

THEORETICAL ANALYSIS OF THE THERMAL PERFORMANCE OF R600A, R290 AND THEIR MIXTURES IN A RETROFIT R134A REFRIGERATION SYSTEM

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ABSTRACT

In this research, a theoretical analysis was developed to evaluate the feasibility of the R134a retrofit by hydrocarbons R600a, R290 and their various mixture compositions of R600a/R290 in a vapour compression refrigeration system. The evaporation and condensation temperatures were ranging from -25 to 3°C and 25 to 65°C, respectively. Superheating and sub-cooling degrees were kept constant at 5°C. The thermodynamic and thermo-physical properties were obtained using REFPROP 9.1. The effect of evaporation and condensation temperatures on refrigeration performance indexes such as the refrigeration effect, work input, coefficient of performance, discharge temperature, mass flow rate and volume flow rate were studied. Results show that both pure R600a and R290 cannot be recommended as drop-in substitutes for R134a due to their significant differences in thermal performance. A mixture of R600a/R290 50%/50% composition was found to be the most appropriate alternative considering comparative thermal performance and practical aspects.

Keywords: Refrigerant, retrofit, R600a, R290, thermal performance

1. INTRODUCTION

Refrigerants are gradually going through radical developments due to global environmental concerns such as ozone-depletion and climate change. As a result, the choice of a suitable refrigerant for various applications is subject to factors which include, but not limited to, the chemical, the physical, and the heat transfer properties of the substance, and more important is the substance's ozone depletion potential (ODP) and global warming potential (GWP). For this reason, the production and eventually the use of many popular refrigerants such as R134a will be terminated in the near future.

Studies have shown that Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) greatly contribute to the depletion of the ozone layer and this effect poses a serious threat to human survival. Their molecules are composed of such as chlorine, fluorine and carbon. They are very stable and do not break up easily when released into the atmosphere. HFCs were recommended alternative refrigerants to CFCs and HCFCs in refrigeration and air-conditioning systems (Bolaji and Huan, 2013; Abrate et al., 2013). Different from CFCs and HCFCs, HFCs contain no chlorine atoms, which makes them ozone-depletion safe; they also have very low to zero toxicity levels. Nonetheless, their GWP levels are still relatively high.

Consequently, alternative refrigerants to HFCs are required, in which case the hydrocarbons (HCs) may be considered. Many HCs are suitable as refrigerants. The use of these chemicals as refrigerants in domestic refrigerators has immense potential (Mohanraj, et al., 2011; Liu et al., 2015;). They have zero ODP and very low GWP levels that are acceptable. The ongoing scientific research work related to retrofit of systems by HC's is largely experimental and comprised of studies in which modification of the components in the refrigeration system was carried out, and those in which no modification was completed; most of which address the replacement of CFC-12. The reason is possibly due to the flammability aspect of HC's.

For studies where refrigeration system components were not modified, the performance of a vapour compression refrigeration system (VCRS) was investigated for R12, R290 and various mixtures of R290 and R600a under similar experimental conditions by Richardson and Butterworth (1995). The system employed a hermetic compressor of 6.24 cm³ displacement. From the experimental work, they showed that various mixtures of the hydrocarbons can be used as a direct replacement for R12, resulting in an improvement in the COP of the system.

An experimental performance study on a VCRS initially designed to operate with R12, using R134a and a mixture of R600/R290 32%/68% by weight, conducted by Mani and Selladurai (2008), demonstrated that the HC mixture had 28.6% - 87.2% higher refrigeration capacity, consumed more energy and had a higher COP than R134a. The discharge temperature and pressure of the HC mixture was close to those of the R134a.

A thermodynamic performance analysis of R134a and various mixtures of HCs R290, R600 and R600a used in a 239 L domestic refrigerator designed to work with R134a, showed that the mixture of R600/R290 40%/60% was the best alternative for R134a (Wongwises and Chimres, 2005).

For studies where refrigeration system components were modified, Yoon et al. (2012) demonstrated that optimum charging of refrigerants using R290/R600 increased with increasing length of the capillary tube because of the decrease in refrigerant flow rate and evaporating temperature.

Using a R600a/R290 54.8%/45.2% by weight mixture in a 200 L domestic refrigerator with different mass charges of 40, 50, 60 and 70 g, Mohanraj et al. (2009) reported that for a maximum coefficient of performance (COP), the mixture demanded lengthening of the capillary tube by about 25% compared to that used for R134a. They further observed that the discharge temperature of the mixture was about 8.5-13.4 K lower than that of R134a, which can improve the life of the compressor. Also, the COP of this domestic refrigerator showed improvement by 3.6%.

In the study using HCs R600a and R290 and their various mixtures, Yu and Teng (2014) observed in the experiments that all the various mixtures of the HC refrigerants could be used as substitute refrigerants in the R134a refrigerator after recalculating and changing the capillary tube lengths.

In the study that concentrated on the performance of VCRCs with R600a as the refrigerant, Lee and Su (2002) experimented with a single capillary tube and two capillary tubes in parallel. They reported that the system employing the parallel connection of two capillary tubes performs better in cold storage and air-conditioning applications, whereas the single tube system is suitable in freezing applications.

Castel et al. (1999) designed an experimental system using standard R12 components to evaluate the performance of two types of R12 expansion valves: (1) the thermostatic expansion valve of the R12 cross-charged type and (2) an electronic expansion valve, using CARE30 (i.e., R600a/R290 in the mass ratio 54.8/45.2). Because of the very similar saturation pressure/temperature characteristics and volumetric refrigerating effect of R12, R134a and CARE30, it was demonstrated that the two expansion devices can be used with R134a and with CARE30 by adjusting their superheat setting to compensate for the temperature glide associated with zeotropic refrigerants.

Experiments conducted by Rasti et al in 2013 on a domestic refrigerator using R436A (R290/R600a mixture with 56/44 mass ratio) and R600a as R134a replacements, HFC- and HC-type compressors were used. It was observed that, in comparison to 105g R134a charge, the optimum charges were 60g and 55g for R436A and R600a, respectively. With the use of HFC-type compressor, the amount reduced to 50g for HCs. Furthermore, the power consumption reduced by 14%, 7%, 14.6% and 18.7% for R436A and R600a with HFC- and HC-type compressors, respectively (Yu et al., 2015; Kumma et al., 2023).

A retrofitted system must be tailored to and integrated with existing systems with the motivation related to environmental friendliness, energy conservation, and safety, and economy, etc. The use of environmentally-unsafe refrigerants is still rife in many domestic and commercial refrigeration systems. One of the factors for this increased use of such refrigerants is associated with costs attached to the replacements of existing systems.

In the present study, a theoretical analysis was developed to evaluate the feasibility of HCs R600a, R290 and R600a/R290 mixtures of different compositions as alternative refrigerants to R134a in the vapour compression refrigeration system. The effect of evaporation and condensation temperatures on refrigeration performance indexes such as the refrigeration effect (Q_e), work input (W_{in}), coefficient of performance (COP), discharge temperature (T_{dis}), mass flow rate (\dot{m}) and volume flow rate (\dot{V}) were studied.

2. PROPERTIES OF REFRIGERANTS AND PERFORMANCE OF THE VAPOUR COMPRESSION REFRIGERATION CYCLE (VCRC)

2.1. Properties of refrigerants

The CFCs, HCFCs and HFCs are classes of chemicals whose use became very popular in the refrigeration and air-conditioning industries. Their popularity in many industries around the globe occurred as a result of the many other good chemical properties that they possess, for example, non-flammability, low toxicity levels and their compatibility with a wide range of materials. Since the discovery of the ozone layer depletion and subsequently global warming in the 1990s (Joybari et al., 2013), these chemicals are being phased out completely. The industry world-wide is now being restricted by the new regulation to use environmentally safe refrigerants and to seek alternative chemicals to CFCs, HCFCs and HFCs.

HCs are the simplest organic compounds consisting of only hydrogen and carbon atoms. They are naturally occurring substances whose majority can be found in crude oil, where decomposed organic matter provides an abundance of carbon and hydrogen. They can be used as single chemical components, as blends of different HCs and as components of blends containing halocarbon refrigerants. The use of HCs in domestic refrigerators is very attractive since they are inexpensive and moreover, they have high latent heat (Wongwises and Chimres, 2005; Trech, 2015); meaning that their refrigeration effect is higher than that of HFCs. The ideal refrigerant should have a high latent heat of evaporation or condensation in order to produce the highest refrigeration or heating effects and hence minimise the size of the system.

Flammability limits are some of the main indices of fuel gases that must be known or determined to ensure safety during operation of industrial processes which involve the use and storage of flammable compounds (Mendiburu et al., 2015). They are used in the estimation of flame stability and explosion features of fuel gases (Hu et al., 2014). When working with flammable substances it is vital to consider the substance's concentration between the lower and the upper explosion limit in air or other oxidisers at the given conditions (Pekalski and Pasman, 2009).

2.2. Performance of the VCRC

Fig. 1 shows the pressure-enthalpy ($p-h$) diagram of the cycle which is used for the VCRC analysis. The following performance indexes, namely: Q_e , W_{in} , COP , T_{dis} , \dot{m} , and (\dot{V}) were analyzed at different working conditions. The necessary thermo-physical properties of the refrigerants were obtained using REFPROP 9.1 software. The equations of the cycle performance analysis were used as follows below; the indicated points correspond to those shown in Fig. 1.

$$Q_e = h_{1'} - h_4 \quad \text{Eq. (1)}$$

where Q_e is refrigerating effect per unit mass in kJ/kg, $h_{1'}$ is the specific enthalpy at compressor suction point in kJ/kg, and h_4 is the specific enthalpy at evaporator inlet in kJ/kg.

$$W_{in} = h_2 - h_{1'} \quad \text{Eq. (2)}$$

where W_{in} is work input per unit mass in kJ/kg, h_2 is the specific enthalpy at compressor exhaust point in kJ/kg. The coefficient of performance (COP_{ref}) of the refrigerator is defined by,

$$COP_{ref} = Q_e / W_{in} \quad \text{Eq. (3)}$$

Discharge Temperature,

$$T_{dis} = T_2 \quad \text{Eq. (4)}$$

where, T_2 is the temperature at the compressor exhaust point in K. Mass flow rate (\dot{m}) per kilowatt of refrigeration capacity in kg/s is given by,

$$\dot{m} = \dot{Q} / Q_e \quad \text{Eq. (5)}$$

where, \dot{Q} is the refrigeration capacity. The volume flow rate \dot{V} in m^3/s is given by,

$$\dot{V} = \dot{m}v \quad \text{Eq. (6)}$$

where, v is the specific volume of the refrigerant at the compressor suction point in m^3/kg .

3. THEORETICAL ANALYSIS

3.1. Data analysis

Fig. 1 shows the pressure-enthalpy ($p-h$) diagram of the theoretical vapour compression cycle used in the analysis. This analysis was carried out at evaporation temperatures ranging from -25 to 3°C , condensation temperatures ranging from 25 to 65°C , superheating degree of 5°C and sub-cooling degree of 5°C .

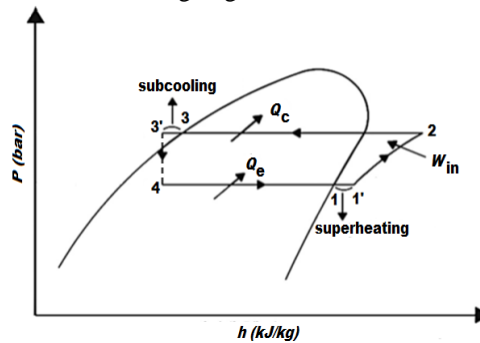


Fig. 1. The pressure-enthalpy diagram of the cycle used in the analysis.

The comparison of the performance of the cycle for the fluids in question was carried out under conditions of constant evaporation temperature and also at a constant condensation temperature based on the results obtained. For the constant condensation-temperature process, 45°C was maintained and -25°C was used for the constant-evaporation-temperature process. Various temperatures are represented as follows: T_{sup} –superheating degree, T_{sub} –subcooling degree, T_c – condensation and T_e – evaporation.

The present analysis uses the following mixture compositions as viewed by mass fractions of R600a/R290:

(i) 25%/75% (ii) 37.5%/62.5% (iii) 44.4%/55.6% (iv) 45.5%/54.5% (v) 50%/50% (vi) 54.5%/45.5% (vii) 55.6%/44.4% (viii) 62.5%/37.5% and (ix) 75%/25%.

4. RESULTS AND DISCUSSION

4.1. Comparison of the saturation pressure-temperature curves of R134a, R600a, R290 and R600a/R290 mixtures

Fig. 2 shows the saturation pressure-temperature curves which indicated that the saturation pressure of R290 can be up to (about) ~30% higher than that of R134a and that of R600a is ~47% lower than that of R134a for the given temperature range. When the saturation pressure of a refrigerant is different, it may lead to different working conditions of the system and hence cannot be suitable for retrofit purposes, and higher discharge temperatures may be resulted from the higher saturation pressure, as a result this condition for pure R290 and R600a makes them unfavourable choice for a suitable substitute in a R134a retrofit system. The most possible substitute with the above considerations in place is therefore narrowed to a mixture of the two HCs. The saturation pressure-temperature variations of the HC mixtures in respect to R134a are found to be within 30%, with the 50%/50% varying by up to ~11%.

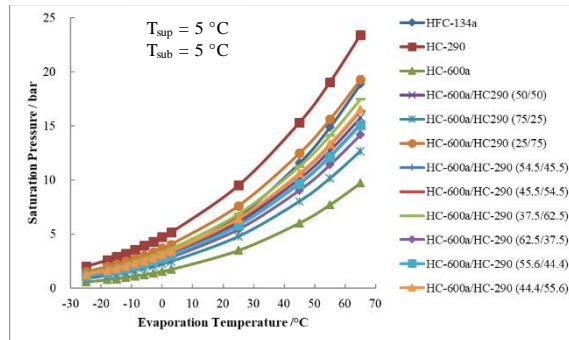


Fig. 2. Comparison of saturated pressure-temperature curves for various refrigerants and refrigerant mixture compositions.

4.2. Comparison of the refrigeration effect of R134a, R600a, R290 and R600a/R290 Mixtures

As shown in Figs. 3 and 4 depict the refrigeration effect as a function of evaporation temperature and condensation temperature respectively. The hydrocarbons and their various compositions have a higher refrigeration effect than R134a. At a constant condensation temperature, the refrigeration effect increases with increasing evaporation temperature for all the refrigerants. However, when the evaporation temperature is kept constant, the refrigeration effect for all the refrigerants decreases when increasing condensation temperature. This shows that the overall performance of the system can improve if the temperature difference between the evaporator and the condenser is decreased by elevating the evaporator temperature or by lowering the condenser temperature or by applying both methods. On average, the refrigeration effect of the hydrocarbons and their mixtures is more than 40% higher than for R134a. The results obtained here in Figs. 3 and 4 suggest that smaller charge amounts of hydrocarbons and their mixtures will be required in practice to obtain an equivalent amount of refrigeration capacity obtained when using R134a. This may be a positive result since it means that smaller amounts (almost half) of the hydrocarbon refrigerants (which have been found to be flammable) will be used in retrofit R134a refrigeration and air-conditioning systems. This fact will further alleviate any possibility of fire hazards.

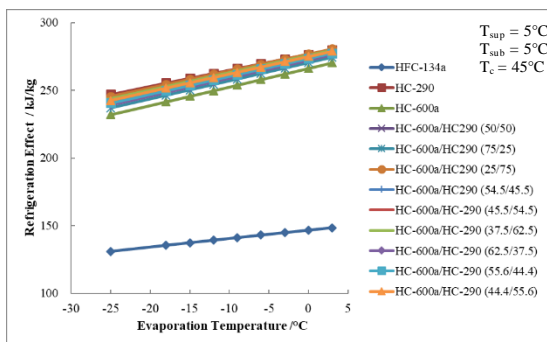


Fig. 3. Comparison of the refrigeration effect for various refrigerants at increasing evaporation temperatures.

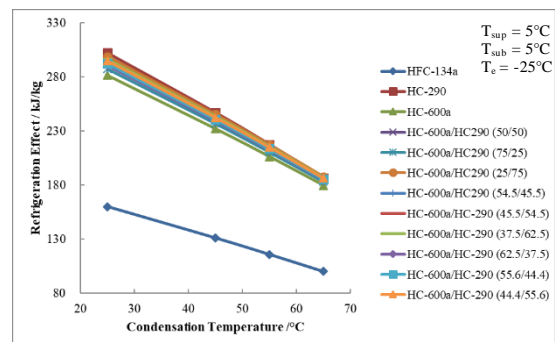


Fig. 4. Comparison of the refrigeration effect for various refrigerants at increasing condensation temperatures.

4.3. Comparison of the work input of R134a, R600a, R290 and R600a/R290 mixtures

Fig. 5 shows that at constant condensation temperature, the compressor work required decreases with increasing evaporation temperatures. This finding agrees with the recommendation to use higher evaporation temperatures for an

improved system performance. R600a provides the lowest work input at constant condensation temperature. But under the same conditions, its saturation pressure is significantly low, and it gives the lowest refrigeration effect among the HCs, but still much higher than for R134a as seen in Figs. 2 and 3. The work input of the other refrigerants and mixtures range between 70% and 90% more than those for R134a. The 75%/25% composition gives the lower work input after R600a and a comparable refrigeration effect, but its saturation pressure is quite significantly low. This may be due to its higher R600a content. The work input of the 50%/50% composition is ~80% higher than for R134a and under these conditions, its saturation pressures are similar to those of R134a and it provides a good refrigeration effect.

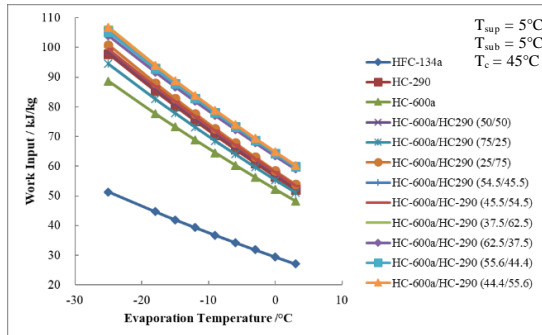


Fig. 5. Comparison of the work input for various refrigerants at increasing evaporation temperatures.

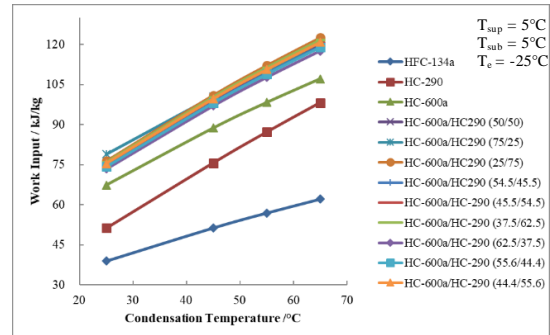


Fig. 6. Comparison of the work input for various refrigerants at increasing condensation temperatures.

At a constant evaporation temperature, the compressor work required increases with increasing condensation temperatures as shown in Fig. 6. Again, this observation supports the recommendation made in section 4.3. In Fig. 6, refrigerants R290 and R600a provide the lowest work input compared to those of the mixtures. However, under the same conditions, R600a cannot be considered based on the reasoning stated above. On the other hand, although R290 provides the highest refrigeration effect and the lowest work input, its saturation pressure is significantly high compared to that of R134a; hence it stands as an eliminated probability for substitution. The work input of the mixtures is larger than those of R134a by more than 80%, including the 50%/50% composition.

4.4. Comparison of the COPs of R134a, R600a, R290 and R600a/R290 Mixtures

Fig. 7 indicates that the COP increases when the evaporation temperature increases, whereby R600a will have the highest COP values. The variation in COPs of the HCs is as much as 16%. Fig. 8 shows that at conditions of constant evaporation temperature, the COPs of all the HC refrigerants, except for R290, are relatively similar to those given by pure R134a; the deviation in COPs of HCs is less than 14% on average.

In practice, a system leakage can result in the change mainly in composition which will further change the COP, refrigeration effect, work input as stated previously, the operation overall pressure and hence the evaporation temperature and performance, as well as corresponding charge amount and the flow rate. The mixture compositions such as 25%/75% & 75%/25% and 37.5%/62.5% & 62.5%/37.5%, in which one of the constituents is fairly lower compared to the other; from a practical consideration, based on these ratios, a minor leakage from a system may cause a significant shift in composition because the R600a/R290 mixtures may be considered zeotropic. The other compositions give results that are close to those of the 50%/50% composition.

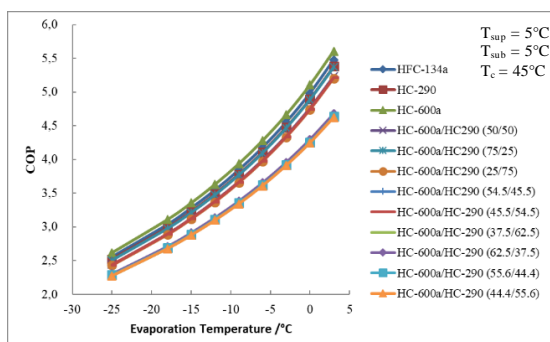


Fig. 7. Comparison of the COP for various refrigerants at increasing evaporation temperatures.

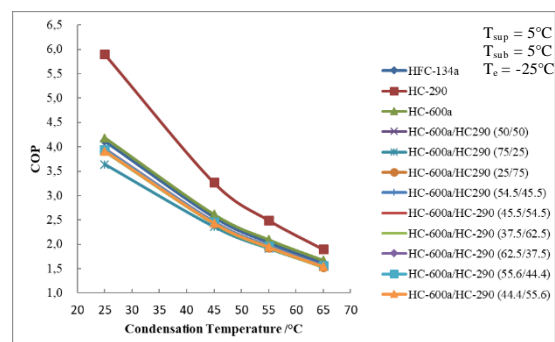


Fig. 8. Comparison of the COP for various refrigerants at increasing condensation temperatures.

Fig. 8 shows that when the evaporation temperature is kept constant with increasing condensation temperature, the COP decreases. On average, R290 provides ~42% higher COP values compared to the rest of the other refrigerants including R134a. At higher condensation temperatures, R600a and other compositions have COP values that are well within ~93% of those for R134a (i.e., they are very similar). The COP has a direct bearing on the running cost of the refrigeration system; the higher COP value is preferred.

4.5. Comparison of the discharge temperatures of R134a, R600a, R290 and R600a/R290 Mixtures

Fig. 9 shows that at constant condensation temperature, the discharge temperatures decrease with increasing evaporation temperatures with R600a displaying the lowest discharge temperatures that are ~18-25% lower than those of R134a. Under both conditions, the performance by R290 match that of R134a, which gives high values of discharge temperature. A high discharge temperature may result in a high condensation temperature, which deteriorates the system's performance.

As observed from Fig. 10, when the evaporation temperature is kept constant, the discharge temperatures increase with increasing condensation temperatures. The discharge temperatures of all the HC refrigerants are close and even slightly lower (~10%) than those of R134a, except for those given by R600a which are the lowest by ~20%.

Once more, founded upon the practical consideration, if the 50%/50% mixture is used in a retrofit system and leakages occur, the composition curve will definitely move slightly downwards or upwards and still maintain good overall performance, considering mixture composition.

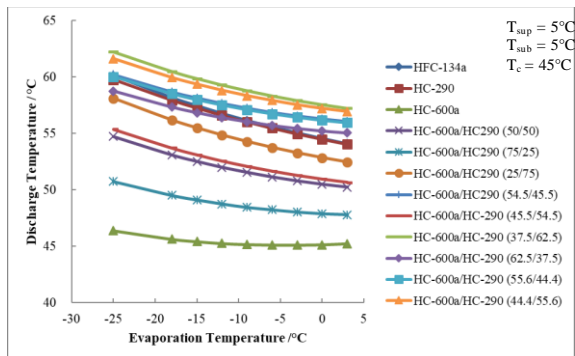


Fig. 9. Comparison of the discharge temperatures for various refrigerants at increasing evaporation temperatures.

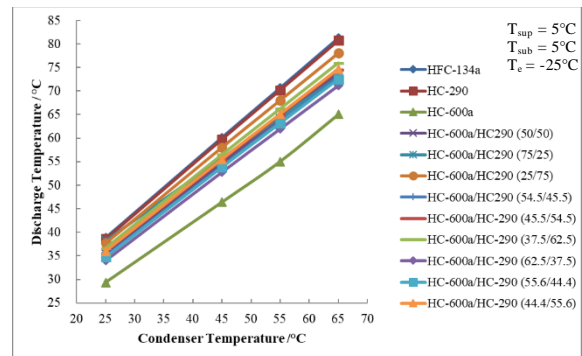


Fig. 10. Comparison of the discharge temperatures for various refrigerants at increasing condensation temperatures.

4.6. Comparison of the mass flow rates of R134a, R600a, R290 and R600a/R290 Mixtures

Judging from the results of the mass flow rates obtained in Figs. 11 and 12, it is evident that in practice, a smaller equivalent charge amount of the hydrocarbons will be required for replacing a given amount of R134a in the system. Under conditions of constant evaporation and condensation temperature processes, ~46% less charge amount of a hydrocarbon or a mixture thereof will be required for the replacement of R134a. This is a good outcome because it confirms that only small amounts of the HC refrigerants will be used.

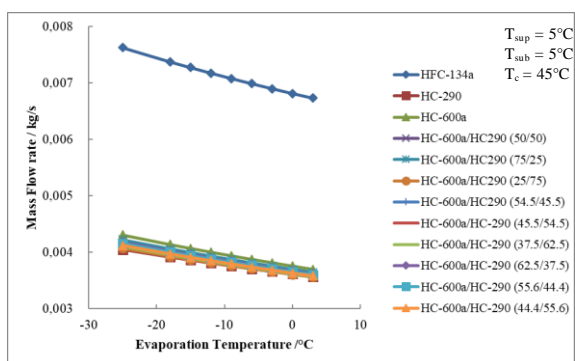


Fig. 11. Comparison of mass flow rates for various refrigerants at increasing evaporation temperatures.

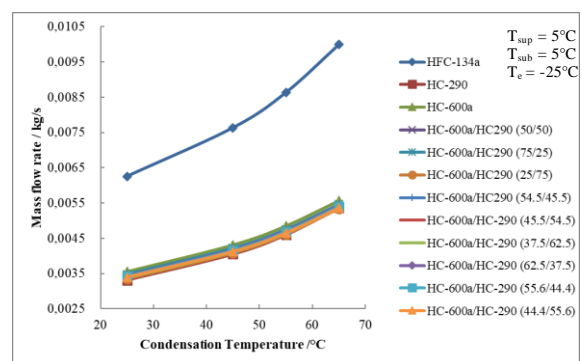


Fig. 12. Comparison of mass flow rates for various refrigerants at increasing condensation temperatures.

4.7. Comparison of the volume flow rates of R134a, R600a, R290 and R600a/R290 Mixtures

The volume flow rate is the most important aspect in refrigerant substitution. This is so because it determines whether the same system components such as the compressor and expansion device can be used as they exist or whether modifications will be required. The type of compressor to be used also depends on the volume flow rate required.

Very low volume flow rates are indicated in Figs 12 and 13 for pure R290, which may imply that an R134a system may be too large for R290 for the system to maintain the recommended fluid velocities in the pipes. Also, under both conditions, pure R600a displays the highest volume flow rates. This could mean that an R134a system may be too small for R600a direct retrofit.

The mixture compositions 25%/75% and 37.5/62.5% with higher content of R290, show volume flow rates that are close to those of R134a. Up to a point, this effect in terms of the volume flow rate may even extend the range of possible substitutes to 25%/75%, 37.5/62.5% and 44.4%/55.6% for the systems in which the possibility of high leakages can be mitigated by keeping low operating pressures.

Figs. 12 and 13 show that the results of the volume flow rates for R600a, 75%/25% and even 62.5%/37.5% are significantly high under both conditions and may require the system to be modified. It is also clear that compositions with a high R600a (including R600a itself) content fall considerably out of the range for possible substitutes with regards to the volume flow rate parameter. It is flawless to conclude that mixtures with lower R600a content or lower R600a/R290 ratio are preferred as substitutes for R134a. A full summary indicating the effect of R600a is given in Table 1.

The volume flow rates for the other compositions (including 50%/50%) are on average 20% more or less than for R134a for both processes; therefore, taking into consideration the other parameters, the 50%/50% composition is representative of a range of mixtures that are favourable as substitute compositions, excluding the ones with a much higher R600a content: pure R600a, 75%/25% and 62.5%/37.5%.

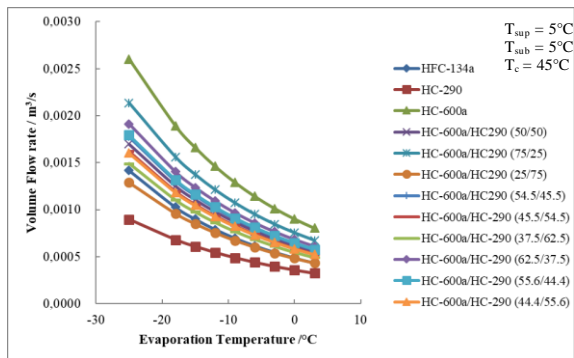


Fig. 12. Comparison of volume flow rates for various refrigerants at increasing evaporation temperatures.

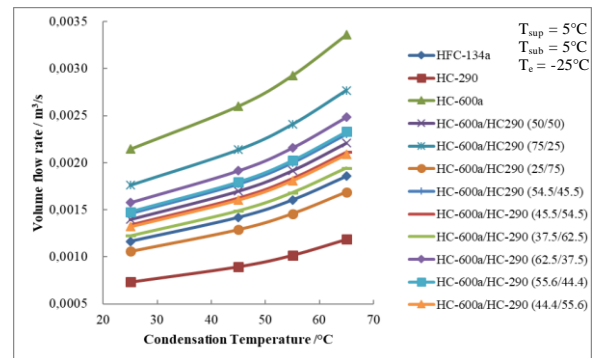


Fig. 13. Comparison of volume flow rates for various refrigerants at increasing condensation temperatures.

The results discussed above are summarised in Table 1 showing the percentage discrepancies in relation to the performance of R134a at constant condensation temperature (although the same conclusion can be drawn using constant evaporation temperature results). The negative sign represents a value lower than that of R134a (i.e., the particular index for R134a falls above this value) and a positive sign represents the exact opposite (i.e., R134 index falls below this value). The percentage content of R600a in relation to R290 is presented in the table in a similar manner. The average values for pure HC refrigerants and their mixture compositions were used in drawing up this table in order to establish the general tendencies in their performances.

Table 1. Summary of the theoretical analysis

Refrigerants / Mixtures	P _{sat}	Q _e	W _{in}	COP	T _{dis}	ṁ	V̇	R600a %
R290	60	88	92	(-)2	0	(-)47	(-)30	0
R600a	(-)47	80	76	2	(-)20	(-)44	85	100
75%/25%	(-)24	83	87	(-)2	(-)14	(-)45	54	67
62.5%/37.5%	(-)13	84	110	(-)12	0	(-)46	39	40
55.6%/44.4%	(-)7	85	113	(-)13	2	(-)46	31	20
54.5%/45.5	(-)6	85	113	(-)13	2	(-)46	29	16.5
50%/50%	(-)1	86	95	(-)4	(-)8	(-)46	24	0
45.5%/54.5%	3	86	96	(-)5	(-)7	(-)46	19	(-)16.5
44.4%/55.6%	4	87	115	(-)13	4	(-)46	18	(-)20
37.5%/62.5%	11	87	115	(-)13	5	(-)47	10	(-)40
25%/75%	25	88	98	(-)5	(-)3	(-)47	(-)3	(-)67

5. CONCLUSION

The performances of the HC blends that have lower R600a content were observed to be better than those of the pure substances R600a and R290. The R600a/R290 50%/50% composition was found to be representative of a range of mixtures that are favourable as drop-in substitutes for R134a. Therefore, the 50%/50% blend and blends with slightly higher R290 content can be considered to be the most appropriate alternatives to R134a for a retrofit. Performance, if anything, should improve if halocarbon refrigerants can be replaced by an equivalent amount of the blend of hydrocarbon refrigerants. Based on this analysis, a smaller charge amount of hydrocarbons and their mixtures should be required for retrofitting purposes in order to obtain an amount of refrigeration effect that is equivalent to that of R134a.

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