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Experimental analysis of a new refrigerant mixture as drop-in replacement for CFC12 and HFC134a

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Abstract

An experimental performance study on a vapour compression refrigeration system with the new R290/R600a refrigerant mixture as drop-in replacement was conducted and compared with CFC12 and HFC134a. The vapour compression refrigeration system was initially designed to operate with R12. Experimental results showed that the refrigerant R290/R600a had 19.9% to 50.1% higher refrigerating capacity than R12 and 28.6% to 87.2% than R134a.The refrigerant R134a showed slightly lower refrigerating capacity than R12. The mixture R290/R600a consumed 6.8% to 17.4% more energy than R12. The refrigerant R12 consumed slightly more energy than R134a at higher evaporating temperatures. The coefficient performance of R290/R600a mixture increases from 3.9% to 25.1% than R12 at lower evaporating temperatures and 11.8% to 17.6% at higher evaporating temperatures. The refrigerant R134a showed slightly lower coefficient of performance than R12. The discharge temperature and discharge pressure of the R290/R600a mixture was very close to R12. The R290/R600a (68/32 by wt%) mixture can be considered as a drop-in replacement refrigerant for CFC12 and HFC134a.The refrigeration efficiency of the system were also studied.

Keywords: Hydrocarbon mixture; Alternative refrigerants; ODP; Global warming; CFC

1. Introduction

The refrigerants chlorofluorocarbon (CFCs) and hydrochlorofluorocarbon (HCFCs) both have high ozone depleting potential (ODP) and global warming potential (GWP) and contributes to ozone layer depletion and global warming. Therefore these two refrigerants are required to be replaced with environmentally friendly refrigerants to protect the environment. The hydrofluorocarbon (HFC) refrigerants with zero ozone depletion potential have been recommended as alternatives. R134a is the long-term replacement refrigerant for R12 because of having favourable characteristics such as zero ODP, non-flammability, stability and similar vapour pressure as that of R12 [1–3]. The ODP of R134a is zero, but it has a relatively high global warming potential. Many studies are being carried out which are concentrating on the application of environmentally friendly refrigerants in refrigeration systems. The issues of ozone layer depletion and global warming have led to consideration of hydrocarbon refrigerants such as propane, isobutene, *n*-butane or hydrocarbon blends as working fluids in refrigeration and air-conditioning systems. Hydrocarbons are designated as A3 (highly flammable) refrigerants by ASHRAE standard 34, the industry standard for refrigerant classification. The hydrocarbon (HC) as refrigerant has several positive characteristics such as zero ozone depletion potential, very low global warming, non-toxicity, high miscibility with mineral oil, good compatibility with the materials usually employed in refrigerating systems. The main disadvantage of using hydrocarbons as refrigerant is their flammability [4,5]. If safety measures are taken to prevent refrigerant leakage from the system then a flammable refrigerant could be as safe as other refrigerants.

Fig. 1 shows the saturated vapour pressure versus temperature for R12, R134a and R290/R600a (68/32 by wt%) mixture. It was observed from Fig. 1 that the saturated vapour pressure for propane–isobutane mixture of propane concentration equal to 68% is very close to the vapour pressure curves of the refrigerant R12 and R134a and can be used as a potential retrofit refrigerant.

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Nomenclature

CFC	chlorofluorocarbon	
CEC	compressor energy consumption	kW
COP	coefficient of performance	
GWP	global warming potential	
HCFC	hydrochlorofluorocarbon	
HFC	hydrofluorocarbon	
HC	hydrocarbon	
ODP	ozone depletion potential	
RC	refrigerating capacity	kW
RE	refrigeration efficiency	

Subscript

c	condensing/condenser

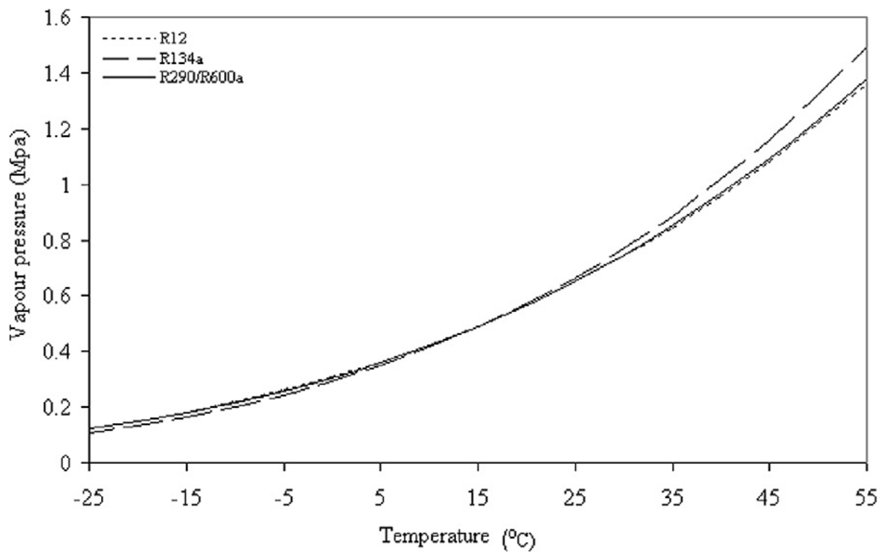

Fig. 1. Vapour pressure curves for R12, R134a and R290/R600a (68/32).

2. Literature review

Many studies have been concentrated on the research of substitutes for CFC12. The refrigerant propane/isobutane mixture is being sold under different brand names as substitutes for CFC12. But this R290/R600a (68/32 by wt%) mixture is a new HC blend composed of propane 68% and iso-butane 32% on mass basis and performed better than other propane/isobutane mixtures.

Richardson and Butterworth [6] investigated the performance of HC290/HC600a mixture in a vapour compression refrigeration system. It was shown that propane and propane/isobutane mixtures may be used in an unmodified R12 system and gave better COPs than R12 under the same operating conditions. Mixtures of around 50% propane and 50% isobutane have very similar saturation characteristics to R-12 but COP would seem to improve as the proportion of propane is increased. Dongsoo Jung et al. [7] tested the performance of R290/R600a mixture in the composition range of 0.2 to 0.6 mass fractions of R290 yields an increase in COP of 1.7% to 2.4% as compared to R12. R290/R600a mixture at 0.6 mass fraction of R290 showed a 3% to 4% increase in energy efficiency and a faster cooling rate as compared to R-12. Evelyn Baskin [8] studied different mixtures of HC600a/HC290 performance in residential refrigerator/freezers. The 60/40% and 70/30% (isobutane/propane) were the best overall mixtures. Kuijpers et al. [9] theoretically showed that 21/79 wt% propane/iso-butane mixture should be considered as a substitute to CFC-12. This composition has an evaporation pressure and volumetric refrigeration capacity comparable to CFC-12. Hammad and Alsaad [10] carried out experimental study with four ratios of propane, butane and isobutene as possible alternative to R12 in an unmodified R12 domestic refrigerator. The hydrocarbon mixture with 50% propane, 38.3% butane and 11.7% isobutene showed better performance among all other hydrocarbon mixtures investigated. Experimental results of Jung et al. [11] indicated that the mixture of propane and iso-butane with 60% mass fraction of propane has higher COP, faster cooling rate, shorter compressor on-time and lower compressor dome temperatures than R12. Akash and Said [12] conducted performance test with LPG (30% propane, 55% n-butane and 15% iso-butane by mass fraction) as a possible substitute for R12 in domestic refrigerator. The cooling capacity and COP were comparable to those of R12. Tashtoush et al. [13] conducted experimental study with butane/propane/R134a mixtures as alternative to R12. The results showed excellent performance with this new refrigerant mixture as an alternative to R12 in domestic refrigerators, without changing the compressor lubricating oil used with R12.

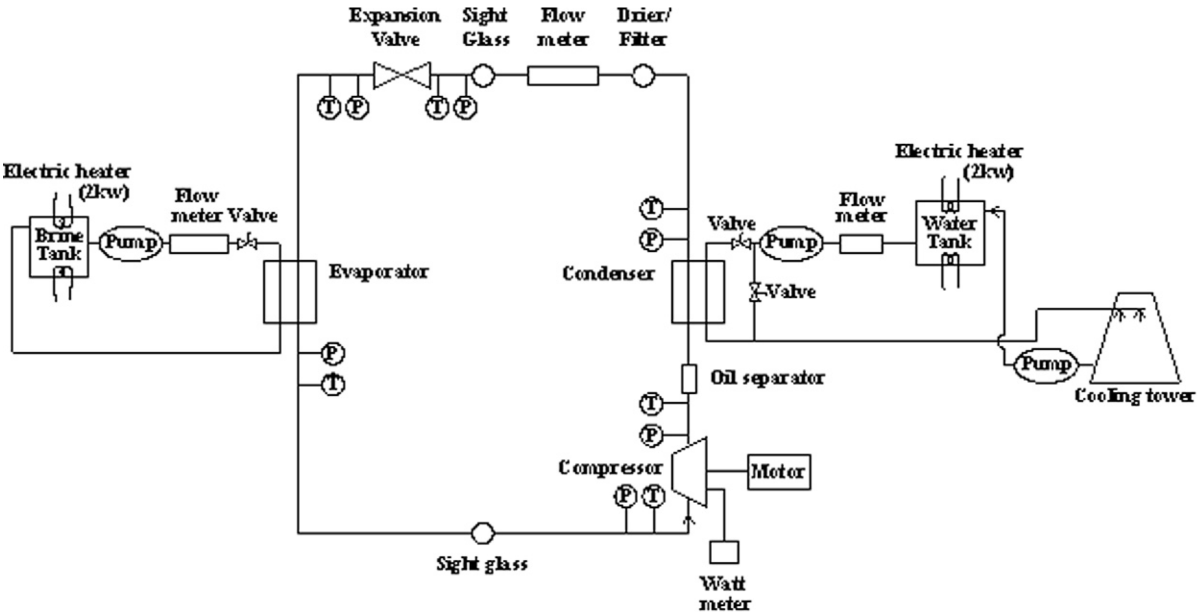

Fig. 2. Schematic diagram of the experimental setup.

In this experimental work, the new environmentally friendly alternative refrigerant R290/R600a (68/32) was studied and comparison between this new refrigerant mixture and R12, R134a under different rated working conditions were carried out to prove its potential as a promising alternative refrigerant.

3. Experimental apparatus

An experimental setup of vapour compression refrigeration system was built up to investigate the performance R12, R134a, R290/R600a (68/32 by wt%) mixture refrigerants. Fig. 2 shows the schematic diagram of the experimental setup. It consisted of two loops; a main loop and a secondary loop. The main loop was composed of compressor, condenser, a filter-drier, refrigerant flow meter, sight glass, expansion valve and evaporator. The compressor was an open, reciprocating type. The rotating speed of the compressor was 855 rpm and its speed could be changed by a variable diameter belt pulley of the electrical motor.

The condenser and evaporator are of both copper double tubes. In the double tube condenser, the refrigerant flows through the inner tube while the cooling water flows through the annular space between the inner and outer tubes. In the double tube evaporator the brine solution (calcium chloride/water solution) flows through the inner tube and the refrigerant flows through the annular space between them. For minimizing the heat loss, the outer tube was well insulated. Two sight glasses were incorporated into the system, one in the liquid line at the condenser outlet and another in the vapour line at the evaporator outlet in order to give a visual indication of the refrigerant circulation. The secondary loops were composed of a pump, a flow meter and an electrically heated unit within the insulated tank. One tank was filled with cooling water and circulated through the condenser tubes while the other tank was filled with brine solution and circulated through the evaporator tubes. The hot water coming out of the condenser tube was supplied to a cooling tower and gets cooled. This cooled water again pumped to the cooling water tank through a separate pump.

4. Experimental procedure

The objective of the study was to compare the refrigeration performance of different refrigerants in terms of refrigerating capacity, compressor energy consumption and COP. Rotameters were used to measure the flow rates of the cooling water and brine solution with an accuracy of ±0.05 lpm. The refrigerant rotameter was used to measure the refrigerant flow rate with an accuracy of ±0.0125 kg/min. RTD type thermocouples were used to measure the temperatures with an accuracy of ±0.1 °C and pressures were measured using calibrated pressure gauges with an accuracy of ±1 psi. The thermocouples were located in the pockets on the surface of the tubes and each sensor was calibrated to reduce experimental uncertainties. The range and accuracy of equipment used in the experimental test setup are summarized in Table 1.

The temperatures and pressures of the refrigerant and secondary fluid temperatures were measured at various locations in the experimental setup as shown in Fig. 2. The compressor

Table 1
Range and accuracy of the equipment used in the test setup

Item	Range	Accuracy
Temperature sensor	−100 to 100 °C	±0.1 °C
Pressure gauge 1	0–300 psi	±1 psi
Pressure gauge 2	0–150 psi	±1 psi
Refrigerant rotameter meter	0–2.30 kg/min	±0.0125 kg/min
Rotameter	5 lpm	±0.05 lpm
Power meter	10 rev	±2 s
Electronic balance weight	50 kg	±1 g

Table 2
Comparison between R12, R134a and R290/R600a (68/32 by wt%) mixture results at $T_c = 40\,^\circ C$ and evaporating temperatures between 2 °C and −18 °C

Evaporating temperature (°C)	Refrigerants	Refrigerating capacity (kW)	Compressor energy consumption (kW)	Coefficient of performance (COP)	Refrigeration efficiency (RE)
2	R12	1.65	0.689	2.39	0.331
	R134a	1.53	0.656	2.34	0.323
	R290/R600a	2.12	0.793	2.68	0.370
−2	R12	1.34	0.624	2.15	0.333
	R134a	1.23	0.584	2.10	0.325
	R290/R600a	1.65	0.695	2.37	0.368
−8	R12	0.87	0.532	1.65	0.298
	R134a	0.85	0.517	1.64	0.297
	R290/R600a	1.11	0.603	1.85	0.334
−14	R12	0.53	0.448	1.18	0.247
	R134a	0.47	0.446	1.06	0.220
	R290/R600a	0.74	0.537	1.38	0.288
−18	R12	0.35	0.402	0.88	0.200
	R134a	0.28	0.395	0.72	0.163
	R290/R600a	0.53	0.482	1.10	0.250

energy consumption was measured using a wattmeter with an accuracy of ±2 s for 10 revolution of the energy meter disc. A manual type expansion device was used to regulate the mass flow rate of refrigerant and to set pressure difference.

The refrigerant was charged after the system had been evacuated. The working fluids were R12, R134a, R290/R600a (68/32 by wt%). The refrigerant R290/R600a (68/32 by wt%) is a zeotropic blend, which is charged in the liquid phase due to its composition shift and temperature glide. Drop-in experiments were carried out without any modifications to the experimental apparatus. The experiment was started with R12 to set up the base reference for further comparisons with the other two refrigerants. The desired evaporating and condensing temperatures were obtained by adjusting all the other parameters in the system such as cooling water flow rate and its temperature, refrigerant flow rate and brine solution flow rate and its temperature. The thermal load of the system was changed with an electrically heated unit in the secondary loop insulated brine tank. Two electric heaters each of 2 kW capacities is fitted in the secondary loop insulated brine and water tank. The water temperature for condensation was changed with a temperature sensor provided with the electrical heaters.

The thermodynamic properties of the refrigerants were taken from the NIST [14] REFPROP database. The readings were taken after the system had reached steady state conditions. The absolute errors in the refrigerating capacity, compressor energy consumption and COP estimated by the single sample analysis according to ASHRAE Guideline 2 [15] were ±0.044, ±0.0315 and ±0.175 respectively.

5. Results and discussion

The experimental results obtained from the performance analysis of R12, R134a, R290/R600a (68/32 by wt%) are discussed with respect to the parameters such as refrigerating capacity, compressor energy consumption, COP and refrigeration efficiency. Table 2 shows the experimental results of the parameters at $T_c = 40\,^\circ C$ and evaporating temperatures between 2 °C and −18 °C.

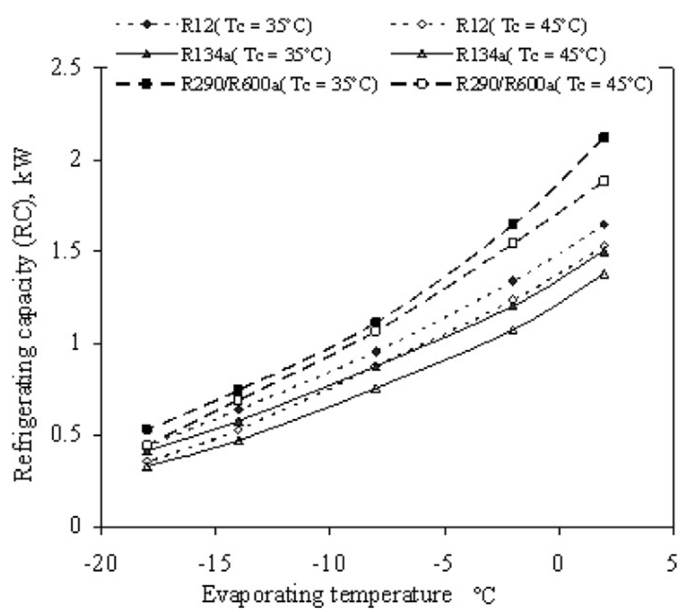

Fig. 3. RC vs evaporating temperature for $T_c = 35\,^\circ C$ and 45 °C.

5.1. Refrigerating capacity

Fig. 3 shows the variations of refrigerating capacity against evaporating temperature for condensing temperatures of 35 °C and 45 °C. It was observed that the refrigerant mixture R290/R600a (68/32) had the highest refrigerating capacity than R12 and R134a. The refrigerating capacity of R290/R600a (68/32) mixture was 19.9%–50.1% higher than R12 and 28.6%–87.2% higher than R134a for the lower evaporating temperatures below −5 °C. The refrigerant R290/R600a (68/32) showed

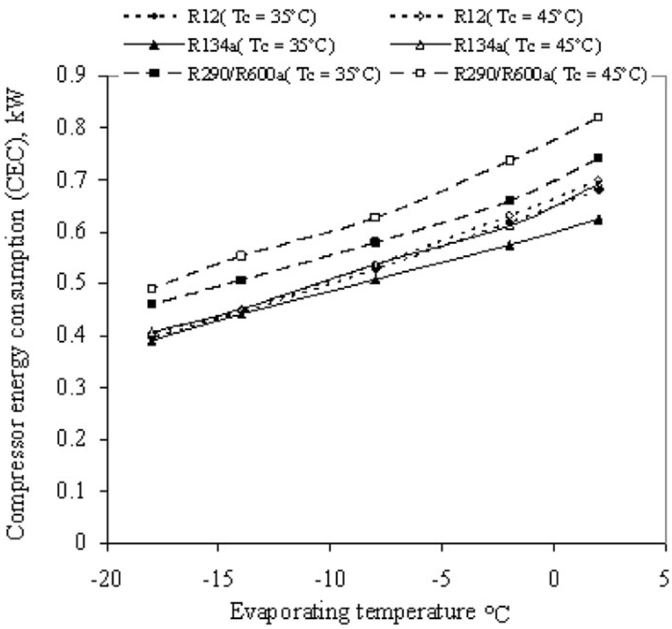

Fig. 4. CEC vs evaporating temperature for $T_c = 35$ °C and 45 °C.

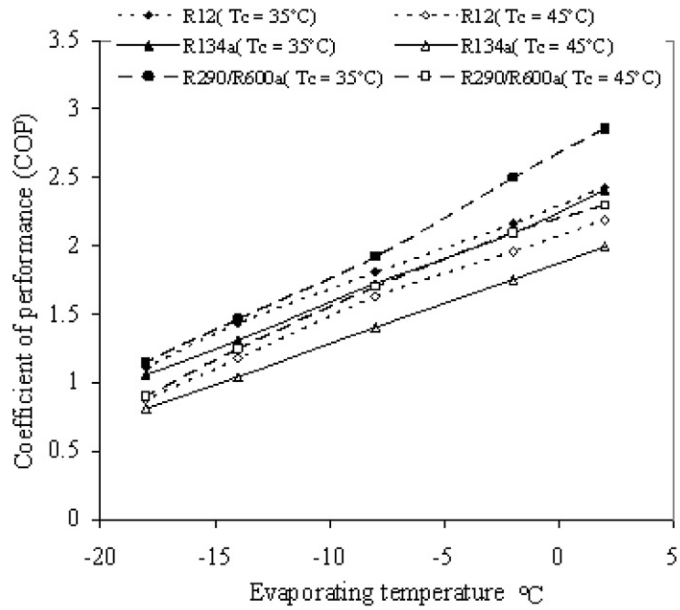

Fig. 5. COP vs evaporating temperature for $T_c = 35$ °C and 45 °C.

higher refrigerating capacity in the range 21.2%–28.5% higher than R12 and 30.7%–41.3% higher than R134a for the higher evaporating temperatures above −5 °C. R134a showed a slightly lower refrigerating capacity than R12 for all the operating conditions. It was observed that the R290/R600a (68/32) mixture showed a faster cooling rate than R12 at higher evaporating temperatures above −5 °C. It was observed from Fig. 3 that the increase in condensing temperature decreases the refrigerating capacity of the refrigerants.

5.2. *Compressor energy consumption*

Fig. 4 showed that the energy consumed by the compressor increases as the evaporating and condensing temperature increases. Test results showed that the energy consumed by the system with R290/R600a (68/32) mixture was higher by 6.8%–17.4% than R12 and 8.9%–20% higher than R134a for all the operating conditions. The energy consumed by the system with R134a was slightly lower than R12 at higher evaporating temperatures above −10 °C. At lower evaporating temperatures below −10 °C both R12 and R134a consumed nearly the same energy.

5.3. *Coefficient of performance*

Fig. 5 shows the coefficient of performance for R12, R134a and R290/R600a (68/32 by wt%) mixture for various evaporating temperatures with condensing temperatures of 35 °C and 45 °C. It was observed that the COP of R290/R600a (68/32 by wt%) mixture was 3.9% –25.1% higher than R12 at the lower evaporating temperatures below −8 °C. The refrigerant R290/R600a showed 11.8%–17.6% higher COP than R12 at the higher evaporating temperatures above −8 °C. The COP of R134a was lower than R12 for all the operating conditions.

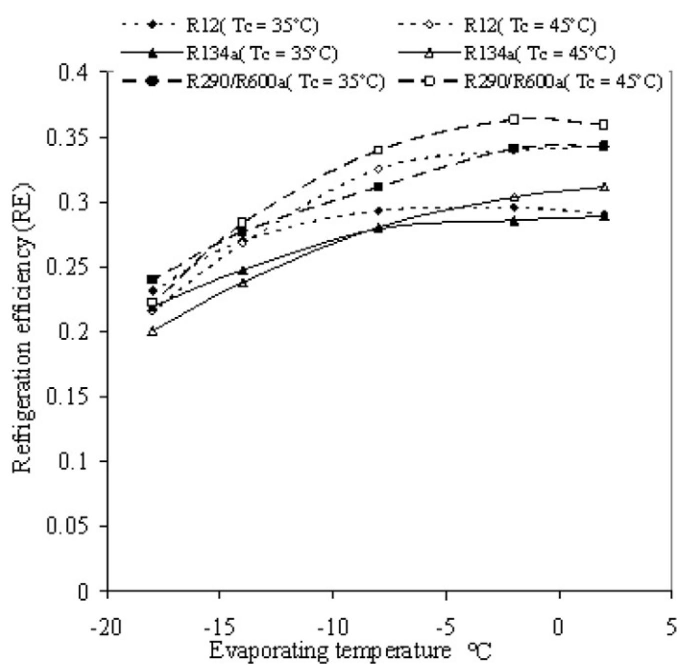

Fig. 6. RE vs evaporating temperature for $T_c = 35$ °C and 45 °C.

5.4. *Refrigeration efficiency*

Fig. 6 showed that the refrigeration efficiency of the system increases with the increase in condensing and evaporating temperature. At lower evaporating temperatures below −14 °C, the refrigeration efficiency decreases as the condensing temperature increases while above −14 °C the refrigeration efficiency increases as the condensing temperature increases. The R290/R600a (68/32 by wt%) mixture showed higher RE than that of R12 and R134a.

6. Conclusions

A performance analysis on a vapour compression refrigeration system with the new refrigerant blend as substitute for CFC12 and HFC134a was made and the following conclusions were drawn.

- Refrigerating capacity of R290/R600a (68/32 by wt%) mixture was higher in the range 19.9–50.1% in the lower evaporating temperatures and 21.2–28.5% in the higher evaporating temperatures than R12.
- Refrigerating capacity of R290/R600a (68/32 by wt%) mixture was higher in the range 28.6–87.2% in the lower evaporating temperatures and 30.7–41.3% in the higher evaporating temperatures than R134a.
- Energy consumption of R290/R600a (68/32 by wt%) mixture was higher in the range 6.8–17.4% than R12 and 8.9–20% than R134a.
- COP of R290/R600a (68/32 by wt%) mixture was higher in the range 3.9–25.1% in the lower evaporating temperatures and 11.8–17.6% higher in the higher evaporating temperatures than R12.
- The refrigeration efficiency of the system increases with the increase in condensing and evaporating temperature.
- The discharge temperature and discharge pressure of R290/R600a (68/32 by wt%) mixture was nearly equal to those of R12 and R134a.

During the experimental test R290/R600a mixture were found to be safe. However care should be taken when using R290/R600a mixture in a refrigeration/heat pump system. From the two major environmental impact (ozone layer depletion and global warming) point of view this R290/R600a (68/32 by wt%) mixture can be used as a drop-in replacement refrigerant for CFC12 and HFC134a.

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