Experimental and Theoretical Investigation of Propane/Butane and Propane/Isobutane Mixtures as an Alternative to R134a in a Domestic Refrigerator

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ABSTRACT:

In the present work, theoretical and experimental investigation have been carried out with two hydrocarbon refrigerant mixtures as a possible alternatives to R134a. Theoretical performance of an ideal vapor compression refrigeration cycle using R290/R600 and R290/R600a was studied and the results were compared with those of R134a. The performance of the hydrocarbon mixtures of R290/R600 and R290/R600a were experimentally investigated as a drop-in alternatives to replace R134a in 297 liter domestic refrigerator designed to work with R134a. The results showed a lower freezer air temperature, lower cabinet air temperature, lower discharge temperature, higher coefficient of performance, lower pressure ratio and lower electrical power by about 3.2°C, 2.3°C, 3.1°C, 4.9%, 7% and 9.4%, respectively, for R290/R600 (60/40) % with 60g mass charge and 50% longer capillary tube compared with those of R134a with 120g mass charge.

Keyword: Hydrocarbon mixtures, drop-in replacement, domestic refrigerator, R134a.

تحقيق عملي ونظري في خليط بروبان\بيوتان وخليط بروبان\ايزوبيوتان كبديل عن R134a في الثلاجة المنزلية

الخلاصه:

في العمل الحالي تم اجراء تحقيق نظري وعملي لخليطين من موائع التثليج الهيدروكربونية كبديلين محتملين لمائع التثليج R134a. تم دراسة الأداء النظري لدورة التثليج الانضغاطية المثالية باستخدام بروبان\بيوتان و بروبان\ايزوبيوتان وقورنت النتائج مع نتائج مائع التثليج R134a. ان اداء الخليطين الهيدروكربونين المكونان من بروبان\بيوتان و بروبان\ايزوبيوتان تم التحقيق به عمليا كبديلين لمائع التثليج R134a في ثلاجة منزلية سعة 297 لتر صممت للعمل على مائع التثليج R134a. اظهرت النتائج العملية ان بروبان\بيوتان (بنسبة كتلية للبروبان مقدارها 60% وشحنة 60g للخليط 50% زيادة في طول الانبوب الشعري) له درجة حرارة حجرة تجميد اوطأ ودرجة حرارة حجرة تبريد اوطأ ودرجة حرارة اوطأ لمائع التثليج الخارج من الضاغط ومعامل اداء اعلى ونسبة انضغاط اوطأ وطاقة كهربائية اقل بمقدار 3.2°C و

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2.3°C و 3.1°C 4.9% و 7% و 9.4% على التوالي, مقارنة مع تلك عندما يكون R134a مستخدما كمائع تثليج بشحنة 120غم.

INTRODUCTION:

Chlorofluorocarbons (CFCs) have been used extensively for the past few decades due to their excellent thermodynamic properties and chemical stability. In particular CFC12 has been predominantly used for small refrigeration units including domestic refrigerator/freezers. CFCs have been stopped because of their effects on stratosphere ozone and their potential contribution to global warming, CFCs are now controlled substance by the Montreal protocol [1, 2].

Hydrofluorocarbon-134a, have been used to replace CFC12 used in refrigeration and air conditioning. HFC134a has such favorable characteristics as zero ozone depleting potential (ODP), non-flammability, stability, and has a close match to CFC12 [3, 4 and 5]. The **ODP** of HFC134a is zero, but it has relatively high global warming potential.

Many studies are being carried out which are concentrated on the application of environmentally friendly refrigerant in refrigeration system. The issue of ozone layer depletion and global warming has led to consideration of hydrocarbon refrigerants such as propane, isobutene, n-butane or hydrocarbon blends as working fluids in refrigeration and air-conditioning system. The hydrocarbon (HC) as refrigerant has several positive characteristics such as zero ozone depletion potential, very low global warming, low-toxicity, miscibility with MO and POE lubricant, good compatibility with the materials usually employed in refrigerating system. The main disadvantage of using hydrocarbons as refrigerant is their flammability [6].

Maclaine-cross and Leonardi [7] confirmed that hydrocarbon refrigerants have environmental advantages and are safe if they used in small quantities, thereby R290 can replace R22 and hydrocarbon mixture can replace both R12 and R134a in refrigeration and air-conditioning system.

Garland and Hadfield [8] studied the environmental impacts of hydrocarbon refrigerant R600a deployed in the domestic refrigerator hermetic compressor. The test was done by sliding tests to establish wear mechanism and friction coefficient and compared the results with R134a. The results showed that R600a compressor continues to perform at the end of its 15-year cycle whereas the performance of the R134a compressor deteriorates rapidly at and beyond 15-years.

Fatouh and El Kafafy [9] experimented with Liquefied Petroleum Gas (LPG) (composed of 60% of R290 and 40% of commercial butane) as an alternative to R134a in 283liter domestic refrigerator at 43°C ambient temperature. Their results reported that **COP** of the refrigerator using **LPG** was higher than that of R134a by about 7.6% with lower values of energy consumption and on-time ratio by about 10.8% and 14.3%, respectively.

Experimental results of Jung et al. [10] 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 shell temperature than R12.

Dalkilic and Wongwises [11] studied the theoretical performance in an ideal vapor-compression refrigeration system with refrigerant mixtures based on R134a, R152a, R32, R290, R1270, R600 and R600a with various ratios. The results were compared with R12, R22 and R134a as possible alternative replacements based on considering the comparison of performance coefficients (COP) and pressure ratios of the tasted refrigerants and also the main environmental impacts. Refrigerants blends of R290/R600a (40/60 by weight %) and R290/R1270 (20/80 by weight %) are found to be the most suitable alternatives among refrigerant tested for R12 and R22 respectively.

Ali H. Tarrad and Ayad Al-Nadawi [12] studied the performance of R407C and R407A as an Alternative of R22 Refrigerant in a Window Type Air Conditioner. The cooling capacity is improved by (14.5%) and (30%) for R407C and R407A, respectively, as compared with the R22. Also, R407C exhibits a lower power consumption than that of the R22 tests by a value ranging between (3%) and (4%). On the contrary, R407A shows a higher power consumption than that of R22 by a value ranging between (4%) and (10%). The corresponding mean value of (**C.O.P**) shows a significant increase up to (19%) and (21.7%) for R407C and R407A respectively.

Khalid A. Joudi et al. [13] studied the performance of an automotive air condition system using R134a, R290, R600a and a mixture of propane and isobutane (62/38, molar percentage) as alternatives to replace R12. The results showed a close similarity between R290/R600a (62/38, molar percentage) and R12 in the working pressure, energy consumption, and coefficient of performance.

In this paper, a locally made domestic refrigerator operated with the refrigerant R134a will be used to test two of zoetrope refrigerants as possible alternatives to replace the greenhouse worming refrigerant R134a. To accomplish the goals of the study, experimental investigation for a suitable mixing of R290/R600, produced by South Oil Company in Iraq and R290/R600a will be carried out. Power consumption and cooling performance will be monitored during the tests. Theoretical analysis for the performance of the vapor compression refrigeration cycle will be introduced using R290/R600 and R290/R600a in the comparison with R134a to visualize the behavior of the refrigerants examined under alternate conditions. The experimental data and the theoretical analysis of this work are important and helpful tool to reach to a satisfactory replacement of an ozone depleting/green-house warming refrigerants for further use and maintain cheap Iraqi made refrigerants in the future.

Experimental investigation:

The experimental investigation is conducted with a single door, manual defrost and tropical class Ishtar refrigerator with total and freezer volumes of 10.5ft^3 (297 Liter) and 1.1ft^3 (31 Liter), respectively. It is originally manufactured to work with R134a as a circulating refrigerant with 120g mass charge and (VG22) polyol ester (POE) oil .The compressor oil has not been changed following Garland and Hadifield [14] and Navarw et.al. [15] as they indicated that the hydrocarbon refrigerant could be used with POE oil . The refrigerator consists of a cabinet, an evaporator, a compressor, a condenser and a capillary tube. Figure (1) and (2) shows the test unit, and manifests the instrumentation and the system modifications.

Instrumentations:

In order to evaluate the performance characteristics of the refrigerant 134a and LPG in the domestic refrigerator, measuring and control instruments have been used included:

1.Temperature measurements: eleven Type-T thermocouples are used in the refrigerator, five of them are used to measure the refrigerant temperatures, and another five are used to measure the refrigerator inside air temperature (two in the freezer and three in the lower cabinet) as shown in Figure (3). One thermocouple was used to measure the dry bulb air temperature inside the test room .

2. Pressure Measurements: five pressure gauges were used to indicate the pressure and the pressure drop at high and low pressure sides of the refrigerant circuit.

3.Power Instruments: a backup power supply was used in case of the electrical shutting down during the test period, voltage regulator was used to insure a uniform voltage and digital clamp meter was used to measure the current of the domestic refrigerator.

4. Refrigerant Charging Equipment: two refrigerant charging hoses with a digital charging scale were used to measure the refrigerant mass charge for each test.

Refrigerant Charging:

It is interesting to highlight the method used to charge the refrigerant. The pure refrigerant can be charged as a liquid or vapor phase but, for the mixed refrigerant like the hydrocarbon mixture, it has to be charged only in a liquid phase to avoid composition shifting problems. In the present work, the hydrocarbon components were each contained in different cans and charged one at a time using the digital charging scale to measure the required mass to be charged. The thermodynamic properties for R134a and the hydrocarbon mixtures are all estimated using REFPROP.

Experimental Setup:

The refrigerator was run at steady state condition with the freezer unloaded for two hours period in order to study the performance characteristics for the refrigerants examined. In another test, load of 2 bottles (1/2 kg each) of water at 30^{o}C were placed in the freezer compartment with a thermocouple inside each water bottle to measure the water temperature till the water reaches 0^{o}C in order to simulate the actual cooling performance. During the entire test period, the refrigerator with closed door was placed in a room in which dry bulb air temperature was about 30°C. The readings of temperatures, pressure gauges and the clamp meter for R134a and the hydrocarbon mixtures were recorded every five minutes from the starting time of each experiment till steady state of the operating conditions was reached. After the test was done, the refrigerator door was kept open for at least six hours to allow the refrigerator temperature to reach the ambient temperature again. Moreover, some random tests were repeated to ensure reproducibility of the data. The experimental data of the steady state were used to evaluate the performance characteristics of the domestic refrigerator.

Theoretical analysis:

The hydrocarbon mixtures R290/R600 and R290/R600a with different compositions are used as working fluids to investigate the performance of the vapor compression refrigeration cycle for the comparison with the refrigerant R134a in order to obtain better performance. The p-h diagrams shown in Figure (4) represent the theoretical vapor-compression refrigeration cycle for pure and zeotrope mixture. The only difference between pure substance and zeotrope mixture are the changes in temperature during condensation and evaporation. Condensation and evaporation processes are not isothermal for the mixtures used in the present study due to the shift in composition during condensation and evaporation. Therefore, condensation temperature is considered as the average temperature of the dew temperature $t_{2'}$ and the bubble temperature t_3 while evaporation temperature is the average temperature calculated from both sides of the evaporator, [16].The effects of the refrigerant type and composition on the evaporation pressure (P_{evap}), pressure ratio (PR), isentropic compression work (W_{comp}), refrigerating effect (RE), power per ton of refrigeration, volumetric refrigeration capacity (VRC), suction vapor flow rate (SVFR) and coefficient of performance (COP) are investigated at evaporating temperatures ranging between (-30 to 5)°C and a constant condensation temperature of 50 °C typically found in the Iraqi climates.

The thermodynamic properties of R134a and hydrocarbon mixtures were used to determine the performance of the theoretical vapor compression cycle for the all mixture ratios and pure substance using the following performance parameters.

Pressure ratio (PR) is defined by:

$$PR = \frac{P_{cond}}{P_{evap}} \quad \ldots(1)$$

The refrigerating effect (RE) is given by:

$$RE = q_{evap} = h_1 - h_4 \quad \ldots(2)$$

Isentropic compression work in the compressor (w_{comp}.) can be expressed as:

$$w_{comp} = h_2 - h_1 \quad \ldots(3)$$

Power per ton of refrigeration is obtained by:

$$\text{Power per ton of refrigeration } \left(\frac{P}{TR}\right) = 3.5\,\frac{w_{comp}}{RE} \quad ..(4)$$

In the vapor-compression system of Figure (1), the volumetric refrigerating capacity (VRC) is:

$$VRC = \rho_1 \times RE \quad ..(5)$$

The suction vapor flow per kW of refrigeration is:

$$SVFR = \frac{1}{(\rho_1 \times RE)} \quad ..(6)$$

The coefficient of performance (COP) of the refrigeration system's cycle is determined by:

$$COP = \frac{RE}{w_{comp}} \quad ..(7)$$

The performance parameters were plotted against the evaporating temperature (T_{evap}) for the evaporation and condensation temperatures considered.

Results and Discussions:

Theoretical Results and Discussion

Theoretical cycle performance for R134a and the hydrocarbon mixtures was obtained and the results showed deviations between R134a and the hydrocarbon mixtures. Table (1) shows the deviations of R290/R600 (70/30) from the values of R134a for the present study compared with those of the previous study.

Evaporation Pressure

In the relationship between the evaporation pressure (P_{evap}) and the evaporation temperature (T_{evap}) shown in Figure (5), the hydrocarbon mixtures R290/R600 (70/30), R290/R600a (70/30) and R290/R600a (60/40) showed higher evaporation pressure than R134a by about (1.3to10.7)%, (15.5to33.6)% and (4.4to18)%, respectively, for an evaporating temperature range (5to-30)°C. The hydrocarbon mixture R290/R600a (50/50) showed higher evaporation pressure by about (0.3to3.9)% for an evaporating temperature range (-19to-30)°C, the same evaporation pressure at -18°C and lower evaporation pressure by about (0.3to5.9)% for an evaporating temperature range (-17to5)°C compared with that of R134a. The other mixtures showed lower evaporation pressure as compared with that of R134a. The advantage of the hydrocarbon mixtures with higher evaporation pressure may show more flexibility in decreasing the evaporator temperature in the actual work by adjusting the evaporator pressure. Therefore, R290/R600a is more effective than R290/R600 when they are used as a drop-in alternatives for R134a.

Pressure Ratio

It can be seen from Figure (6) that R290/R600 (30/70) and R290/R600 (40/60)% have a higher pressure ratio than R134a by about (2.9to7.9)% and (0.4to2.5)%, respectively, for the evaporator temperature range (5to-30)°C, while R290/R600a (70/30)% yields the lowest pressure ratio among the other candidates and this will lead to an improve in the performance.

Coefficient of Performance

As a result of the refrigeration effect and the isentropic compression work, the coefficient of performance increases with an increase in the evaporating temperature due to the increase in the refrigerating effect (RE) and the decrease in the compression work (W_{comp}). For all the tested alternative refrigerants, the coefficient of performance was slightly higher than that of R134a as shown in Figure (7). It can be seen that the hydrocarbon mixture R290/R600 (30/70)% has the highest coefficient of performance among other alternatives and therefore, the hydrocarbon mixture R290/R600 has generally higher coefficient of performance of R290/R600a.

Power Per Ton of Refrigeration

The changes in power per ton of refrigeration with the evaporation temperature (T_{evap}) represented in Figure (8) shows a lower compressor power consumption for all the alternative refrigerants compared with that of R134a. The refrigeration power decreases as the evaporating temperature increases. The hydrocarbon mixture R290/R600 showed lower values of the compressor power consumption as compared with R290/R600a and the power consumption decreases as the propane concentration decreases. Therefore, R290/R600 (30/70) % has the lowest power consumed per ton of refrigeration while R290/R600a (70/30) % has the highest.

Volumetric Refrigeration Capacity

The volumetric refrigeration capacity is also a very important parameter, this because the alternative refrigerant should give the same volumetric capacity to maintain the vapor compression refrigeration cycle with the same duty that it has when the refrigerant R134a is used as a working fluid. The results showed no match in the volumetric refrigeration capacity between R134a and R290/R600 except for R290/R600 (70/30)% at -6°C and higher value of that of R134a by about 7.3% at -30°C (Fig. 9a). Another match in the volumetric refrigeration capacity between R134a and R290/R600a (60/40)% at about -5°C and gets 9.3% higher at -30°C as shown in Figure (9b). The hydrocarbon mixture R290/R600a (70/30)% showed higher volumetric refrigeration capacity by about (4.8to20.9)% compared with that of R134a for the evaporating temperature range (5to-30)°C when the other mixtures showed lower volumetric refrigeration capacity as compared with that of R134a. It can be seen that the volumetric refrigeration capacity for the hydrocarbon mixtures is generally increased with decreasing the evaporating temperature as compared with R134a. Therefore, the volumetric refrigeration capacity for the hydrocarbon mixtures in the actual work is expected to increase by decreasing the evaporator pressure.

Suction Vapor Flow per Kw of Refrigeration

The changes between the suction vapor flow needed for refrigeration (SVFR) with the evaporating temperature (T_{evap}) were obtained to verify the cycle performance advantages of alternative refrigerants. The specific volume of the suction vapor decreases, causing an increase in the mass flow rate as the evaporating temperature (T_{evap}) increases. The effect of increasing the concentration for propane (R290) in the hydrocarbon mixture causes a decrease in the suction vapor flow per ton of refrigeration due to the lower specific volume as shown in Figure (10), which causes an increase in the mass flow rate.

Experimental Results and Discussion

The hydrocarbon mixtures R290/R600 and R290/R600a were used as possible alternatives to replace R134a. The experimental data were collected and REFPROP program [17] was used to analyze the data. Table (2) shows the deviations of R290/R600 (60/40) from the values of R134a for the present study compared with those of the previous study.

Freezer and Cabinet Air Temperature

For all the hydrocarbon mixtures tested, the results showed a different freezer and cabinet air temperatures during the test period. It can be seen form Figure (11) that the lower refrigerator inside air temperature refers to a higher concentration of propane due to the lower boiling point of propane. R290/R600 (70/30)%, R290/R600a (55/45)% and R290/R600a (60/40)% showed a lower freezer air temperature than the baseline refrigerant R134a by about 0.2°C, 0.7°C and 1.3°C, respectively, and lower cabinet air temperature, Figure (12), by about 1.1°C, 0.9°C and 2.3°C, respectively, compared with the baseline cabinet air temperature. The other hydrocarbon mixtures, R290/R600 (40/60)%, R290/R600 (50/50)%, R290/R600 (60/40)%, R290/R600a (40/60)% and R290/R600a (50/50)%, showed a higher freezer air temperature by about 3.5°C, 2.2°C, 0.5°C, 1.8°C and 0.2°C, respectively, and higher cabinet air temperature except for R290/R600 (60/40)% and R290/R600a (50/50)% which showed a lower cabinet air temperature by 0.4°C and 0.1°C, respectively, compared with the baseline cabinet air temperature.

Selecting the Proper Composition

The important criteria for the hydrocarbon mixture to be a replacement fluid is to produce the right specific volume of suction vapor and the right pressure drop for the unchanged compressor and capillary tube, respectively, in order for the system to be functioning typically. These requirements depend on the components concentration of the hydrocarbon mixture. In another meaning, the hydrocarbon mixture is not only measured with increasing the propane concentration to produce higher cooling capacity, it has to be subjected into several processes which identify the system acceptability to the replacement fluid. In the present study, there is no standard to verify the right specific volume of the suction vapor or the pressure drop other than using a combination of the hydrocarbon mixtures and studying their cooling performance and the system response to that performance. Another point to be observed is that; the compressor with the hydrocarbon mixture R290/R600 (60/40)% and R290/R600a (40/60)% was running cooler than R134a and it gets louder with higher propane concentration. The compressor operation was very quiet with R290/R600 (40/60)%.

Effects of Capillary Tube Length

Depending on the theoretical results on increasing the refrigerating capacity for the domestic refrigerator by decreasing the evaporator pressure of the hydrocarbon mixtures. A group of tests were carried out by using the hydrocarbon mixture R290/R600 (60/40)

% with 50% longer capillary tube of the original length in a comparison with R134a and R290/R600 (60/40) % with the original capillary tube length at 22°C ambient temperature. A steady state test and water test were performed in order to analyze the performance for the examined refrigerants. From the result obtained for the hydrocarbon mixture R290/R600 (60/40)% and R134a, the lower ambient temperature showed an enhancement in the freezer and the cabinet air temperature for the hydrocarbon mixture with the original length of the capillary tube more than that of R134a. The effect of longer capillary tube on the hydrocarbon mixture showed a superior performance when compared with that of R134a. Freezer and cabinet air temperature were -12.5°C and -4.2°C for R134a, -14.5°C and -5.7°C for R290/R600 (60/40)% with the original capillary tube length and -15.7 and -6.5 for R290/R600 (60/40)% with 50% longer capillary tube, respectively. Pull down time for R134a refrigerant was 110min and 39min to reach -12°C in the freezer and 6°C in the lower cabinet, respectively, according to ISO8187 as mentioned by Ref. [18]. R290/R600(60/40)% (with standard capillary tube length and 60g mass charge) required 80min and 39min to reach the pull down time in the freezer and the lower cabinet, respectively, while, R290/R600(60/40)% (with 50% longer capillary tube and 60g mass charge) required 65min and 34min to reach the pull down time in the freezer and the lower cabinet, respectively. The increased pressure ratio for the hydrocarbon refrigerant with longer capillary tube increases the refrigerating effect with higher values of the specific work results in slightly lower coefficient of performance as compared with those of the unchanged capillary tube. The power consumed by the compressor decreased as the capillary tube length for the hydrocarbon refrigerant increased as compared with those of the unchanged capillary tube due to the reduced pressure of the compressor suction line. The hydrocarbon mixture with longer capillary tube was tested by placing one liter of water in the freezer compartment and it showed a faster cooling time as compared with that of R134a by about (6)min, (3)min and (1)min at mass charge of 60g, 65g and 70g, respectively.

CONCLUSIONS:

1. The tuning of the hydrocarbon mixtures with R134a compressor was found to be better with R290/R600. The compressor with the hydrocarbon mixture R290/R600 (60/40)% was running cooler than R134a refrigerant. The compressor operation was very quiet with R290/R600 (40/60)%.
2. Further findings were reached for both R134a (with its standard capillary tube and 120 mass charge) and R290/R600 (60/40)% (with 50% longer capillary tube and 60g mass charge). Freezer air temperature, discharge temperature, pressure ratio and electrical power for R290/R600 (60/40)% were lower than those of R134a by about 3.2°C, 3.1°C, 7% and 9.4% respectively. The coefficient of performance for R290/R600 (60/40)% was higher than that of R134a by about 4.9%.
3. The a mount of the refrigerant charged for the hydrocarbon mixtures was 50% lower than that of R134a.

4. The usage of the hydrocarbon mixtures didn't show any degradation in the lubricant along the entire tests which shows the good miscibility of the hydrocarbon mixtures with the **POE** lubricant.

The hydrocarbon mixture R290/R600 (60/40) % considered to be a viable alternative to replace R134a in domestic refrigeration system depending mainly on its compatibility with R134a compressor, availability, cheapness and environmentally safe refrigerant. In addition to that, higher cooling capacity, higher **COP**, lower power consumption for all mass charges examined of R290/R600 (60/40)% as compared with R134a performance.

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Nomenclatures:

COP Coefficient of performance
P_{evap} Evaporator pressure
PR Pressure ratio
RE Refrigerating effect
SVFR Suction vapor flow rate
VRC Volumetric refrigeration capacity
w_{comp} Specific work

Table (1): Comparison of the experimental results between the present and the previous studies for replacing R134a in domestic refrigerators.

Reference	Replacement fluid	Pull down time	Freezer air temperature	Cabinet air temperature	Discharge temperature	Pressure ratio	Power consumption	Coefficient of performance
Fatouh and El Kafafy [9]	**R290/R600 (60/40)%**	-7.6%	-1°C	-1°C	-4.1°C	-5.5%	-4.3%	+7.6%
Mohanraj et al. [18]	**R290/R600a (45/55)%**	-23.8%	-----	-----	-12°C	-----	-5.1%	+11.4%
Mohanraj et al. [18]	**R290/R600a (45.2/54.8)%**	-11.6%	-----	-----	-8.5°C to -13.4°C	-----	-0.92% to -1.06%	+3.25% to +3.6%
Present study	**R290/R600 (60/40)%**	-40.9%	-3.2°C	-2.3°C	-3.1°C	-7%	-9.4%	-----

Table (2): Performance characteristics of the ideal vapor compression refrigeration cycle using R290/R600(70/30)% and R134a.

Reference	Replacement fluid	P_{evap}	P_{cond}	Pressure ratio	COP	VRC	SVFR	Power per ton of refrigeration
Dalkilic and Wongwises [11]	**R290/R600(60/40)%**	-12.3 %	-16.4 %	-4.7%	9.6 %	-21.1 %	+26.7 %	+10.6%
Present study	**R290/R600(60/40)%**	+7.6 %	-6.1	-12.7	+2.2	+4.0	-3.9	-2.2

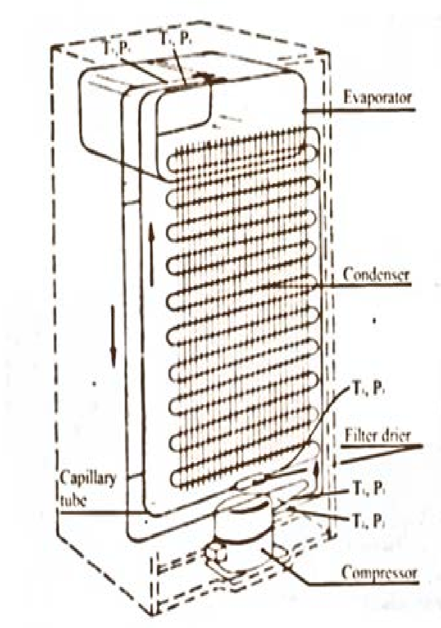


Figure (1): Piping and instrumentation diagram for the refrigerant side system.

(a) (b)

Figure (2): Test apparatus and modifications, (a): Refrigerator, (b): Modifications.

(a) (b)

Figure (3): Air side thermocouples, (a): at freezer, (b): at cabinet.

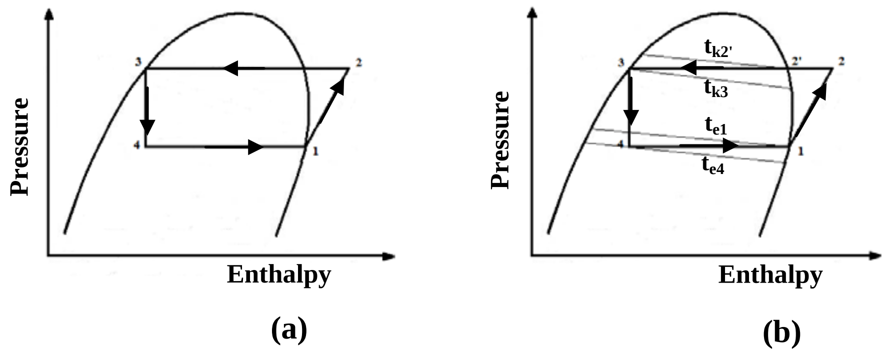
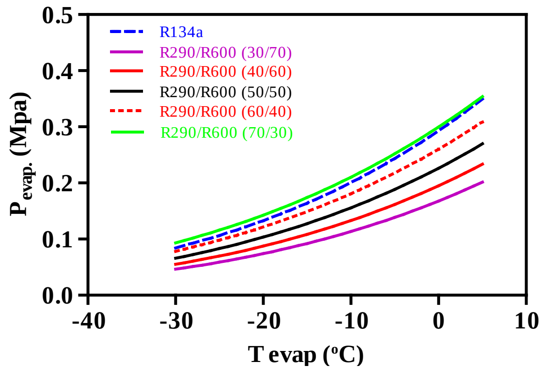
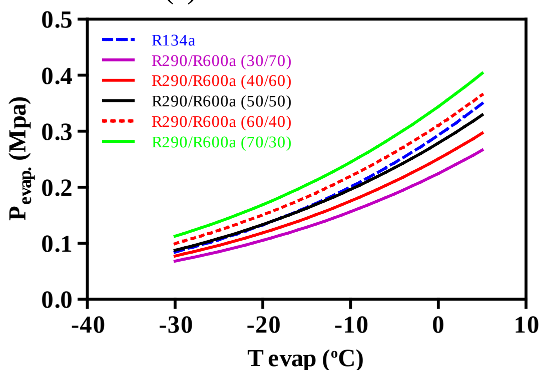


Figure (4): P-H diagram of an ideal vapor compression cycle, (a) Pure refrigerant, (b) Zeotropic mixture.

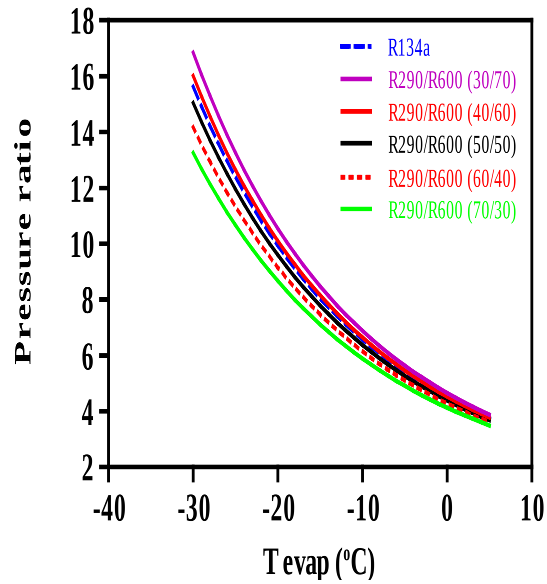


(a) R290/R600.

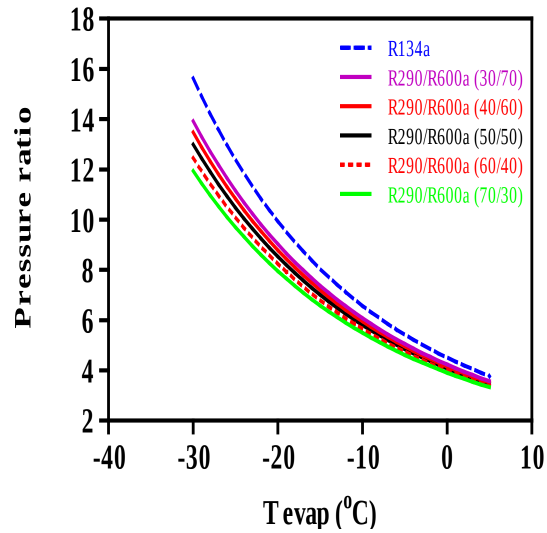


(b) R290/R600a.

Figure (5): Comparison of the variation of evaporating pressures with evaporating temperatures for several HC mixtures and R134a refrigerants.

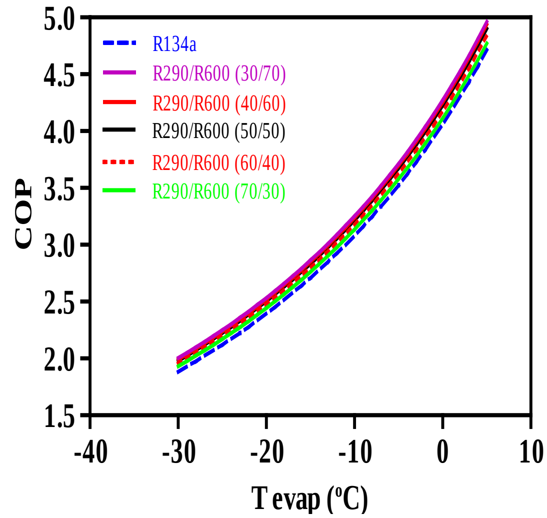


(a) R290/R600.

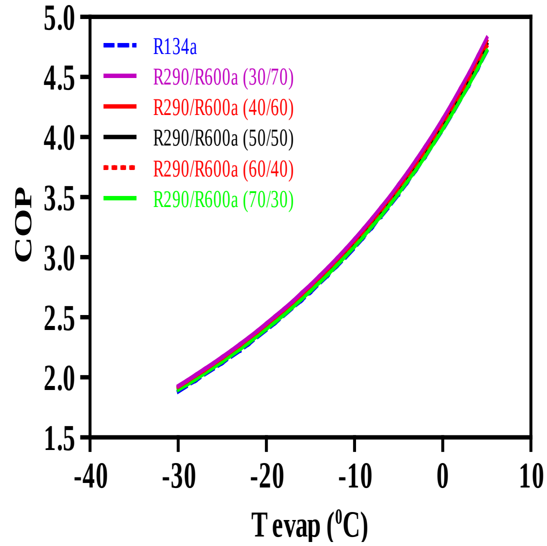


(b) R290/R600a.

Figure (6): Comparison of the variation of pressure ratios with evaporating temperatures for several HC mixing percentage and R134a refrigerants.

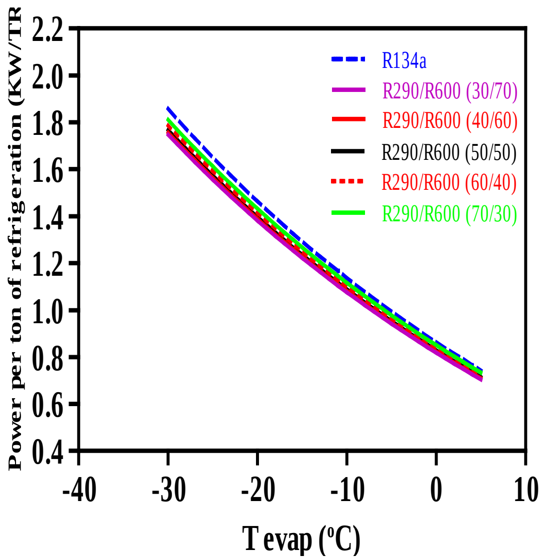


(a) R290/R600.

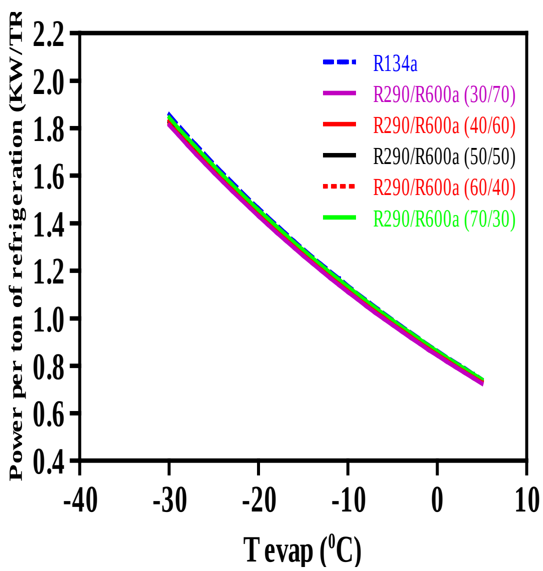


(b) R290/R600a.

Figure (7): Comparison of the variation of C.O.P with evaporating temperatures for several HC mixing percentage and R134a refrigerants.

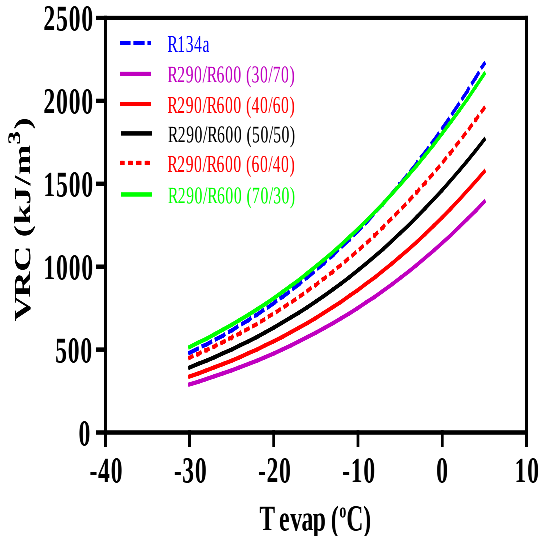


(a) R290/R600.

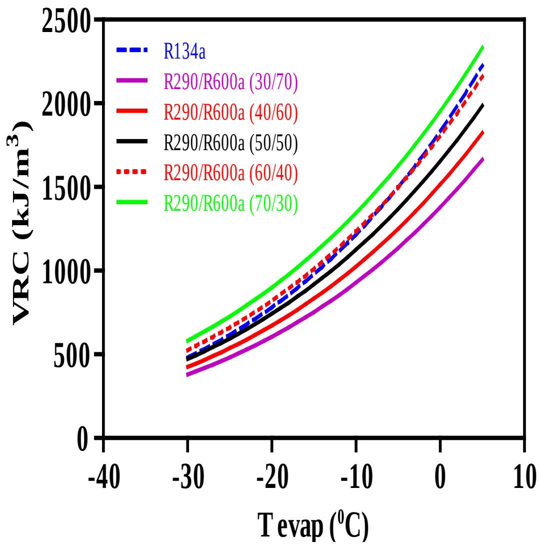


(b) R290/R600a.

Figure (8): Comparison of the variation of Power per ton of refrigeration with evaporating temperatures for several HC mixing percentage and R134a.

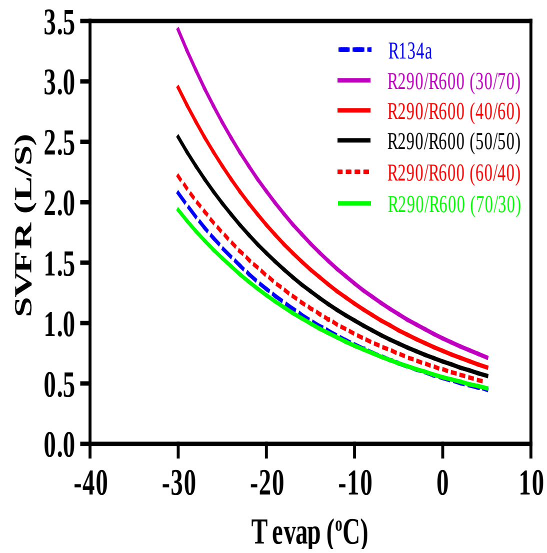


(a) R290/R600.

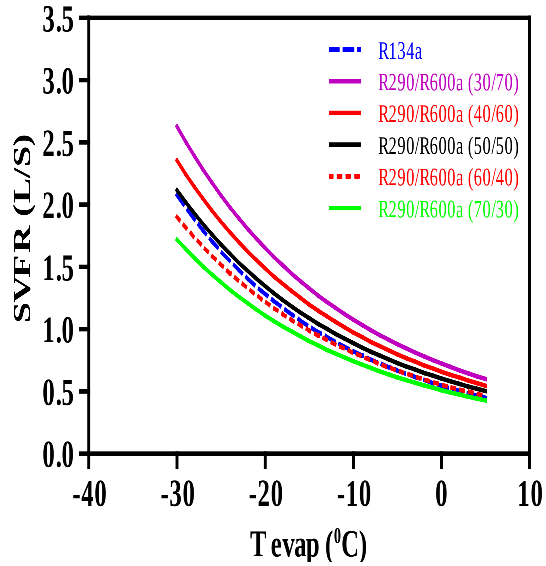


(b) R290/R600a.

Figure (9): Comparison of the variation of Volumetric refrigerating capacity with evaporating temperatures for several HC mixing percentage and R134a refrigerants.

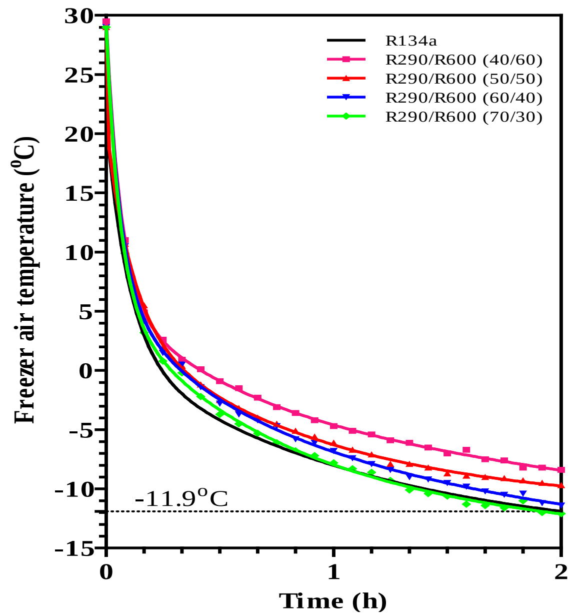


(a) R290/R600.

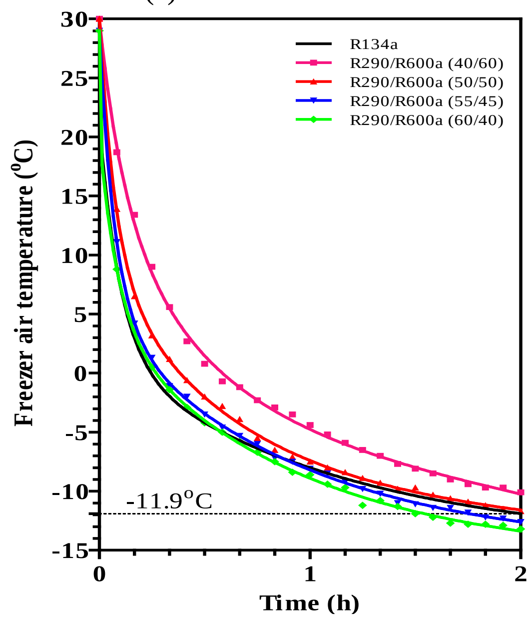


(b) R290/R600a.

Figure (10): Comparison of the variation of Suction vapor flow rate with evaporating temperatures for several HC mixing percentage and R134a refrigerants.

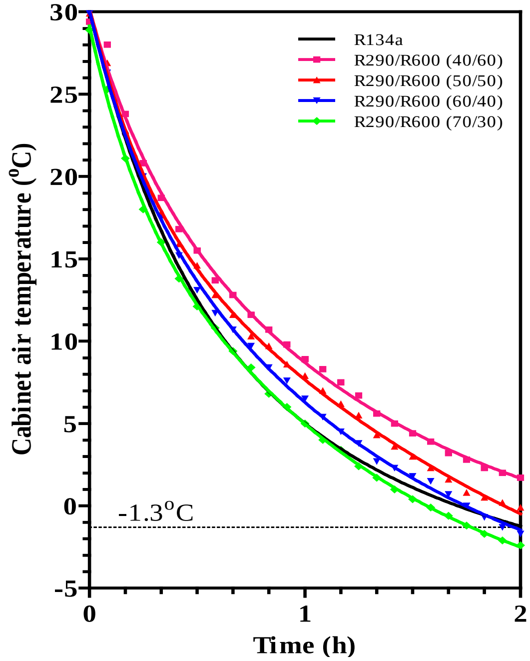


(a) R290/R600.

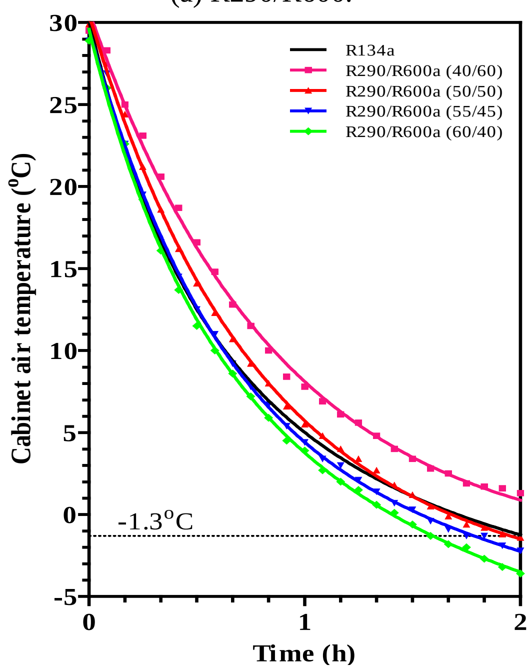


(b) R290/R600a.

Figure (11): Effect of the mass charge of 60g on the freezer air temperature.



(a) R290/R600.



(b) R290/R600a.

Figure (12): Effect of the mass charge of 60g on the cabinet air temperature.