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A Theoretical investigation on HC Mixtures as Possible Alternatives to R134a in Vapor Compression Refrigeration

This paper provides a theoretical comparison of the performance of refrigerants in use in a vapor comparison cycle. It is about the phase-out of R134a from actual refrigeration system, comparison being performed for this chemical and two more ecological mixtures: R290/R600a described as (30/70) and (40/60). Were investigated effects of condensation temperatures and evaporation temperatures on performance measures as COP (Coefficient of Performance) and VCC (volumetric cooling capacity). COP is a measure of the performance of the refrigeration cycle, while VCC is an indicator of compressor size. Results of this study will reveal that R290/R600a (30/70) is a good option when it is about substitution of R134a, from energy efficiency point of view, in terms of COP. R290/R600a (40/60) has VCC values bellow the ones of R134a, but comparable.

Keywords*: evaporation, condensation, temperature, performance, compressor*

1. Introduction

This paper is a focus on the theoretical comparative analysis of the refrigerant impact on the performance characteristics of a basic one stage vapor compression refrigeration system.

Increase concerns about climate change led to the ban of CFC and HCFC refrigerants because of their chlorine content, high ozone depleting potential (ODP) and global warming potential (GWP). After '90s, several studies comparing performance of Hydrofluorocarbons (HFC), Hydrocarbons (HC) and other natural refrigerants were developed for different applications.

R134a is a wide spreaded HFC refrigerant often used to replace chlorine-containing refrigerants. Despite of the fact that this chemical is safe, efficient, reliable, available on the market, cheap and friendly with the ozone layer (ODP=0), it contributes to the global warming (GWP=1320) [1]. This drawback can be passed by using refrigerants belonging to HC family instead [2]. The use of R290 (known also as propane) and of R600a (known also as isobutane), both of them HC refrigerants, in order to replace HCFCs, but also HFCs, is a running process around the world. These two HCs present a null ODP and only a fraction of the global warming potential of the refrigerants they are intented to substitute. They are flammable, but they have acceptable levels of toxicity.

In Table 1 are given some refrigerant information for the chemicals involved in this study [3]. In this table, shown pressures correspond to 7.0^{o}C dew-point temperature.

Table 1. Selective refrigerant properties

Refrigerant	Saturated Vapor Pressure	Molar Mass (g mol^{-1})	Molar Vapor Specific Heat (J mol^{-1}K^{-1})	Safety Designation	GWP (100 years horizon)
R134a	374.6	102.03	94.93	A1	1320
R290	584.4	44.096	81.88	A3	20
R600a	199.5	58.122	97.79	A3	20

In the following will be presented results regarding performance characteristics of mixtures of R290 and R600a (30/70 and 40/60) versus R134a, in terms of COP (Coefficient of Performance) and VCC (volumetric cooling capacity).

High COP values indicate high performance of the refrigeration cycle, while high VCC is an indicator for small size compressor requirement. Also when comparing VCC values for different refrigerants, close values show that a potential substitution requires same size of the compressor.

2. Analysis of vapor compression system

The one stage vapor compression refrigeration system is the one considered for the proposed study; it is composed by a mechanical piston compressor, a condenser, an expansion valve and an evaporator (see Figure 1).

The refrigerant vapor having low pressure and temperatures enters in the compressor with state 1; here it is compressed isentropically, resulting vapor with a higher temperature and pressure (2). These vapors are led, in the condenser to be turned unto liquid, by heat rejection to the environment. The high pressure liquid (state 3) is introduced in the expansion device for pressure decrease (isenthalpic 3–4), being reached a low pressure (evaporator pressure). With state 4, the refrigerant enters in the evaporator where it absorbs heat. Results refrigerant vapors which will be sucked by the compressor making the cycle to continue in order to keep the temperature in the evaporator much under the atmospheric temperature.

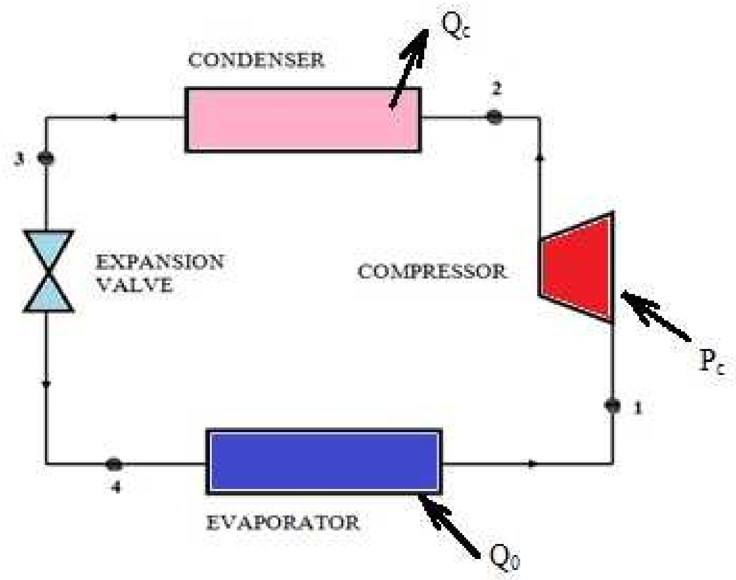

Figure 1. Representation of a basic vapor compression system

The theoretical analysis of this system is based on the thermodynamic analysis involving assumptions and equations given bellow [4,5,6]:

Assumptions:

- the system is in steady state,
- the refrigerant is in state of saturated vapor when enters in the compressor,
- pressure losses along pipes and in valves are neglected.

The volumetric cooling capacity (VCC) is a measure of the compressor size for required working conditions. It is expressed by the effect of cooling obtained per $1m^3$ of refrigerant entering in the compressor:

$$VCC = \frac{(h_1 - h_4)\eta_{vol}}{v_1}, \quad (1)$$

where:

h – specific enthalpy,

v – specific volume.

The volumetric efficiency from eq. (1) is found with:

$$\eta_{vol} = 1 + C + C\beta^{\frac{1}{n}}, \qquad (2)$$

where:

C – clearance ratio,

β – pressure ratio (ratio between the condensation pressure and evaporation pressure).

Refrigeration industry have developed standards for measuring energy efficiency. One of the terms in use is COP (Coefficient of Performance).

The Coefficient of Performance (COP) is the rate between the heat extracted at low temperature and the work supplied, as:

$$COP = \frac{Q_0}{P_c}, \qquad (3)$$

The cooling capacity (the refrigerating effect) Q_0, and power required by the compressor, P_c are evaluated with:

$$Q_0 = m_{ref}\left(h_1 - h_4\right), \qquad (4)$$

$$P_c = m_{ref}\left(h_2 - h_1\right), \qquad (5)$$

where:

m_{ref} – refrigerant mass flow.

3. Results of the analysis and discussions

The comparative theoretical assessment is done for R134a – as actual refrigerant, and two ecological mixtures formed by R290 and R600a described by the concentrations: R290/R600a (30/70) and R290/R600a (40/60) – as possible substitutes.

Will be analyzed the influence of temperature on COP and VCC for a specific evaporation temperature, for the three mentioned refrigerants. The condensation temperatures vary in the range (30 ÷ 50)°C and the evaporation temperature is fixed at –9°C.

Will be analyzed the influence of evaporation temperature on COP and VCC for a given condensation temperature of the three specified refrigerants. The evaporation temperatures vary in the range (–25 ÷ –5)°C while the condensation temperature is fixed at 38°C.

In Figure 2 it is depicted the variation of COP with varying condensation temperature, at constant evaporation temperature (t_0).

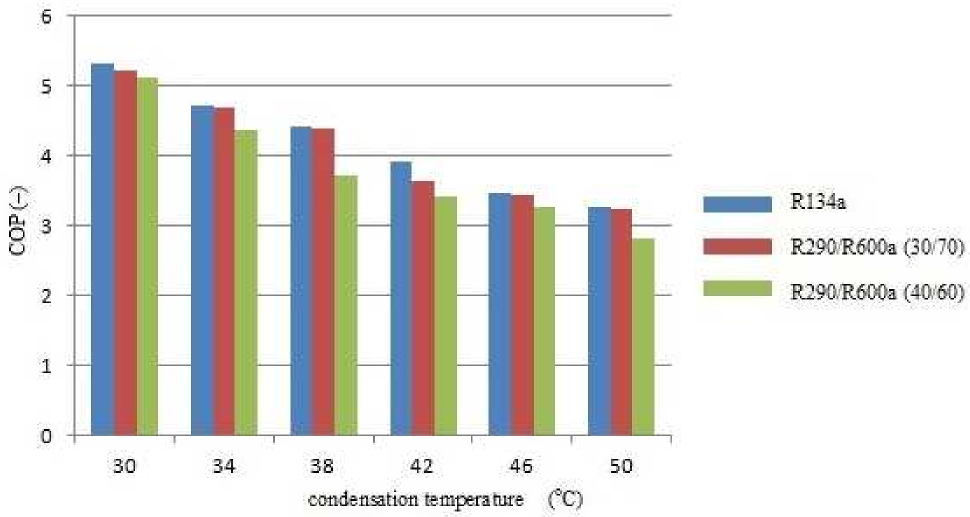

Figure 2. COP versus condensation temperature, when t_0 = –9°C

COP values decrease with the increase of condensation temperature, when evaporation temperature is kept constant. Best COP values, in this situation are seen for the actual refrigerant (R134a), while COP for substitutes (the two mixtures) is lower. But R290/R600a (30/70) presents COP values closer to the ones of R134a. Moreover, for high condensation temperatures, COP values for R290/R600a (30/70) are almost similar with the ones of R134a.

In Figure 3 it is shown the variation of VCC with varying condensation temperature, at constant evaporation temperature (t_0).

VCC decrease with the increase of the condensation temperature, when evaporation temperature is kept constant. The best cooling capacity is observed also for R134a, but the mixtures present much lower values. Still, the closer it is found to be for R290/R600a (40/60).

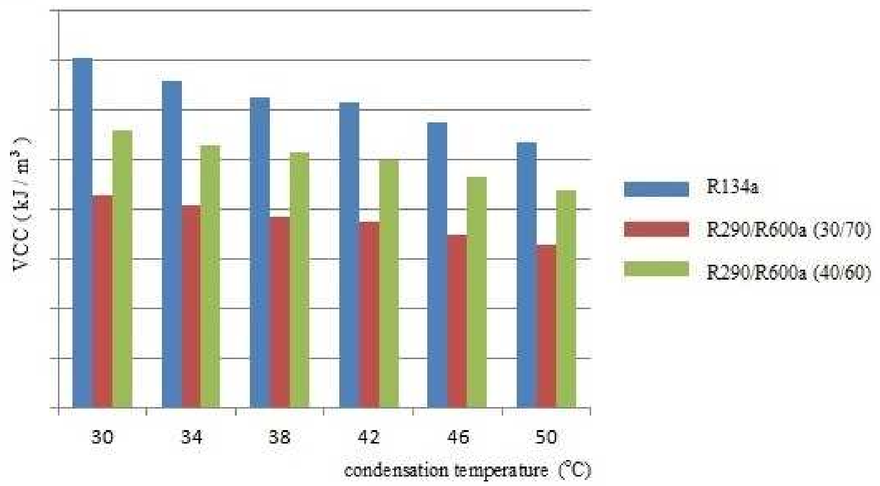

Figure 3. VCC versus condensation temperature, when t_0 = –9°C

In Figure 4 it is presented the variation of COP as a function of evaporation temperature, at constant condensation temperature (t_c).

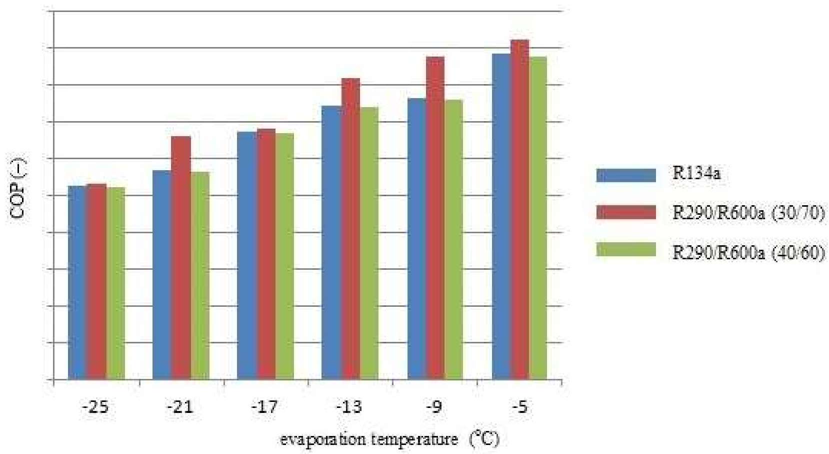

Figure 4. COP versus evaporation temperature, when t_c = 38°C

When the condensation temperature is kept constant while increasing evaporation temperature, results for COP an increasing trend. This time, R290/R600a (30/70) indicates the best performance in COP terms. R134a and R290/R600a (40/60) show cvasi identic COP values.

In Figure 5 one can see the variation of VCC as a function of evaporation temperature, at constant condensation temperature (t_c).

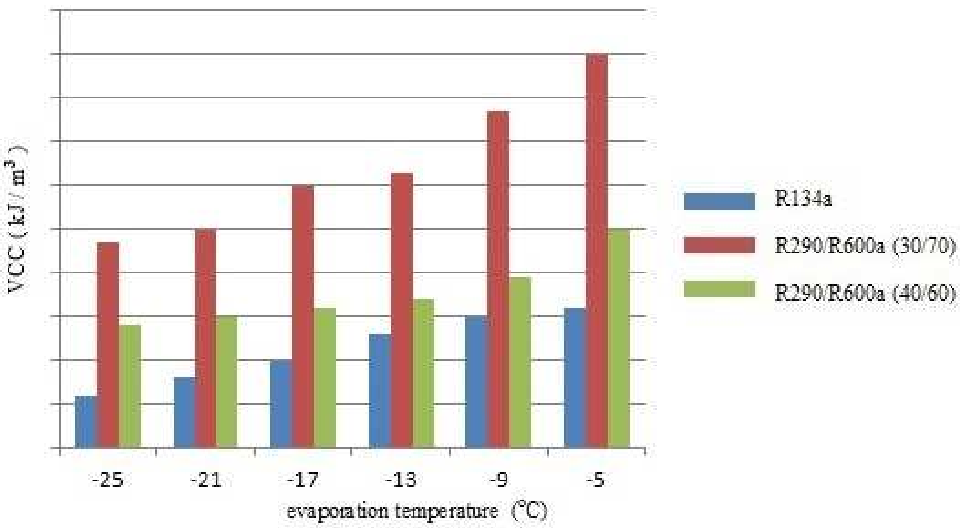

Figure 5. VCC versus evaporation temperature, when t_c = 38°C

Together with the increase of the evaporation temperature, it is possible to get higher VCC values for all working refrigerants, when condensation temperature is kept constant. Maximum cooling capacity for this study, it is reached for R290/R600a (30/70), R290/R600a (40/60) having also higher VCC values compared with R134a, but the difference is less.

4. Conclusion

R134a is free from chlorine and has zero ODP, but has relatively high GWP.

For this reason, this paper was discussing about candidates to replace it in ideal one stage vapor compression refrigeration systems.

For comparison of the theoretical data, R134a was chosen as reference refrigerant, while two ecological mixtures, R290/R600a (30/70) and (40/60), are selected as substitutes.

The investigation revealed the following:

- R290/R600a (30/70) offers COP values slightly under the ones of R134a, when condensation temperature varies and evaporation temperature is constant; but when evaporation temperature varies and condensation temperature is constant R290/R600a (30/70) shows the higher COP values among all three refrigerants; for the given case of study, best COP is 4,62 and it is reached for $t_0 = -5^oC$ and $t_c = 38^oC$;

- when condensation temperature varies and evaporation temperature is constant, the best cooling capacity is offered by R134a, while when evaporation temperature varies and condensation temperature is constant, R290/R600a (30/70) shows higher VCC values and therefore it requires small size of compressor;
- in the both situations, R290/R600a (40/60) has closer VCC values to the ones of R 134a in comparison with R290/R600a (30/70), comparable VCC values meaning that a substitution requires same size of compressor.

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