Diyala Journal of Engineering Sciences

ISSN 1999-8716
Printed in Iraq

Vol. 09, No. 01, pp. 1-17, March 2016

PERFORMANCE INVESTIGATION OF VAPOR COMPRESSION REFRIGERATION SYSTEM WITH INTEGRATED MECHANICAL SUB-COOLING CIRCUIT USING HYDROCARBON BLENDS

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(Received: 13/7/2014; Accepted: 22/12/2014)

ABSTRACT: - This work presents an experimental study to investigate the performance of vapor compression refrigeration system using hydrocarbon mixtures. A sub-cooling circuit and phase separator are integrated with main vapor compression refrigeration system and used to predict the performance of hydrocarbon blend R-290/R-600a as alternative refrigerant with three mass fractions of (60/40, 50/50 and 40/60) and compared with R-134a. The results showed that, the enhancement in the system performance was about 14% increase in coefficient of performance, 6% increase in refrigeration effect and reduction percentage in freezing compartment temperature was in range of 12%. Lower values of pressure ratio and discharge temperature are noticed for R-290/R-600a blends comparing with R-134a. The reduction percentage in compressors power was in range of 9% during operation period. It can be concluded that the hydrocarbon refrigerants are an efficient, economically feasible and environment friendly alternative refrigerants to R-134a in vapor compression refrigeration system with sub-cooling circuit. Hydrocarbon refrigerants are flammable, therefore, safety implications of using such fluids may require specific system design and suitable operating and maintenance routines to prevent ignition and leakage sources from refrigeration system components.
Keywords: Refrigeration system, Hydrocarbon refrigerant, Mechanical sub-cooling.

NOMENCLATURE

CFC	Chlorofluorocarbon
COP	Coefficient of performance
c_p	Specific heat at constant pressure (kJ/kg.^{o}C)
GWP	Global warming potential
h	Enthalpy (kJ/kg)
HC	Hydrocarbon
HCFC	Hydro chlorofluorocarbons
HFC	Hydro fluorocarbons
$\dot{m}$	Refrigerant mass flow rate (kg/ s)
m	Mass of water (kg)
ODP	Ozone depletion potential
p	pressure (bar)
$\dot{Q}$	Rate of heat transfer (kW)
RE	Refrigeration effect (kJ/kg)
T	Temperature (^{o}C)

VCR Vapor compression refrigeration
W Compressor work (kJ/kg)

Subscripts

c Condenser
e Evaporator
m Main cycle
s Sub-cooler cycle

1- INTRODUCTION

Mechanical sub-cooling circuits are commonly installed in refrigeration systems to enhance system performance and to insure proper system operation. The function of integrating sub-cooling circuit in the refrigeration system is to prevent flash gas formation at inlet to expansion device and evaporating any residual liquid that may remain in the compressor suction line. Integrating mechanical sub-cooling cycles in VCR systems using hydrocarbon refrigerants can contribute in energy saving and then decreasing power consumption particularly in refrigerating and air conditioning of large scale commercial and industrial applications. Due to the effects of the release of HCFC's and HFC's refrigerants on the global environment caused by the high global warming potential of these substances, there is a large interest in refrigeration and air conditioning applications for the use of hydrocarbons as alternative refrigerants (1),(2). Hydrocarbon (HC) refrigerants such as, isobutane (R-600a) and propane (R-290) or blend of them which have a good thermo-physical and thermodynamic properties beside to zero ozone depletion potential ODP and a negligible global warming potential GWP are a possible replacement for other refrigerants that have a high impact on the environment. Hydrocarbon refrigerants are seen as the most viable and low cost alternative for domestic and commercial refrigeration appliances to phase out CFCs. Using hydrocarbon refrigerants in the refrigeration appliances may require specific system design and suitable operating and maintenance routines due to the safety precautions with respect to the flammability of the hydrocarbon refrigerants (3),(4).

The performance of refrigeration systems with integrated sub-cooling cycles using hydrocarbon refrigerants have been studied by a number of researchers. Srinivas et al. (5), presented performance analysis of a refrigeration system using liquid-suction heat exchanger with hydrocarbon blend. Non azeotropic mixture using existing non-CFC refrigerants was tested to evaluate the performance characteristics, benefits, disadvantages and limitations. Bolaji et al. (6), investigated theoretically the performance of some environment-friendly refrigerants selected from methane and ethane derivatives in a sub-cooling heat exchanger refrigeration system. Sub-cooling heat exchanger was used to evaluate the impact of selected refrigerants on the exchanger effectiveness, system capacity and coefficient of performance COP and the results obtained showed excellent performance for the selected refrigerants. Ahmed et al. (7), studied the exergy analysis in the vapor compression refrigeration system with hydrocarbon refrigerants R290, R600a and R134a. Exergy parameters are compared for different operating temperatures. It is found that hydrocarbon refrigerant (R600a) have 50% higher efficiency than R134a. Vaibhav et al (8), Baskaran and Mathews (9) conducted a performance comparison of vapor compression refrigeration system using hydrocarbons as alternative refrigerants and the results showed that the alternative refrigerants investigated in the analysis have slightly higher COP than R134a, R22 and other used refrigerants. The effects of the main parameters of performance analysis such as refrigerant type, degree of sub cooling and super heating on the refrigerating effect, coefficient of performance and volumetric refrigeration capacity were also investigated for various evaporating temperatures. Bukola et al. (10) presented a comparative analysis of the performance of hydrocarbon refrigerants with R22 in a sub-cooling heat exchanger refrigeration system. The results obtained showed that, the R290, R600a and R1270 have slightly better performance in terms of lower power per ton of refrigeration than R22 in sub-cooling heat exchanger refrigeration system but its saturation pressure and specific volume deviate significantly from that of R22. Bukola et al. (11) and Ashish et al. (12) conducted a performance analysis of vapour compression refrigeration system to investigate the effect of sub-cooling and superheating using alternative and hydrocarbon refrigerants comparing with R22 and R134a. The results obtained showed that, the thermodynamic performance of hydrocarbon and alternative refrigerants was similar to R-22 and R134a and the refrigerating effect and other performance parameters were the best.

In the present work, a set of experimental tests are conducted on vapor-compression refrigeration system with integrated mechanical sub-cooling circuit to investigate the effect of sub-cooling using blends of hydrocarbon refrigerants (R-600a and R-290) with three mass fractions of (60/40, 50/50 and 40/60).

2. VCR SYSTEM WITH SUB-COOLING ANALYSIS

Integrating mechanical sub-cooling circuit with main vapor compression refrigeration system is considered as a method to enhance the performance of the VCR system by improving the COP and reducing power consumption. The sub-cooling of the liquid refrigerant leaving the condenser can be accomplished by adding a mechanical-sub cooling loop in a conventional vapor compression cycle as shown in the schematic diagram in figure (1). The p-h diagram of the refrigeration cycle with sub-cooling is shown in figure (2) (13).

The heat transfer rate at the condenser can be calculated using the following equation (3):

$\dot{Q}_c = \dot{m}\,(h_{10} - h_4)$ (1)

Where: $\dot{m} = \dot{m}_m + \dot{m}_s$ (2)

The heat transfer rate in the evaporator can be calculated by:

$\dot{Q}_e = \dot{m}_m\,(h_7 - h_6)$ (3)

The work input to the main cycle compressor can be determined by:

$W_m = \dot{Q}_m\,(h_2 - h_1)$ (4)

The work input to the sub-cooler cycle compressor can be expressed by:

$W_s = \dot{m}_s\,(h_9 - h_8)$ (5)

Applying the energy balance on the sub-cooler heat exchanger, the following equation can be written:

$\dot{m}_m\,(h_4 - h_5) = \dot{m}_s(h_{12} - h_{11})$ (6)

The refrigeration effect (kJ/kg) of the system can be determined by:

Refrigeration effect = $(h_7 - h_6)$ (7)

The COP of the refrigeration system can be determined by:

$$COP = \frac{\dot{Q}e}{w_m + w_s} \quad (8)$$

The thermal load (kJ) of the water placed in the freezing compartment of the refrigeration system can be calculated by:

Thermal load = $m\,Cp\,(\Delta T)$ (9)

3. EXPERIMENTAL WORK

3.1. Mixture of Hydrocarbon Refrigerants

Hydrocarbon refrigerants with zero ozone depletion potential (ODP) and negligible global warming(GWP) effects represent environment friendly refrigerants which have been recommended as alternatives to CFC and HFC refrigerants in the air conditioning and refrigeration applications. These natural refrigerants are a part of petrol gases from natural sources, have favorable thermodynamic properties, good energy efficiency, non-toxic, chemically stable, compatible with many materials and miscible with mineral oils. Hydrocarbon refrigerants such as propane, butane, isobutane and propylene or blends of them are flammable, therefore, safety implications of using such fluids may require specific system design and suitable operating and maintenance routines to prevent ignition and leakage sources from refrigeration system components [(3)].

Presently, propane (R-290), butane (R-600), isobutene (R-600a), propylene (R-1270), and blends of propane, butane, isobutene, and ethane (R-170) are regarded as the most promising HC working fluids in commercial and industrial air conditioning and refrigeration systems [(14)]. The zeotropic refrigerant mixtures of HC refrigerants have potentials to enhance the performance and efficiency of a system due to the temperature gliding effect with range of temperature difference (6-8^{o}C) as shown in figure(3). The blends of HC refrigerants used in the present work are prepared with respect to mass fractions of total system charge mass (4000g) for each pure hydrocarbon refrigerant using precise digital balance and refrigerant charging device as shown in figure (4) and can be described as follow:

- R-290/R-600a: (40% / 60%) mass fractions
- R-290/R-600a: (50% / 50%) mass fractions
- R-290/R-600a: (60% / 40%) mass fractions

Pure refrigerant R-134a is also used in present work for performance comparison with HC refrigerants. Some the thermo physical and thermodynamic properties of the refrigerants used in this work and their application limitations are shown in table (1).The test rig system is charged with 4000g of propane/isobutene mixture with 97.3 % purity depending on specific volume of the refrigerants comparing with that for R-134a charge. If R-600a would be charged into refrigeration system, charge amount counted in grams would be approximately 45 % of R-134a charge or approximately 40 % of R-12 charge in grams, according to the data of refrigerant properties, which also corresponds with empirical values [(15)]. Experience has shown that, any deviation in charge of hydrocarbon refrigerants will affect the refrigeration system performance, especially undercharging tends to give higher energy consumption.

3.2. Experimental Procedure

The experimental setup of refrigeration system consists of two cycles, main cycle and sub-cooler cycle connected to each other via a sub-cooler heat exchanger as shown in figures (1) and (5). The experimental setup is consists of, scroll compressor (2700 W) for main refrigeration system, reciprocating compressor (264W) for sub-cooling cycle, air cooled condenser, air cooled evaporator, sub-cooler heat exchanger (shell and tube), two thermostatic expansion valves, flow meters, phase separator, oil separators, accumulators, pressure gauges, freezing compartment with dimension of (1.6*0.9*1.9 m^3) and other accessories. The specifications and capacity of the refrigeration system components are indicated in the table (2).

The phase separator is installed after condenser in the refrigeration system to separate liquid refrigerant leaving condenser and entering sub-cooler heat exchanger to investigate experimentally the effect of sub-cooling after integrating phase separator in system test rig and using hydrocarbon blends as alternative refrigerants. At the beginning, the refrigeration system is charged with a single refrigerant R-134a, and the main system was operated with sub-cooling circuit turned on and thermal load applied in the freezing compartment to ensure proper operation. The readings are taken every 5 minutes to reach steady state of operation at about 60 minutes of system operation at different measuring points including, many sets of temperature readings, suction and discharge pressures, refrigerant mass flow rate and system power consumption. Then, the system is charged with blends of hydrocarbon refrigerants propane/isobutane (R-290/R-600a) with different mass fractions (40/60), (50/50) and (60/40), and the procedure mentioned above is repeated for refrigeration system with sub-cooling.

4. RESULTS AND DISCUSSION

In present study, the performance of the refrigeration system with sub-cooling circuit is studied experimentally using different blends of hydrocarbon refrigerants and compared with that for system at R-134a with thermal load 7980 kJ of water placed in the freezing compartment. Figures (6) and (7) show the variation of evaporator inlet and freezing compartment temperatures with system operating time, it can be seen that, the lower values of temperature are for propane/ isobutane blends 60/40, 50/50 and 40/60 respectively comparing with R-134a due to the effect of glide temperature (about 8ºC) produced by the difference in boiling temperatures for propane and isobutane in the HC blend as zeotropic mixed refrigerant. This effect is obvious as well in in figure (8) which shows a higher sub-cooling degree for HC blends. The variations of RE and COP for system with operating time are indicated in figures (9) and (10) which show a higher values for system performance parameters when the system works with hydrocarbon refrigerants comparing with R-134a. Figures (11), (12) and (13) show the variations of pressure ratio, discharge pressure and suction pressure respectively with time, it can be seen from these figures, that the values of pressure ratio and discharge pressure increase at beginning of operation period with reduction in suction pressure and then become steady after 40 minutes of system operation with lower value of pressure ratio for HC blends comparing with R-134a.This behavior of the system is indicated as well in figure (14) for the variations of discharge temperature with time for different refrigerants which displays a normal operation of the refrigeration system with hydrocarbon mixtures as alternative refrigerants. The variation of compressors power with operating time is shown in figure (15) which display a slight increase in power during first period of system operation due to the effect of the thermal load in freezing compartment and then the power decreases throughout the rest of operating time with reduction in power consumption for HC blends relative to R-134a. It can be concluded that, there is a significant improvement in performance parameters for proposed refrigeration system with sub-cooling circuit using alternative hydrocarbon mixtures due to their preferable thermo physical and thermodynamic properties, therefore the HC blends can be significantly used as alternative refrigerants with maintaining safety precautions in the air conditioning and refrigeration systems in many applications.

5. CONCLUSIONS

Experimental investigation of the performance parameters for refrigeration system with integrated sub-cooling circuit is conducted using different hydrocarbon blends and compared with R-134a. It can be concluded that, the improvement in the system performance was approximately 14% increase in coefficient of performance, 6% increase in refrigeration effect and reduction percentage in freezing compartment temperature was in range of 12%. Lower values of pressure ratio and discharge temperature are noticed for R-290/R-600a blends comparing with R-134a. The reduction in compressors power was in range of 9% during 60 minutes of system operation. A feasible improvements in refrigeration system performance can be obtained when hydrocarbon blends used as refrigerants.

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Table (1): Refrigerants properties and application limitations [15], [16].

	Fluorocarbon Refrigerant R-134a	Hydrocarbon(HC) Refrigerants R-600a Isobutane	Hydrocarbon(HC) Refrigerants R-290 Propane
Boiling point (°C) at 101.325 kPa	-26.1	-11.73	-42.07
Molecular mass (g mol^{-1})	102.03	58.13	44.1
Latent heat (kJ/kg)	216.87	364.25	423.33
Critical temperature (C)	101.1	134.7	96.7
Critical pressure (MPa)	4.06	3.64	4.25
GWP (100yrs.)	~1320	~ 20	~ 20
ODP	0	0	0
Compatibility with oils/lubricants			
- Mineral, Alkyl benzene, Polyolester , Semi-synthetic Poly alkyl glycol , Poly-alpha-oelfins	suitable	suitable	suitable
- Polyvinylether (PVE) silicone and silicate based	suitable	not suitable	not suitable
Compatibility with materials			
- Elastomers, plastics	suitable	suitable	suitable
- Natural rubbers, Silicone rubbers	suitable	not suitable	not suitable
Compatibility with system components			
- Compressors (hermetic and semi-hermetic reciprocating, scroll, rotary)	suitable	suitable	suitable
- Heat Exchangers (condenser, evaporator)	suitable for all types	same as for R-134a	same as for R-134a
- Expansion devices and other components	suitable for all types	suitable for all types	suitable for all types
Cost considerations			
- refrigerant (US$/kg) (in local markets)	~ 9.2	~ 7.4	~ 7.4
- appliance production cost	Low	relatively high due to Safety considerations	relatively high due to Safety considerations
- operating cost	high relative to HC refrigerants	low due to good efficiency	low due to good efficiency
Safety considerations			
- toxicity	lower toxicity	lower toxicity	lower toxicity
- flammability	no flame propagation (A1 level)	flammable (A3 level)	flammable (A3 level)

Table (2): Components specifications of experimental setup.

	Type	Capacity (or dimension)	Quantity
Compressor (for main circuit)	scroll, hermetically sealed, model (ZR36K1-PFJ-501)	2700W	1
Compressor (for sub-cooling circuit)	reciprocating, hermetically sealed, model (E1120CZA AC)	264W	1
Condenser	forced-air cooled with two fans of (5400 m^3/h)	5circuits x 4 rows per circuit of 8mm diameter finned tubes with dimensions (1100, 300,700)mm	1
Evaporator	forced-air cooled with two fan of (3170 m^3/h)	2circuits x 8 rows per circuit of 9.5mm diameter finned tubes with dimensions (310, 310, 900) mm	1
heat exchanger	shell and coil model PAC-HXR-500 made of copper and red Brass	Shell length 438mm with 52 mm diameter and coil tube diameter 22 mm	1
expansion valve	thermostatic		2
flow meter	type KF500 digital turbine flow meter	max range of 0.21m^3/sec	2
phase separator	260 mm height, 130 mm in diameter, inlet and outlet nipple of 12.7 mm in diameter pressure limit in the receiver is 30 bar		1
oil separator (for main circuit)	300 mm height and 110 mm diameter with refrigerant inlet and outlet nipple of 12.7 mm diameter		1
oil separator (for sub-cooling circuit)	150 mm height and 90 mm diameter with refrigerant inlet and outlet nipple of 6.35 mm diameter		1
Accumulator (for main circuit)	130 mm diameter and 180 mm height, inlet and out let pipes diameter 19 mm		1
Accumulator (for sub-cooling circuit)	50 mm diameter and 100 mm height, inlet and out let pipes diameter 6.4 mm		1
pressure gauge	Bourdon gauge type	in range (0-34) bar	4
thermocouples (with digital reader)	K type (J, K, PT100)		15
freezing compartment	Dimension (1.6* 0.9*1.9 m^3) with walls made of 0.5 mm in thickness steel sheets separated by 80 mm insulation foam.		1
sight glass		20 mm in diameter	4
manual valves			4
filter dryer		working pressure 40 bar	2

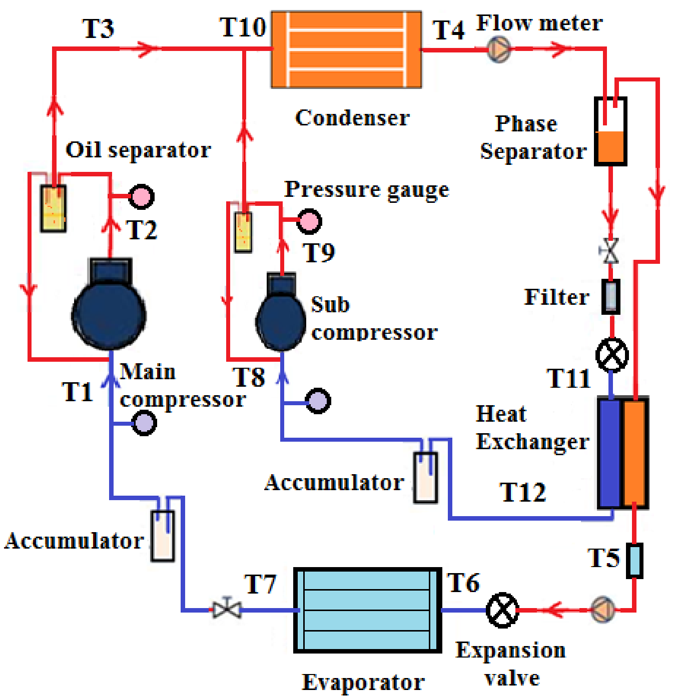

Figure (1): Schematic diagram of vapor compression refrigeration system with integrated mechanical-sub cooling cycle.

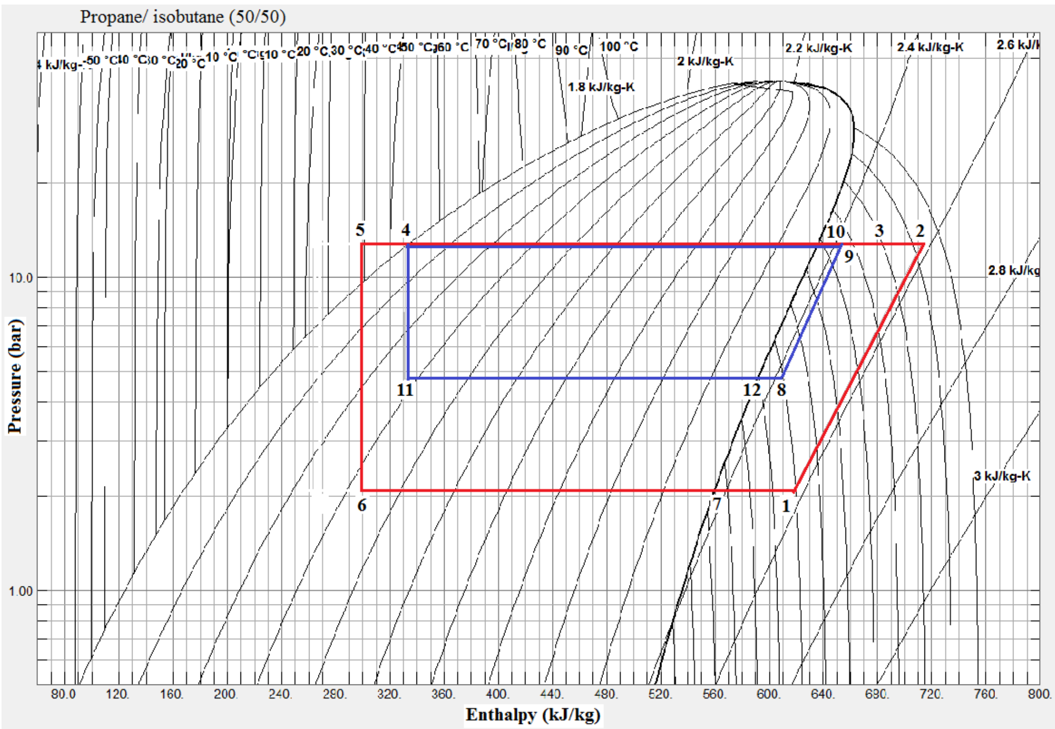

Figure (2): p-h diagram of refrigeration cycle with sub-cooling

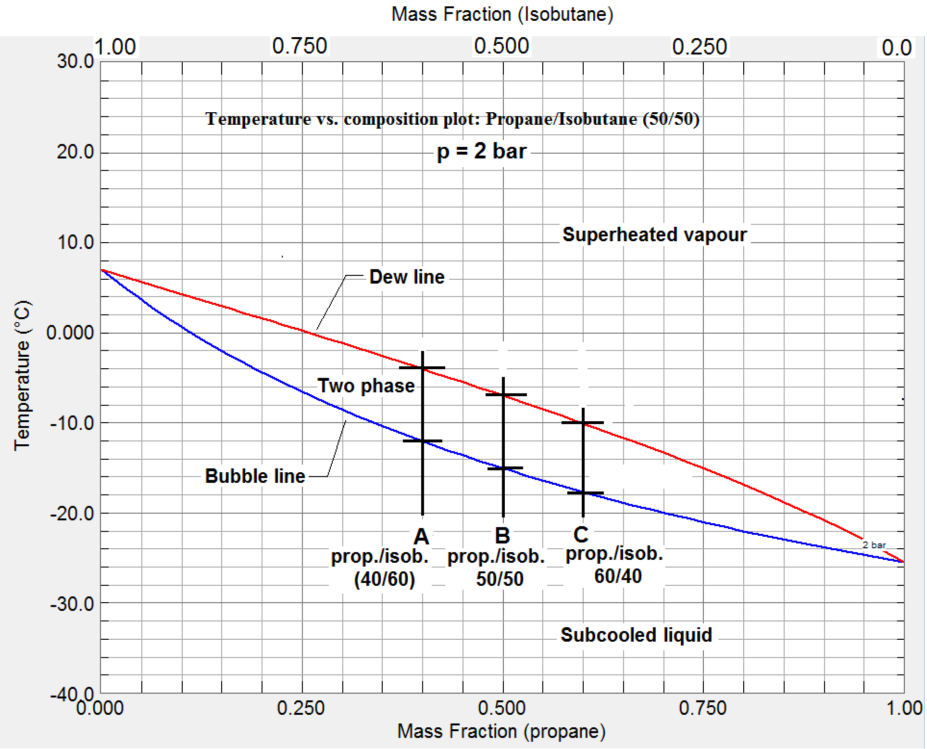

Figure (3): Mass fraction (T-X) diagram for hydrocarbon blends propane/ isobutene (R-290/R-600a at p =2 bar used in present work.

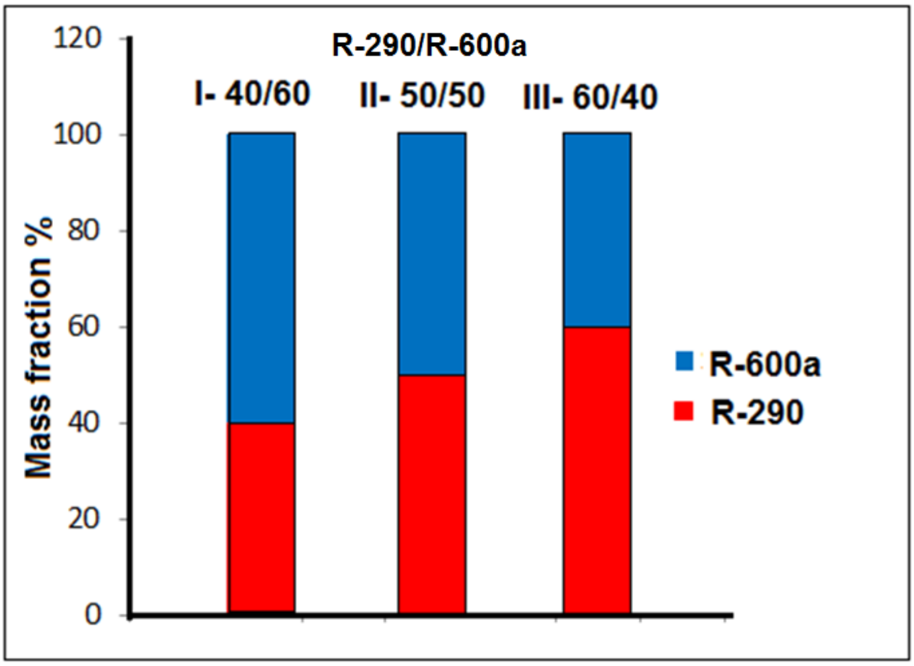

Figure (4): Blends of HC refrigerants

Figure (5): Refrigeration system experimental setup.

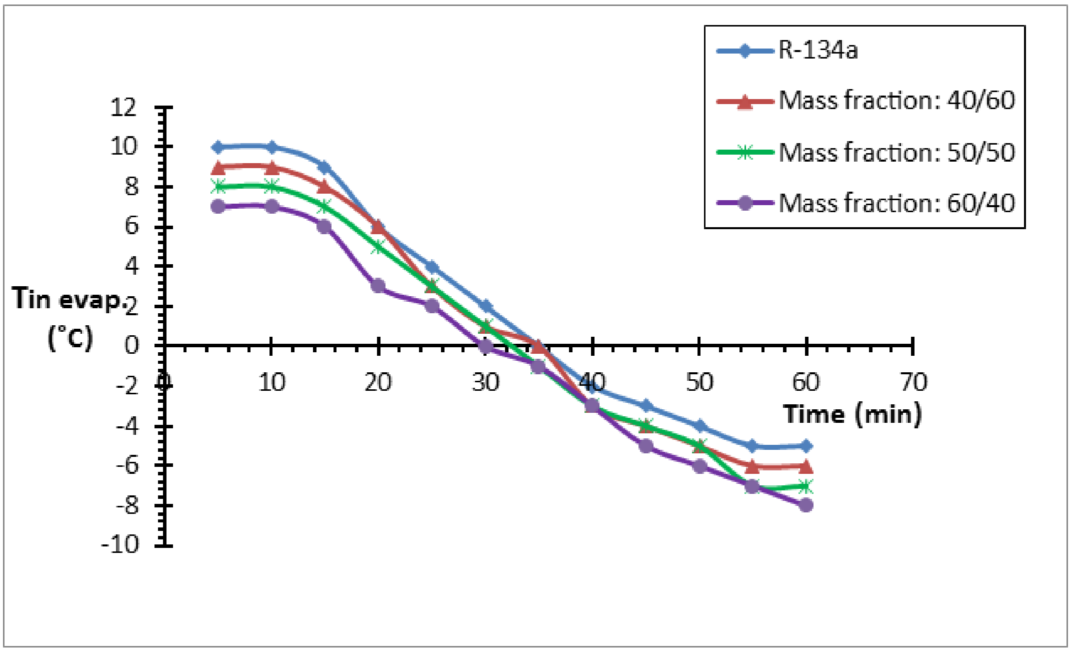

Figure (6): Evaporator inlet temperature as a function of time at different HC blends and refrigerant R-134a.

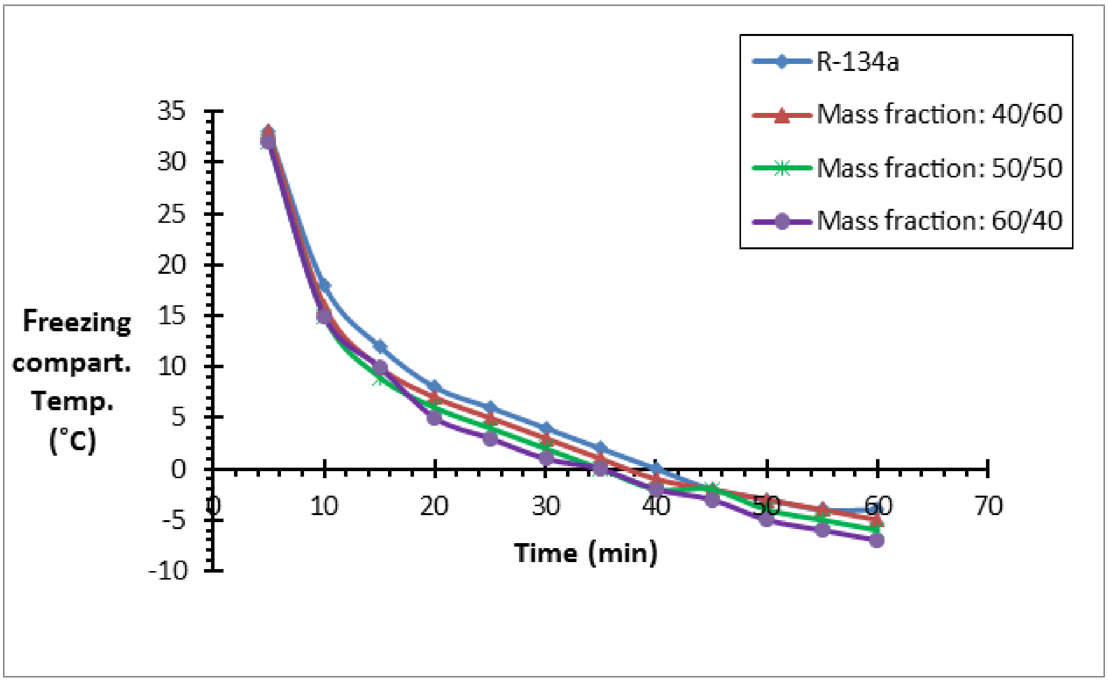

Figure (7): Freezing compartment temperature as a function of time at different HC blends and refrigerant R-134a.

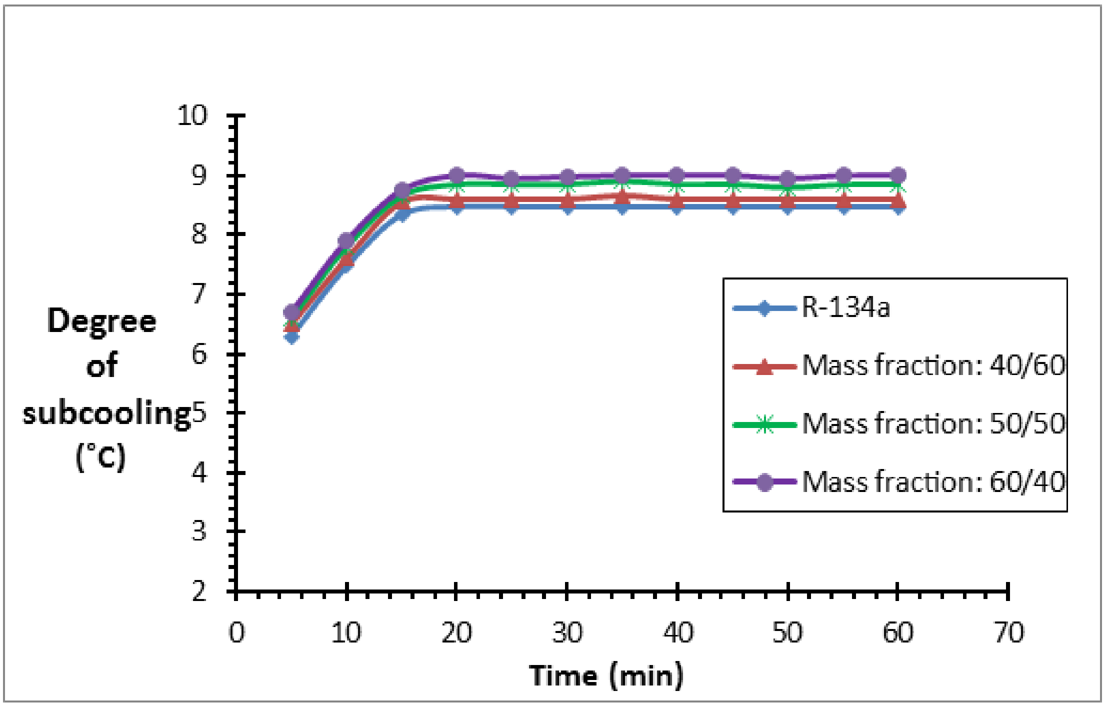

Figure (8): Degree of sub-cooling for refrigeration system as a function of time comparison for different HC blends and refrigerant R-134a.

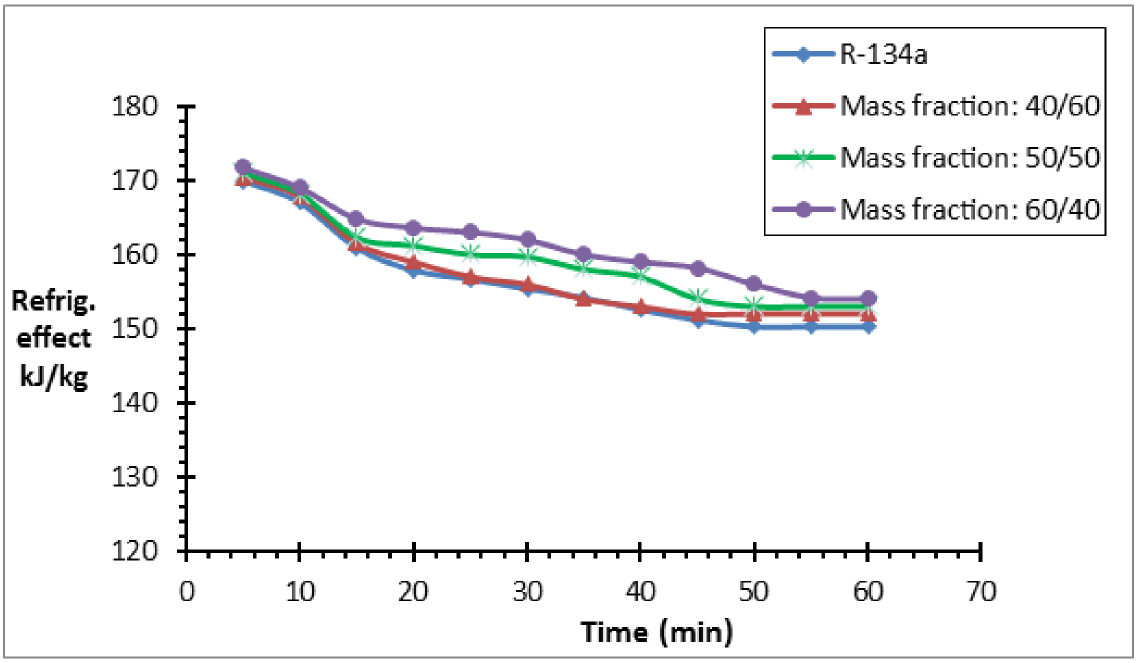

Figure (9): Refrigeration effect of the system as a function of time at different HC blends and refrigerant R-134a.

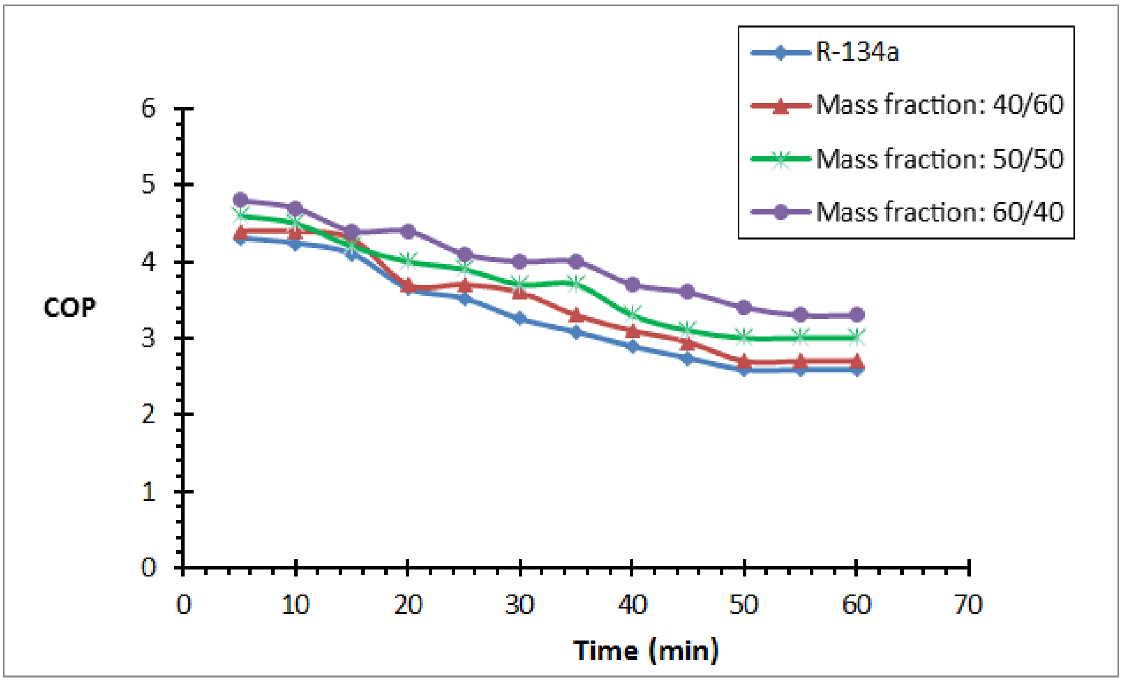

Figure (10): Coefficient of performance of refrigeration system as a function of time at different HC blends and refrigerant R-134a

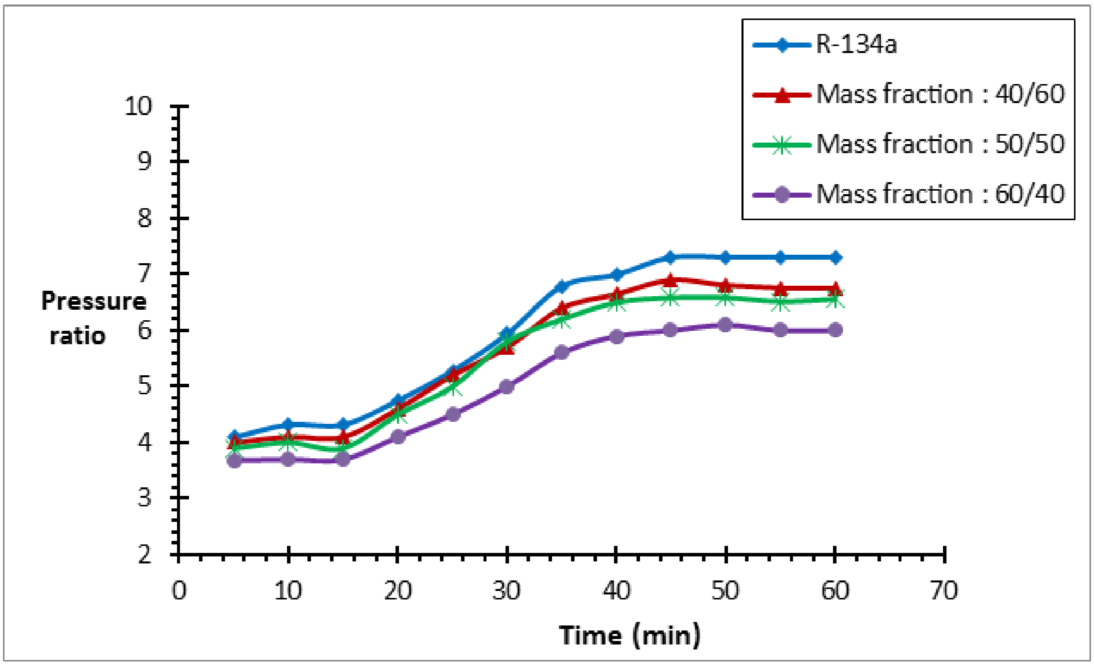

Figure (11): Pressure ratio of the refrigeration system as a function of time at different HC blends and refrigerant R-134a.

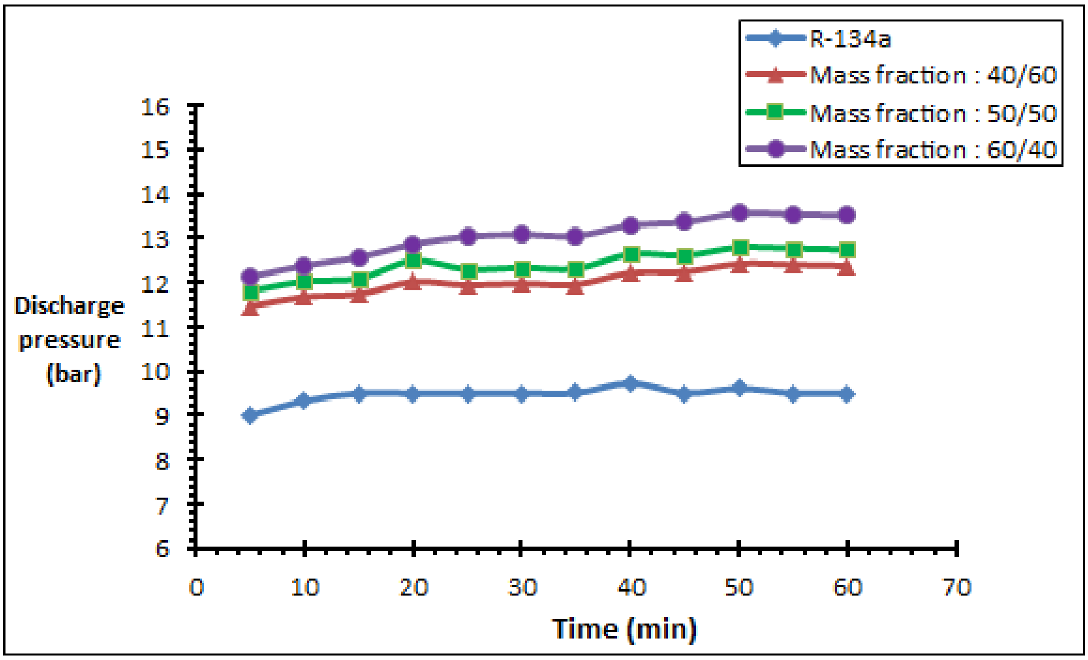

Figure (12): Discharge pressure of the refrigeration system as a function of time at different HC blends and refrigerant R-134a.

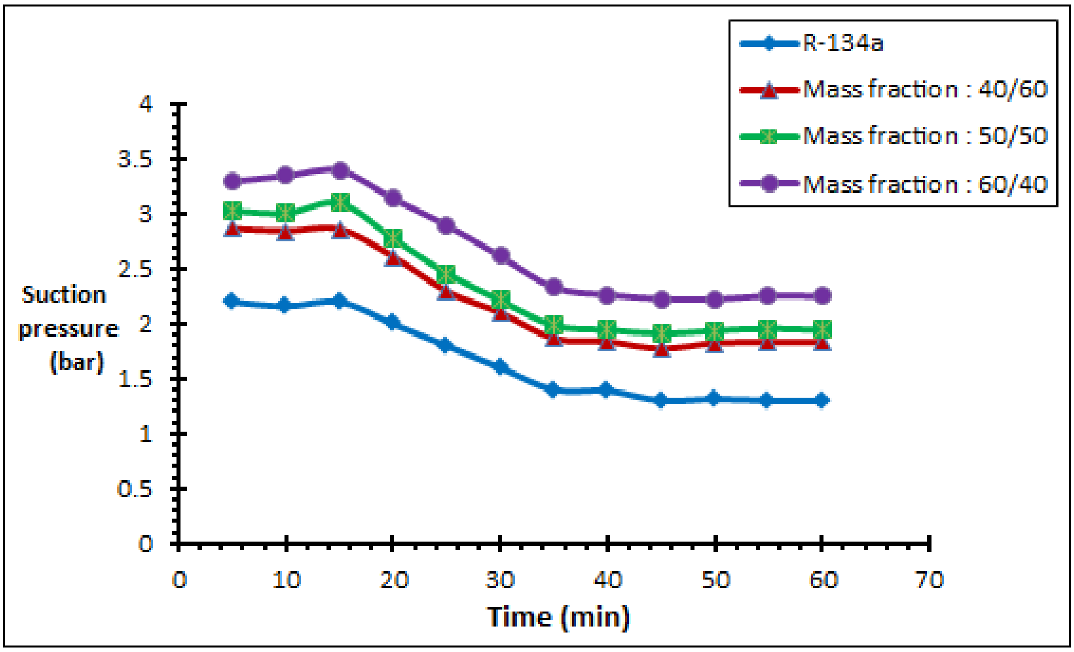

Figure (13): Suction pressure of the refrigeration system as a function of time at different HC blends and refrigerant R-134a.

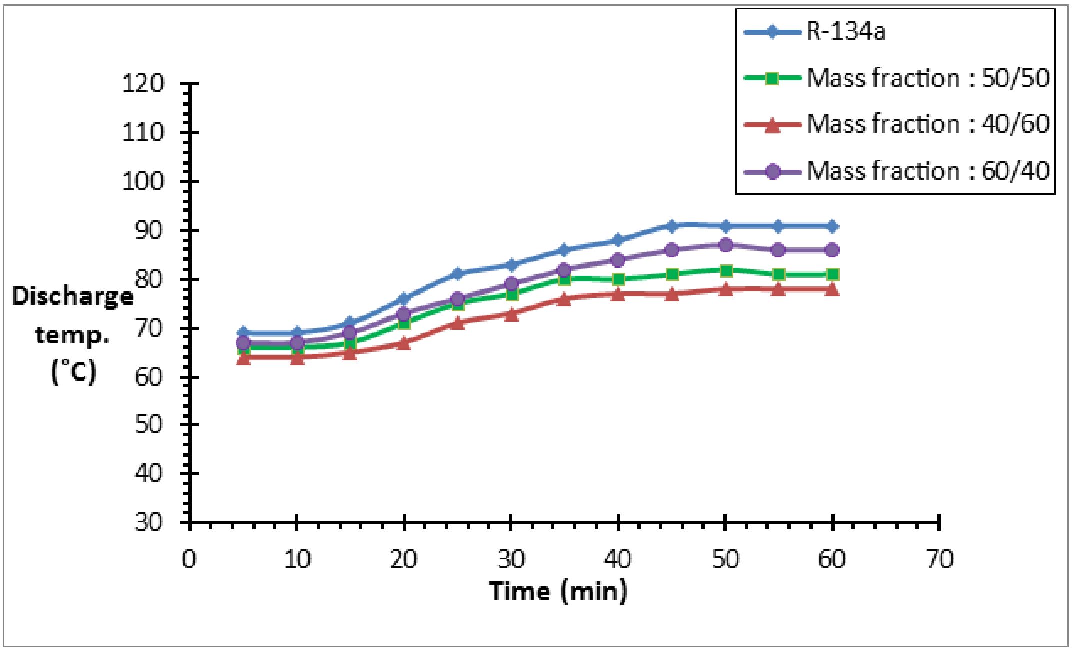

Figure (14): Discharge temperature of the refrigeration system as a function of time at different HC blends and refrigerant R-134a.

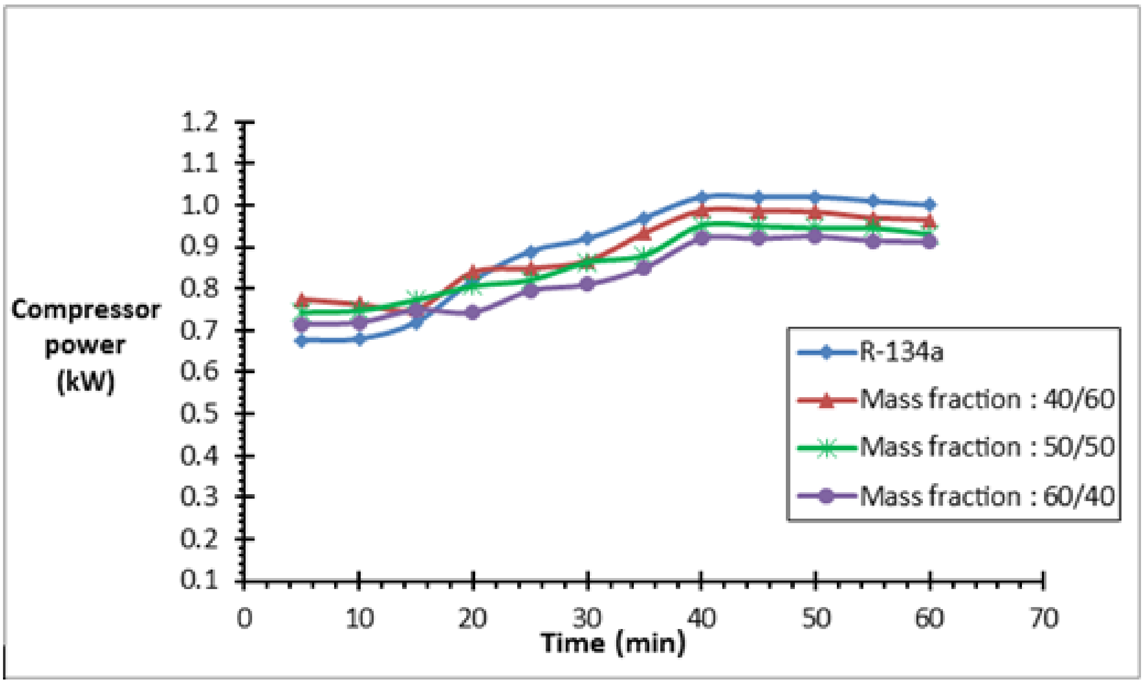

Figure (15): Compressor power of the refrigeration system as a function of time comparison for different HC blends and refrigerant R-134a.

استقصاء اداء منظومة التبريد الانضغاطيه مع دورة تبريد مفرط باستخدام خلائط تبريد هايدروكاربونية

أحمد جاسم حمد

مدرس، قسم هندسة تقنيات التبريد والتكييف، الكلية التقنية الهندسية– بغداد

الخلاصة

يقدم هذا البحث دراسة تجريبية لاستقصاء اداء منظومة التبريد الانضغاطيه باستخدام خليط من وسائط التبريد الهيدروكاربونيه.تم اضافة دورة تبريد مفرط وفاصل طور الى منظومة التبريد الانضغاطيه واستخدمت لفحص اداء خليط هايدروكاربوني من R-290/R-600a وبنسب خلط كتليه 60/40, 50/50 و 40/60 باعتباره وسيط تبريد بديل وقورنت النتائج المستحصله مع وسيط التبريد R-134a. تحليل النتائج قد اظهر وجود تحسين في معامل الاداء بحدود 14% وفي سعة التبريد 6% ونسبة التخفيض في درجة حرارة مقصورة التثليج كانت بحدود 12% مع انخفاض في قيم نسبة الانضغاط ودرجة الحرارة بعد الضاغط للخليط الهايدروكاربوني R-290/R-600a مقارنة مع وسيط التبريد R-134a ونسبة التخفيض في قدرة الضاغط كانت بحدود 9%. يمكن الاستنتاج بان خلائط التبريد الهايدروكاربونيه تعتبر وسائط تبريد كفوءة بديله لوسيط التبريد R-134aفي منظومة التبريد الانضغاطيه مع دورة تبريد مفرط. وسائط التبريد الهايدروكاربونية قابلة للاشتعال لذلك فان استخدامها يتطلب تطبيق اجراءات امان محددة عند تصميم مكونات منظومة التبريد او عند اجراء الصيانة لمنع تسرب أو اشتعال وسيط التبريد.

الكلمات الدالة : منظومة تبريد بانضغاط البخار، وسيط تبريد هايدروكاربوني, تبريد مفرط ميكانيكي.