, K., “Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: An updated overview”, Renewable and Sustainable Energy Reviews 73 (2017) pp 1247–1264.

Illán-Gómez, F., Garcia-Cascales, J.R., “Experimental comparison of an air-to-water refrigeration system working with R134a and R1234yf”, International Journal of Refrigeration 97 (2019) pp 124–131.

McLinden, M. O. Thermodynamic evaluation of refrigerants in the vapour compression cycle using reduced properties. International Journal of Refrigeration. 11 (1988) pp. 134-143.

Mohanraj, M., Jayaraj, S., Muraleedharan, C., “Environment friendly alternatives to halogenated refrigerants—a review”, International Journal of Greenhouse Gas Control 3 (2009) 108–119.

Mohanraj, M., Jayaraj, S., Muraleedharan, C., Chandrasekar, P. “Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator”, International Journal of Thermal Sciences 48 (2009) pp 1036–1042.

Palm, B., “Hydrocarbons as refrigerants in small heat pump and refrigeration systems—a review”, International Journal of Refrigeration 31 (2008) 552–563.

Rangel-Hernández, V.H., Belman-Flores, J.M. Rodríguez-Valderrama, D.A., Pardo-Cely, D., Rodríguez-Muñoz, A.P., Ramírez-Minguela, J.J. “Exergoeconomic performance comparison of R1234yf as a drop-in replacement for R134a in a domestic refrigerator”, International Journal of Refrigeration 100 (2019) pp 113-123.

Yang, M., Zhang, H., Meng, Z., Qin, Y., “Experimental study on R1234yf/R134a mixture (R513A) as R134a replacement in a domestic refrigerator”, Applied Thermal Engineering 146 (2019) pp 540–547.

Yu, C.C., Teng, T.P., “Retrofit assessment of refrigerator using hydrocarbon refrigerants”, Applied Thermal Engineering 66 (2014) pp 507-518.

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