Technical and economic review of the reconversion of refrigerants in an air conditioner: HFCF to HC in Honduras

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1. Introduction

Air conditioning and refrigerators are one of the most known used applications of refrigeration, but this technology can also be found in medicine, refrigerated transport and marine refrigeration applications just to mention a few. But with massive globalization of these systems, comes an even bigger carbon print and greenhouse gases emissions. Even though large efforts are being made for sustainable refrigeration there is still a long way to go.

Synthetic refrigerants were created in 1930 to help commercialized refrigeration systems to domestics’ applications. With this CFC and HCFC were born and sold worldwide for every type of refrigeration application. However, in 1985 the British Antarctic Survey scientists discovered a hole in the ozone layer and rapidly made a connection with the impact that these types of refrigerants were having. This resulted in the creation of the Montreal Protocol in 1987 were laws were created to eliminate and find sustainable alternatives to these types of refrigerants. Then came HFC refrigerants designed to present no ODP, Ozone Depletion Potential, but contribute significatively with greenhouse emissions and have high GWP, Global Warming Potential. Therefore, the Kigaly amendment was created in 2016 to eliminate by 2050 the usage of HFC. This has brought researchers and refrigeration entities such as the ASHRAE, American Society of Heating, Refrigeration, Air-Conditioner Engineers, to study...
natural alternatives like hydrocarbons due to its low impact in global warming and sustainability. R290, R600a and R1270 are just some examples of these refrigerants. It is important to mention that hydrocarbons are one of the original refrigerants, but the usage was stopped due to its flammable properties.

1.1 Current situation
In present days great progress has been made in controlling the usage of CFC and HCFC in developed countries like China whose 85% of refrigerators are being produced using an hydrocarbon like R600a [1]. Germany and the United Kingdom are also producing not only refrigerators but air conditioners to function with blends of these type of refrigerants [2]. There has been lots of advances in substituting the most used refrigerants in working refrigerators like Wongwise & Chimres [3] and Yu & Teng [4] who found better performance with the substitute. With that been said, and even though Europe and Asia are making great advanced applying these green technology, third world countries are still struggling in the elimination on the usage of this harmful substances. A great example of this is Honduras where various environmental organizations have managed to create laws to prohibited the use of the harmful refrigerants but recommend to not use hydrocarbons as substitutes resulting in being left behind in the elimination of ODP compared to other countries in the region like Guatemala and Costa Rica.

1.2 Overview of R290
One of the household appliances where the problem was identified is air conditioners which used to use R22. Even though production of units with this refrigerant has long gone stopped, there is still many systems in various types of applications being used that contained this refrigerant. R290 is one the alternatives that has been pitched to substitute R22 because of its similar boiling point and ideal thermodynamics properties. R290 is not a new refrigerant, in the early 1900’s this was one of the most common refrigerants but because refrigeration technology was in its early stages it was fast replaced by synthetics refrigerants. However, in the present various studies are being conducted to approach this problem. Park & Jung [5] replaced R22 with various mixes of hydrocarbons resulting in better working conditions. Raj & Lal [6] mixed R600A/R290/R407 to create a safe way to use hydrocarbons in air conditioners but found cooling capacity was lower than expected. Wu et al. [7] conducted the direct replacement of R290 in a window air conditioner, to achieve this, the compressor was replaced and the performance was 10% better than the one with the previous refrigerant. Yang & Wu [8] perform experiments replacing R22 to achieve energy efficient systems with the new refrigerants, where it was concluded, through various investigations in controlled environment, that it was possible to obtain better discharge pressures and lower power consumption. Zhou and Zhang [9] compared the performance of R290 with other HCFC and HFC refrigerants and realized that an 8.5% better performance could be obtained. Devotta et al. [10] experimented using R290 in three different types of temperatures and humidity and the COP for the three cases varied between 2.8-7.9 % better than R22.

1.3 Safety requirements
Another aspect to review are safety characteristics when working with R290. As discussed earlier, one of the main reasons this is not a commonly used refrigerant is the fact that it has high flammability properties, classification A3 according to the ASHRAE. In the past years, many controlled experiments were made to show how safe would be a household appliance working with a hydrocarbon, Coulbourne & Suen [11] evaluated the usage of R290 and R600a in refrigerators and air conditioner and found it to be safe when the room is ventilated. Tang et al. [12] concluded these are three factors that could ignite a fire: refrigerant charge, the diameter in the hole that is causing the leak and ventilation. Depending on the type of hydrocarbon and location of the refrigeration system it is possible to calculate the permissible charge that would allow the system to work safely with the following equation [13]:

$$M_{max} = 2.5 \times LFL^5 \times h_0 \times \sqrt{A}$$  (1)
Where LFL is the lower flammability limit in mass terms, h0 is the height of the place the system is installed, and A is the area of the same place.

2. Thermodynamic design and method
An air conditioner of 1TR was modelled to study the substitution of R22 for R290, as air conditioners are the systems that usually carry these types of refrigerants. As well a temperature of 4.49°C for the evaporator and 49°C for the condenser were chosen according to the system optimal application parameters. Another main aspect was defining the internal loads of the place, this will be conducted through the CoolPack software and ASHRAE’ standard 55, as this transforms in thermal power, Pt, which must be removed. It is also important to determine the place where the system would be located as the permissible charge depends on this, in this case a small office with standard measurements of 2.46x2.63x3 m was chosen.

For the system design, an ideal vapor compression system was analyzed, as this helped simulate the system. This was achieved through the analysis of the refrigerant enthalpies in the CoolPack software. A compilation of equations were studied to help solve the system [14] in EES, Engineering Equation Solver, and in here the evaluation of the mechanical system was performed, for example to find the work performed in the compressor in an ideal cycle is through the heat of compression in equation (2):

\[ W_c = (h_z - h_1) \]  

(2)

The condenser is modelled through the rejection heat in the following equation:

\[ Q_H = m(h_z - h_3) \]  

(3)

In the evaporator the refrigeration effect was detected, alongside the cooling capacity, the latter one is determined by the compressor modelled through equations (4) and (5):

\[ RE = (h_1 - h_4) \]  

(4)

\[ Q_L = m(RE) \]  

(5)

Another parameter taken in account was the one that described the efficiency. First, the power for the isentropic process is calculated through equation (6):

\[ P = m \times W_c \]  

(6)

With its results, parameters like compressor ratio, equation (7), coefficient of performance, equation (8), and energy efficiency, equation (9), were analyzed:

\[ RC = \frac{P_2}{P_1} \]  

(7)

\[ COP = \frac{P_1}{P} \]  

(8)

\[ EER = 3.4141 \times COP \]  

(9)

As so, making an economic overview is essential to determinate the viability of the process. This was achieved through a cost benefit analysis was conducted, taking into account the investment to conduct the reconversion and the saving in the cost of energy in a period of five years, equation (10) describes it:

\[ C.B = \frac{\text{Energy}_{R22} - \text{Energy}_{R290}}{\text{Inversion}} \]  

(10)
Lastly, to determine an environmental analysis through the global warming emissions for both refrigerants working in the same system, equation (11) was used:

\[
TEWI = (m \times GWP \times L \times n) + (n \times E \times \beta)
\]

(11)

To analyze this, some assumptions were made like the normal leakage, L, of an air conditioner of 7% [15] and a carbon dioxide emission, \(\beta\), of 0.45 kg·CO₂/kW·hr [16].

3. Results and discussions

All the mechanical, economic and environmental factors were evaluated through the CoolPack and Engineering Equation Solver as shown in the paper. First the internal loads were calculated and resulted in a 1.24 kW load, then the permissible charge for the system was calculated and a charge of 0.317 kg is the maximum. This allows the other factors to be analyzed.

3.1. Mechanical evaluation

To evaluate the mechanical cycle two cases were proposed to achieve the implementation of the new refrigerant: maintaining the same cooling capacity, as this would allow the evaporator to deliver the same conditions and not be changed, and using 50% of the original refrigerant for the substitute, this choice was made taking in account Harby [17] and Cheng et al. [18] investigations. The results are shown in Table 1.

| Property                  | R22   | R290  | R290 (50%) |
|---------------------------|-------|-------|------------|
| Cooling Capacity [kW]     | 4.146 | 4.146 | 3.5251     |
| Flow rate [kg/s]          | 0.02859 | 0.01681 | 0.014295 |
| Refrigeration effect [kJ/kg] | 145  | 246.6 | 246.6      |
| Heat of compression [kJ/kg] | 30.3 | 53.3  | 53.3       |
| Power [kW]                | 0.866 | 0.8959 | 0.7619     |
| Condenser work [kW]       | 5.012 | 5.042 | 4.287      |
| Compressor ratio [-]      | 3.048 | 2.86  | 2.86       |
| COP [-]                   | 1.65  | 1.59  | 1.87       |
| EER [-]                   | 5.788 | 5.5926 | 6.38       |

Through 9 shows the comparation of the two cases with the original refrigerant.

![Figure 1. Cooling capacity of the evaporator.](image1)

![Figure 2. Flow rate of the refrigerants.](image2)
Figure 3. Refrigeration effect.

Figure 4. Compressor work.

Figure 5. Power consumption.

Figure 6. Condenser work.

Figure 7. Compressor ratio.

Figure 8. Coefficient of Performance.

Figure 9. Energy Efficiency Ratio.
Lower refrigerant effect and compressor ratio are maintained through both R290 cases as seen in figure 3 and figure 7, this can be interpreted as a higher capacity to absorb the heat in the system and obtaining a longer life for the mechanical system overall. Also, in figure 2 the flow rate decreases by 42-50% as expected, plus it was discovered that the mass charge was well below the limit making the use of this refrigerant safe in this kind of application.

It can be seen that when maintaining the cooling capacity for both refrigerants in figure 4 and 6, in the R290 system, the compressor and condenser must over work to deliver the same condition. Another aspect to notice in figure 5, 8 and 9 is as the mass rate increases the isentropic power consumption for the system increases too, directly affecting the energy efficiency and performance. This was resolved when using only 50% of the mass not only the efficiency and performance got better, but the mechanical effort was greatly reduced on every component. The cooling capacity in figure 1 was the only property that got reduced by 15%, one reason to explain this is that as the mass rate decreases the condensing and suction temperatures tend to decrease too resulting in an evaporator with lower performance.

3.2 Economical evaluation

To evaluate the investment, first all the standard procedures were considered like identifying, and subsequently isolating, all the ignition sources, then, as it resulted that none of the mechanical components needed to be change, labour was calculated. With this a total cost of $207.5 would be needed to reconvert the system.

For the power consumption, only the original system performance was analyzed and the R290 using the 50% of the charge was considered. To calculate the price of energy an exponential regression was performed in a period of 5 years.

A $213.85 saving can be made by using the new refrigerant, as shown in figure 10. Finally, to determine the economical viability of the project, a cost benefit analysis was calculated in equation (12).

\[ CB = \frac{\$213.85}{\$207.5} = 1.03 \quad (12) \]

Through calculating the economical evaluation it can be found that performing the substitution brings economical benefits because the savings in energy are greater than the investment.

3.3 Environmental analysis

As R290 has lower ODP and GWP than R22 it is to be expected that the carbon dioxide emissions would be significatively smaller. A comparation is presented in table 2.

| Table 2. Carbon dioxide emissions |
|---------------------------------|
| Refrigerant | TEWI         |
| R22         | 2852.69      |
| R290        | 4.072        |
With this it is proven that reconverting, results in a more sustainable system than expected decreasing emission by 142%.

4. Conclusions
This paper presents a non-experimental study in the reconversion of R22 HCFC refrigerant to R290 HC refrigerant in an air conditioner. It was proven that the new refrigerant charge is 50-58 % lower than the original and it was safe to use way below limits of flammability in small rooms such as offices. It was of great use investigating the implementation of the hydrocarbon in two perspectives: maintaining the same cooling capacity and using the 50% of the original refrigerator charge, as this allowed later on to choose the most efficient option to analyze in the economical section.

As it was shown in the results, the system working with the same cooling capacity, even though it offers great heat absorption, to maintain this condition the mechanical components must overwork and this may result later on in a wear for the system and decreased efficiency of the system.

When working with 50% of the original mass, the cooling capacity was minimized but all the mechanical components worked better and efficiency overall increased 14.1% compared to the other two refrigerants. It can be concluded that using this combination would get better results in the reconversion plus a safer system as lower mass is needed.

Also, it can be concluded that R290 shows great promise to be replaced in a small air conditioner because the mass needed is usually well below the limit. Other combinations can be made to get better performance results.

In the economic study, to modify the system a great investment must be made but, by choosing the lower-powered consumption combination, the benefits that outweigh the initial investment are greater. One of the great misconceptions is that there is no economical benefit to reconverting a refrigeration system but it can be concluded that this is not true by evaluating the cost benefit of the process where it was discovered that, in a five year period, it can result in gains.

Ultimately, one of the reasons this refrigerant was chosen is because of its low environmental impact. The carbon dioxide emission was calculated for both refrigerants and R290 emissions were insignificant, this might be due to the low mass used that caused a lower power consumption.

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