Preliminary study on vapor compression refrigeration cycle with an internal phase-separating loop using a R290/R600a mixture in air conditioner

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Preliminary Study on Vapor Compression Refrigeration Cycle with an Internal Phase-Separating Loop Using A R290/R600a Mixture in Air Conditioner

INTRODUCTION

Currently the use of air conditioning (AC) has been most extensively associated with the comfort of human life. However, there are some various problems that are caused by the widespread use of air conditioning, such as the presence of global climate change that affects the ozone layer structure and the greenhouse effect in the atmosphere caused by the amount of air-cooled material released into the earth's atmosphere in the form of a synthetic gas refrigerant, that is, refrigerant containing Hydro / H, Chloro / Cl, Fluoro / F and Carbon / C [1]. The international community's seriousness to eliminate materials potentially causing the depletion of the ozone layer and global warming has been triggered through an international agreement referred to as the Vienna Convention and the Montreal Protocol where the use of CFCs should be abolished [2]. Hence, the demand for the development of refrigerant usage has reached the fourth generation that has required zero / low Ozone Depletion Potential (ODP), Low Global Warming Potential (GWP), Short Lifetime in the atmosphere and high efficiency [3]. Hydrocarbons as refrigerants that have been known since 1920 have attracted interest to be used again as a refrigerant. Hydrocarbons commonly used as coolant are propane (R-290), isobutane (R-600a), n-butane (R-600) and the most frequently used mixtures are R-290/R-600a, R-290/600 and R- 290/R-600 / R-600a [4,5]. Compared to synthetic refrigerants, hydrocarbons have several advantages such as: they are more environmentally friendly which is indicated by a zero ODP value and a negligible GWP, thermo-physical properties and good heat transfer characteristics, low vapor phase density supporting energy-saving use, and good solubility with mineral lubricants [3,6,7].

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TABLE 1. Environmental parameters of some refrigerants

No	Refrigerant	ODP	GWP	ALT
1	R-12	1.0	1500	130
2	R-22	0.06	540	15
3	R-134.a	0	1300	16
4	HC	0	3	<1

where: ODP = Ozone Depletion Potential, GWP = Global Warming Potential and ALT = Atmospheric Lifetime.

The R134a synthetic refrigerant widely used in air conditioning systems today, especially in vehicles, is one of the controlled substances in the Kyoto Protocol of 1997. R134a as an alternative to R12 has good properties, non-toxic, non-flammable and relatively stable. However R134a is relatively expensive, and still has potential as a substance that can cause global warming effect due to high GWP 1300. In addition R-134a is highly dependent on synthetic lubricant which often causes problems with its hygroscopic nature [4,8].

Retrofit is an attempt to refurbish a refrigeration system in order to operate better without making any significant changes to the main components. The principal condition of AC retrofit with an alternative refrigerant is that alternative refrigerant must have the same characteristics of pressure and saturation temperature. Figure 1 shows the relationship characteristics of pressure and saturation temperature between R134a synthetic refrigerant with R290 and R600a hydrocarbon refrigerant. Taking into account the tendency in FIG. 1 to retrofit the conventional air conditioning system of base R134a with R290 as well as with R600a cannot be directly performed because they have different temperature and pressure saturation characteristics. However, taking into account Figure 1 that the R134a graph is squeezed between the graphs R290 and R600a, it is possible to make a mixture of R290 and R600a having saturation characteristics equal to / close to R134a. This possible mixture can be utilized instead of R134a directly.

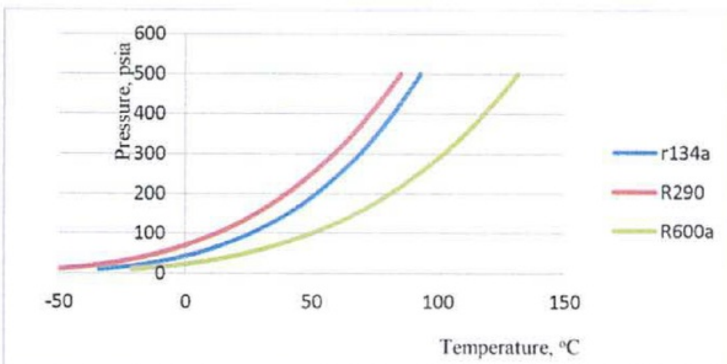

FIGURE 1. Pressure Vs Temperature saturated characteristics of R134a, R290 and R600a. (created by using REFPROP)

The problem that arises when using the R290 / R600a blend refrigerant in a conventional air-conditioning vapor compression refrigeration cycle is the occurrence of a two-phase flow on the condenser exit side caused by the formation of R290 gas. This is because the saturated R290 saturation pressure is under the pressure of the condenser work, while the R600a is maintained in a liquid state because the saturated pressure of R600a is purely higher than the condenser working pressure. This may improve the resistance of the heat transfer rate and further reduce the performance of the vapor compression cycle [9]. In addition, the R290/R600a mixture is zeotropic. This mixture does not evaporate and condenses at a fixed temperature in the vapor dome, but the evaporation and condensation process occurs in a certain range which is known as glide temperature. As a result of the glide temperature makes the relationship of pressure and temperature and thermal properties will change. This glide temperature will greatly affect the process of heat transfer in the evaporator and condenser. In the evaporator the evaporating temperature increases with the evaporation process, whereas in condenser the condensing temperature decreases with the condensation process. Temperature changes occurring at these fixed pressures impair the effects of heat transfer on the evaporator and condenser and decrease the performance of the vapor compression cycle [10].

The purpose of this research is to develop a suitable vapor compression refrigeration cycle to apply the R290 / R600a mixture capable of delivering optimum performance close to or even higher than conventional AC R134a vapor compression cycle performance as a solution to obtain an environmentally friendly R134a replacement.

ILP-VCC VAPOUR COMPRESSION CYCLE

Efforts to improve the efficiency of vapor compression refrigeration cycles have led to more specific studies and innovations in terms of components, systems and energy consumption considerations. To improve the performance of the refrigeration cycle, a gas separator component may be used as a device for separating the gas phase from a two phase fluid flow in a vapor compression refrigeration cycle using zeotropic refrigerant. The system with the gas separator is expected to increase the suction pressure of the compressor and consequently reduce the net compressor work [9].

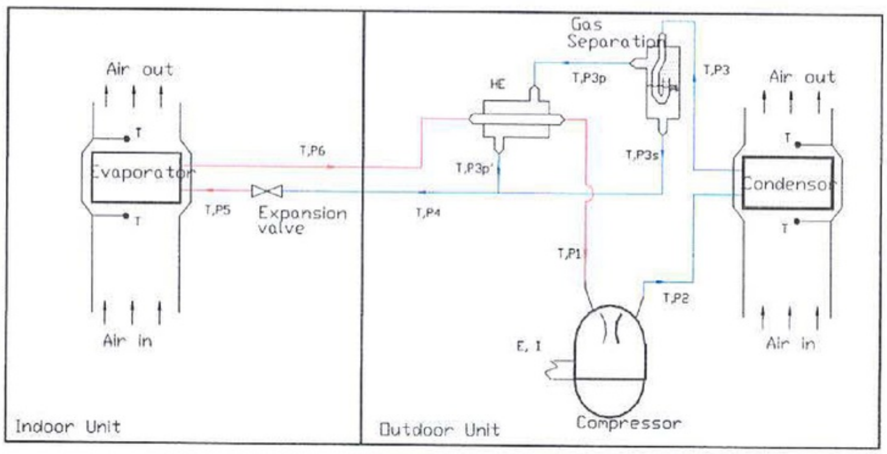

FIGURE 2. Experimental set-up

In this study, a gas phase separator was added to the conventional air-conditioning vapor compression cycle on the refrigerant side out of the condenser, as showed in Figure 2. The vapor compression cycle with phase separator forms an internal loop (ILP-VCC) to convert the gas phase into a liquid phase before entering the expansion valve, ensuring that the refrigerant enters the expansion valve completely in a liquid state.

The refrigeration cycle at ILP-VCC is as follows: a mixture of R290/R600a in gaseous state enters the compressor (state 1) is compressed to superheated steam (state 2) then the mixture is fed to the condenser. In the condensation process because both components have different temperatures and saturation pressures then it is possible that the component having a saturation pressure above the condenser working pressure will remain liquid while the component having the saturation pressure under the condenser working pressure will evaporate into gas. thus the R290 / R600a mixture coming out of the condenser is possible as a two-phase flow. This two-phase mixture is then fed to the phase separation component, the viscous partial liquid is directly fed into the expansion valve and then enters the evaporator (state 4). on the other side the gas from the phase separator is passed to the internal heat exchanger and cooled to below the saturation point so that it turns into liquid phase, the liquid is then flowed to rejoin the partial fluid (state 4) to the expansion valve and then enter the evaporator (state 5) to undergo the evaporation process. The final step, R290/R600a mixture coming out of the evaporator (state 6) in the gas state returns to the compressor inlet (state 1), and so on.

The performance of ILP-VCC can be approximated by mathematical analysis of Coefficient of Performance (COP) values. To simplify, the equation is written in the mass union of the refrigerant at the inlet of the compressor. Pay attention to picture 2, the refrigeration effect can be calculated using the equation,

$$h_3 = (m.h)_{3,R290.\,gas} + (m.h)_{3,R600a.liquid} \quad (1)$$
$$h_4 = (m.h)_{3p',R290.\,\mathrm{liquid}} + (m.h)_{3i,R600a.liquid} \quad (2)$$
$$h_5 = h_4 \quad (3)$$
$$q_r = h_6 - h_5 \quad (4)$$

Where, q_r is the refrigeration effect in Btu/lbm, h_2 is the enthalpy on the evaporator outside in Btu/lbm, h_5 is the enthalpy at the inlet side of the evaporator in Btu/lbm.

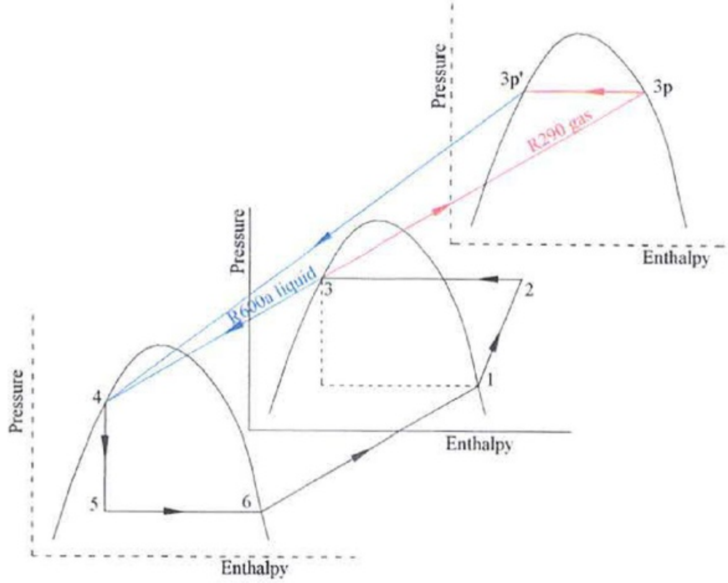

FIGURE 3. P-H diagram of vapor compression refrigeration cycle with phase separator (ILP-VCC)

Volumetric cooling capacity is calculated based on suction compressor:

$$q_{ev} = {}^{q_r}/_{v_1} \quad (5)$$

where q_{ev} is the volumetric cooling capacity in Btu/ft^3, v_1 is the specific volume of refrigerant at point 1 in ft^3/lbm. Specific work is the work equivalent to enthalpy changes during the compression process and formulated as follows:

$$w_c = h_2 - h_1 = \frac{h_{2s} - h_1}{\eta_{is}} \quad (6)$$
$$\eta_{is} = 0{,}8734 - 0{,}013.\frac{P_2}{P_1} \quad (7)$$

where w_c is the specific work of the compressor in Btu/lbm, h_1 is the enthalpy at the beginning of the compression process in Btu/lbm, h_2 is the enthalpy at the end of the compression process in Btu/lbm, η_{is} is the isentropic efficiency of compressor [11]. P_1 and P_2 are the inlet pressure and pressure out compressor in psia. The total compressor power requirement is calculated from the equation:

$$W_{ct} = \dot{m}(h_2 - h_1) \quad (8)$$

where W_{ct} is the total compressor power in Btu/s.

COP is used to express the performance of the refrigeration cycle. The higher the COP that can be achieved the better the performance. COP can be calculated by equation:

$$COP = {}^{q_r}/_{w_c} \tag{9}$$

ANALYTICAL PROCEDURE

This preliminary study mathematically analyzed of the performance of the R290/R600a mixture applied to the developed phase-separating vapor compression cycle (ILP-VCC). The performance of R134a and R290 / R600a in conventional vapor compression cycle (C-VCC) R134a base, was also analyzed. The results were then compared to find out whether there was an increased performance of the R290/R600a mixture applied to ILP-VCC. The thermodynamic properties of R134a and the R290/R600a mixture were obtained from the REFPROP software. Analysis of thermodynamic properties at each spesific state of the cycle was performed using REFPROP software to obtain enthalpy refrigerant values at each cycle spesific state. The performance analysis of R134a on C-VCC was performed at compressor suction working pressure $P_1 = 50$ psia. Assuming that the compression ratio $P_2 / P_1 = 2.7$ we can calculate the compressor discharge pressure obtained by $P_2 = 135$ psia. Both working pressures $P_1 = 50$ psia and $P_2 = 135$ psia are also applayed to study the performance of the R290/R600a mixture on C-VCC and also on ILP-VCC. Furthermore, cycle performance parameters such as refrigerant effect, compressor work, cooling capacity, refrigerant charge and COP are calculated and analyzed. The results of the analysis and calculations that have been obtained are subsequently written on the table and drawn in graphical form then discussed.

RESULTS AND DISCUSSION

Related cycle performance parameters are shown in Figures 4 to 9 below. Figure 4 and Figure 8 prove that the ratio of volumetric cooling capacity of the various refrigerants that have been calculated. R134a on C-VCC has the greatest volumetric cooling capacity compared to R290/R600a in both C-VCC and ILP-VCC. R290/R600a when applied to C-VCC has a lower volumetric cooling capacity than when applied to ILP-VCC.

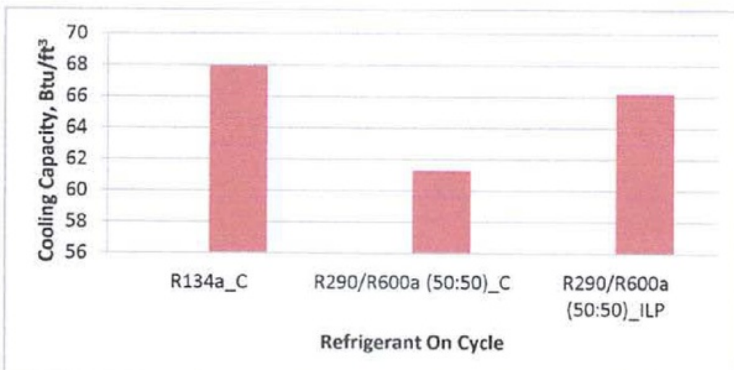

FIGURE 4. Comparison of volumetric cooling capacity of various refrigerant on C-VCC and ILP-VCC.

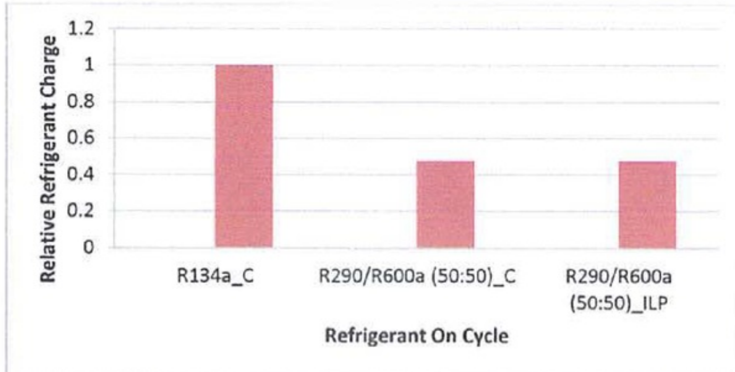

FIGURE 5. Comparison of the refrigerant charge relative to R134a of various refrigerant on C-VCC and ILP-VCC.

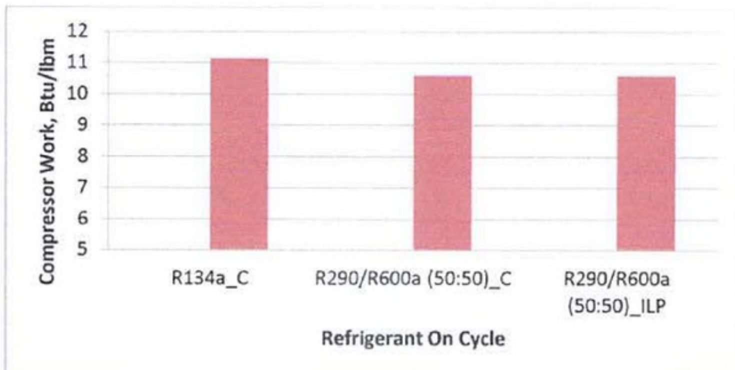

FIGURE 6. Comparison of compressor work of various refrigerant on C-VCC and ILP-VCC.

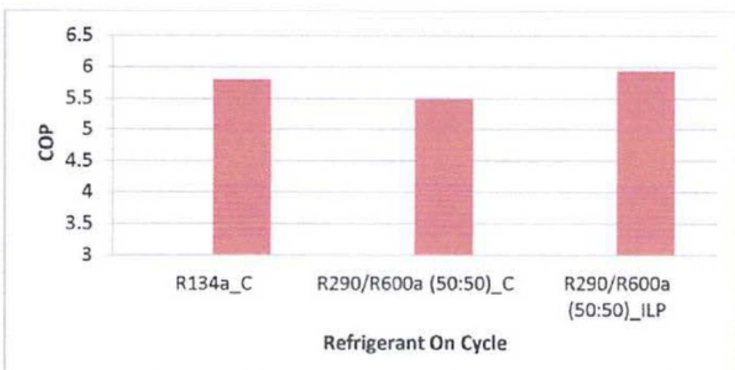

FIGURE 7. Comparison of COP of various refrigerant on C-VCC and ILP-VCC.

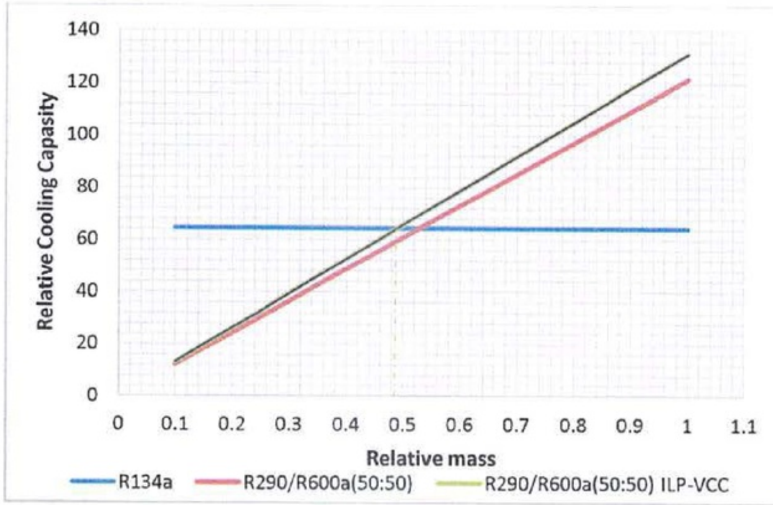

FIGURE 8. Relative cooling capacity vs Relative mass of refrigerant

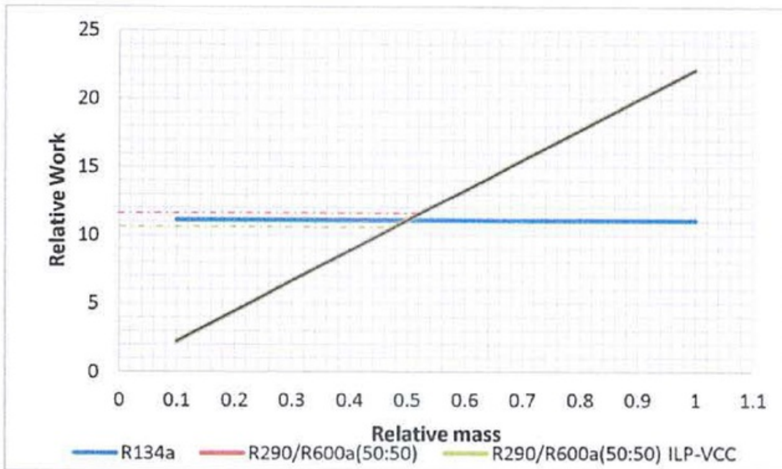

FIGURE 9. Relative work vs Relative mass of refrigerant

In ILP-VCC, volumetric cooling capacity of R290/R600a mixture increased to 6.6% compared to when R290/ R600a was applied to C-VCC and achieved an optimum value in the 50:50 ratio between propane and iso-butane. Comparison of refrigerant charge of various refrigerants which has been analyzed at the same condenser and evaporator pressure are shown in Figure 5. Here it can be shown that the R290 / R600a mixture gives a decrease in refrigerant charge up to 52.2% compared to R134a both in C-VCC. Next Figure 6 compares the compressor's work of the various refrigerants that have been calculated. It can be seen that the use of R290 / R600a mixture can decrease compressor work up to 4.87% compared to R134a in C-VCC. Whereas in Figure 7 it can be seen that the application of the R290 / R600a mixture on C-VCC decreases in COP compared to R134a. In contrast, the application of the R290 / R600a mixture at developed ILP-VCC provides enhanced higher COP beyond R134a at C-VCC up to 6.63%. Figure 9 shows the relationship between the cooling capacity relative to the relative mass of the refrigerant. From Figure 9 it can be seen that at a relative cooling capacity value of R134a of 64.4 the relative masses of R290 / R600a are 0.5294 at C-VCC and 0.49003 at ILP-VCC, respectively. which provides relative work of 11.72 and 10.85 respectively, as shown in Figure 8. Thus ILP-VCC can decrease the relative work of the vapor compression cycle which also means improving performance / COP.

CONCLUSION

From this preliminary study on mixed performance of R290/R600a, it can be concluded that the use of R290/R600a mixture at ILP-VCC can reduce the refrigerant charge by 52.2% and decrease the compressor work by 4.87% compared to using R134a. In the ILP-VCC mixture R290/R600a can provide an increase in volumetric cooling capacity of 6.6% and COP of 6.63% compared to R134a in C-VCC. In general, the mixture of R290/R600a with ILP-VCC provides a better performance than those of R134a and R290/R600a in C-VCC.

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