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Simulation Analysis on Thermo Physical Properties of Hydrocarbon Refrigerants in Vapour Compression Refrigeration System

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Abstract – *This article represents the possibility usage of hydrocarbon refrigerants in vapour compression refrigeration systems as an alternate to conventional refrigerants like R12 and R134a. Hydrocarbon mixtures (HCMs) are having unique characteristics like eco friendly, better heat transfer, zero ODP and negligible GWP. Suitable safety precautions are to be implemented due to their flammability. Based on the thermo physical properties of the refrigerants, the standard performance parameters like pressure ratio, volumetric efficiency, discharge temperature, condenser heat rejection rate and COP are computed at different temperatures. The mixture of Propane (R290) and Isobutane (R600a) is considered as a refrigerant in this analysis at various mass fractions.*

The effect of condenser temperature (30°C to 65°C) with evaporator temperature of -10°C shows that the proposed HCMs having low pressure ratio & discharge temperature, higher volumetric efficiency & condenser heat rejection rate as compared to R12 and R134a. The effect of evaporator temperature (-30°C to 0°C) with condenser temperature of 40°C is also computationally analysised and similar performance results were obtained. Pressure ratio of HCMs is about 6.37% and 17.11% lower than R12 and R134a respectively and the volumetric efficiency is enhanced about 1.06% and 2.12%. The condenser heat rejection rate is also improved about 57.86% and 46.49% greater than R12 and R134 respectively. The results also prove that COP of the HCMs is approached very close to R12 and R134a. ***Copyright © 2013 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: HCMs, COP, Heat Transfer, Condenser and Evaporator Temperatures*

Nomenclature

h	Enthalpy at states 1, 2 , 3 and 4
T	Temperature at states 1, 2, 3 and 4
m_{ref}	Mass flow rate of refrigerant
N	Speed
P_{cond}	Condenser pressure
P_{evap}	Evaporator pressure
P_r	Pressure ratio
Q_{evp}	Refrigeration effect
V_{stroke}	Stroke volume
$Wcomp$	Power input to compressor
η_{comp}	Compressor efficiency
η_{isent}	Isentropic efficiency
η_v	Volumetric efficiency
n	Polytropic index

I. Introduction

Energy requirement for refrigeration systems is escalating very speedily in domestic and industry sectors because of better living conditions, necessity of food storage and storage of medical applications, etc. The performance enhancement of refrigeration system is another important parameter in the refrigerators. Whenever discussing the refrigerators, selection of an ecofriendly refrigerant is the most important criteria with respect to the present global situation. The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) identified that reduction in emissions of six categories of greenhouse gases, including HFCs used as refrigerants [1].

Based on the ecological condition and healthiness, identification of new technology and alternative refrigerants are essential in the refrigeration system. Most of the refrigerators are employed with CFC and HCFC as refrigerants. These refrigerants creating serious ecological impacts in terms of global warming and ozone layer depletion. Hence an alternative refrigerant is solution for this problem with respect to GWP. Many research works are going around the world for alternate refrigerants.

In this regard, hydrocarbons can be used as refrigerant in a refrigerator which is having the properties like non toxic, zero ODP, GWP is 8 and reduction in weight of the system due to higher density. New refrigerants also should execute the other properties like easy availability, cheap and an eco friendly nature.

II. Literature Review

Hydrocarbon mixture of 50% propane, 38.3% butane

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and 11.7% isobutene having better performance and it can be substituted as an alternate refrigerant for R12 [2], [3].

Based on the investigation by Dongsoo et al. [4], the propane and isobutene mixture with 0.6 mass fraction of propane having the fast cooling rate and higher energy efficiency.

Theoretical performance study on various alternative refrigerants for compression refrigeration system was carried out and found out that HC290/HCR600a (40/60 by wt%) was suitable to R12 [5]. R600a was used as a refrigerant in domestic refrigerators with mass of 150g and variation in the input power supply to the compressor was analysised. The variation in performance parameters were experimentally studied [6]. Thermo physical properties and environmental impacts of hydrocarbon refrigerants were studied with executing problems in the refrigeration systems [7]. 44.8% R290 and 55.2% R600a by weight was blended with R134a and used as a refrigerant charge in the refrigerator and performance analysis have been completed by Sekhar et al. [8], Moo-Yeon Leea et al. [9] carried a experimentation on performance characteristic of direct cooled refrigerators using R290/R600a (55%+45% by mass) and found that cooling speed is faster with lower input power supply as compared to R134a as a refrigerant.

The experimental results of Tashoush et al. [10] give that butane/propane/R134a mixture could be used as a substitute for R12 in refrigeration system. From the computational analysis on environmental-friendly alternatives to R134a, R152a having higher unique features to be used as refrigerant in the refrigerators [11].

Wang et al. [12] carried a performance study with binary refrigerants for the temperature of -60°C. Based on the properties of the refrigerants; an algorithm was developed for replacement of CFCc compounds by using hydrocarbon refrigerants and its mixtures [13]. Alsaad et al. [2], [3] suggest that Liquefied Petroleum Gas could be substituted as an alternative refrigerant to R12 and experimental results hold better performance. The mixture of R290+ R600a with (68+32) % by wt having better outcomes like refrigeration capacity, energy consumption, COP, etc with respect to R12 [14]. Senanayake [15] discussed the effect of modified condenser in refrigeration system.

The results shows that significant enhancement achieved in the performance measures like higher heat transfer, evaporator capacity and COP.

These literature review states that hydrocarbon can be used as an alternate refrigerant in vapour compression refrigeration system instead of R12 and R134a.This paper focuses towards the possibility usage of HCMs as refrigerants with different mass fractions in the refrigeration system and the output performance measures are evaluated based on various condenser and evaporator temperatures.

III. Hydrocarbon Refrigerants

Hydrocarbon refrigerants are having similar characteristic feasibility to use an alternate refrigerant for R12 and R134a. The boiling point of R290 is lower than R12 and R134a. The proposed refrigerant HCMs leads to green environmental condition due to their environmental friendly properties. The comparison of thermo physical properties of conventional refrigerants like R12, R134a with hydrocarbon refrigerants is shown in Table I.

The change of saturation pressure with respect to temperature is shown in Fig. 1. The range of refrigerant mixing validated (50-60) % of R290 and (50-40) % of R600a. From the various combinations, the saturation pressure of HCM3, HCM4 and HCM5 are situated above the saturation pressure of R12 and R134a. The mixtures HCM1, HCM2 and HCM6 are having the similar characteristics to R12 and R134a. These mixtures are accounted for further analysis of this study. The highest and lowest saturation pressures are attained for R290 and R600 respectively.

IV. Computational Analysis of Vapour Compression Refrigeration System

Vapour compression refrigeration system:

The conventional compression refrigeration system consists of four major components namely compressor, condenser, expansion device and evaporator. Heat balance and energy balance of each component of the system will make the perfect energy assessment of the total system and obtained by the following relations.

TABLE I
THERMO PHYSICAL PROPERTIES OF REFRIGERANTS

Properties	R12	R134a	R290	R600	R600a
Chemical Name	Di chloro Difluoro Methane	Tetra Fluro ethane	Propane	Butane	Iso butane
Formula	CCl_2F_2	CH_2FCF_3	C_3H_8	C_4H_{10}	C_4H_{10}
Natural	No	No	Yes	Yes	Yes
Boiling Point (°C)	-29.80	-26.10	-42.20	-02.00	-11.7
Flammability limit	Non Flammable	Non Flamma Ble	2.1	1.5	1.7
Vapour density @28°C	39.9	35.38	22.3	6.756	9.9
ODP	1	0	0	0	0
GWP	8500	1300	20	20	20

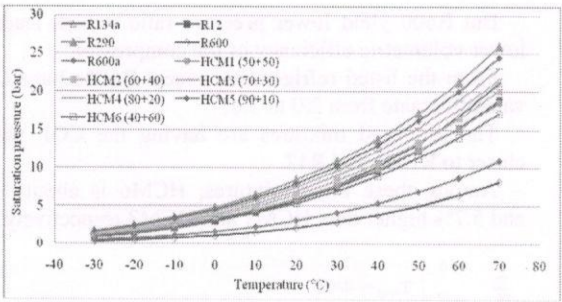

Fig. 1. Saturation pressure vs temperature

The various thermodynamic processes of vapour compression refrigeration system are shown in the P-h diagram (Fig. 2).

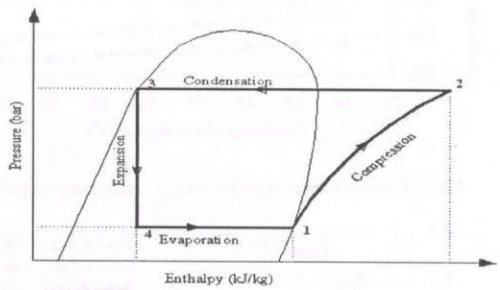

Fig. 2. (P-h) diagram of vapour compression refrigeration system

The following assumptions are considered for thermodynamic analysis of the refrigeration system:

1. The system is under steady state.
2. The refrigerant entered to the compressor is in dry saturated condition. (Dryness fraction is unity).
3. Isentropic compression takes place in the compressor.
4. Heat loss to the environment through the system is neglected.

Compressor - Compression process (1-2) is assumed that very close to in isentropic process and the isentropic efficiency of the compressor is taken as 0.85.

Isentropic compression of refrigerant is carried in the compressor and power input to the compressor is calculated by:

$$T_2 = T_1 + (T_{2iso} - T_1) / \eta_{isent} \quad (1)$$

$$h_2 = h_1 + (h_{2iso} - h_1) / \eta_{isent} \quad (2)$$

$$Wcomp = m_{ref} (h_2 - h_1) / \eta_{comp} \quad (3)$$

Volumetric efficiency of the compressor and mass flow rate of refrigerant are calculated by following equations:

$$\eta_v = 1 - k((P_r)^{1/n} - 1) \quad (4)$$

$$m_{ref} = \eta_v N V_{stroke} / v_1 \quad (5)$$

Condenser - Heat rejected (2-3) from the condenser is evaluated by using the following relation:

$$Q_{cond} = m_{ref} (h_2 - h_3) \quad (6)$$

Expansion device - Throttling process (3-4) is carried out in the expansion device (isenthalpy process) and the pressure of the refrigerant is reduced from P_{cond} to P_{evap}. Pressure ratio is obtained by the following relation:

$$P_r = P_{cond} / P_{evap} \quad (7)$$

$$h_3 = h_4 \quad (8)$$

Evaporator - The required refrigeration effect (4-1) is gained from the evaporator and is given by:

$$Q_{evp} = m_{ref} (h_1 - h_4) \quad (9)$$

The COP of the compression refrigeration system is governed by:

$$COP = Q_{evp} / Wcomp \quad (10)$$

IV.1. Effect of Condensing Temperature

The effect of condensing temperature with constant evaporator temperature is computationally analysised and the results are discussed.

The pressure ratio of HCM1, HCM2 and HCM6 are calculated and variations are shown in Fig. 3.

R290 and R600 offer the lowest and highest pressure ratio respectively at different condensing temperatures from 30-65°C. R600a having the pressure ratio lower than R134a and higher than R12.

So the mixture of R290 and R600a will produce the similar characteristics like R12 and R134a. These mixtures are having lower pressure ratio as compared to R12 and R134a at different condensing temperatures. Higher pressure ratio lead to decrease in volumetric efficiency of the compressor.

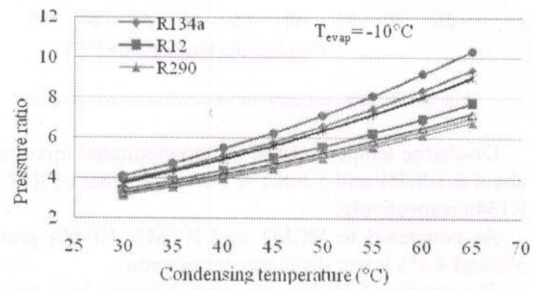

Fig. 3. Pressure ratio vs condensing temperature

The variation of volumetric efficiency with the condensing temperature is shown in Fig. 4.

The volumetric efficiency of proposed mixtures is about 1.1-7.1% greater than R134a and also closer to R12.

Due high pressure ratio, the volumetric efficiency of R600a is having lower values as compared to other refrigerants. Highest volumetric efficiency is reached for R290, but it having highest saturation pressure.

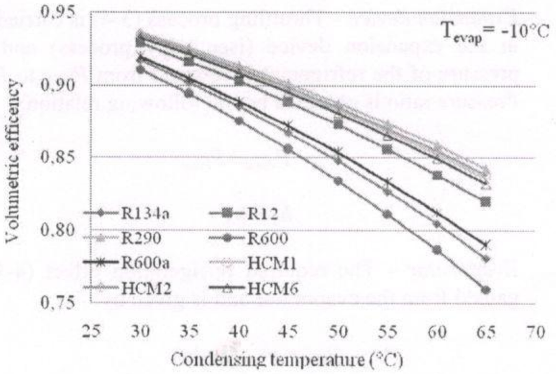

Fig. 4. Volumetric efficiency vs condensing temperature

So R290 could not be used as pure form as a refrigerant. Among the proposed mixtures HCM2 confer the maximum volumetric efficiency of 94%.

Fig. 5 shows the change of discharge temperature with respect to condensing temperature. Increase in condensing temperature leads to increase in the discharge temperature of the refrigerant. R12 and R600a provide the highest and lowest discharge temperature respectively.

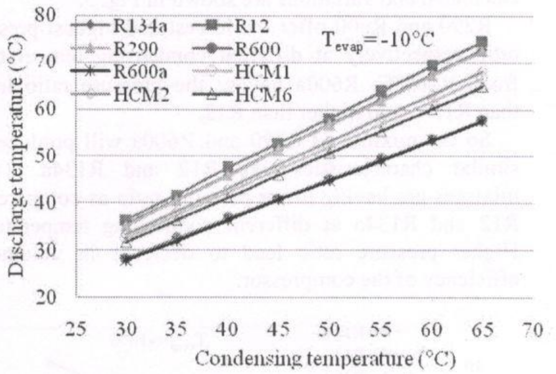

Fig. 5. Discharge temperature vs condensing temperature

Discharge temperature of the premeditated mixtures is about 8.3-9.5% and 5.5-8.1% lower than that of R12 and R134a respectively.

As compared to HCM1 and HCM2, HCM6 provide 3% and 4.4% lower discharge temperature.

The proposed HCMs are having better heat transfer property as compared to other refrigerants.

Under this investigated group refrigerants, HCMs are superior to R12 and R134a which is shown in Fig. 6.

The effect of condensation temperature on COP of the refrigeration system is shown in Fig. 7.

R600 having the highest COP at different condensing temperatures.

But R600 yield lower pressure ratio, which leads to lower volumetric efficiency of the compressor.

From the listed refrigerants, except R600a have COP value fluctuate from 2.0 to 5.6.

The proposed mixtures are having the COP values closer to R134a and R12.

Among these three mixtures, HCM6 is about 1.9% and 5.7% higher than HCM1 and HCM2 respectively.

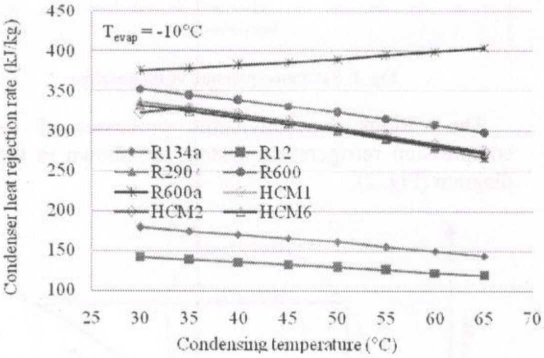

Fig. 6. Condenser heat rejection rate vs condensing temperature

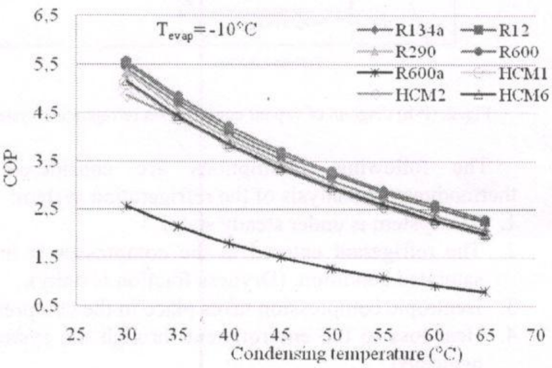

Fig. 7. COP vs condensing temperature

IV.2. *Effect of Evaporator Temperature*

The various characteristics of refrigeration system with HCMs and other refrigerants are represented in the following Figs. 8, 9, 10, 11 and 12 at different evaporating temperatures between -35°C and 0°C.

Fig. 8 shows that all HCMs having very close values of pressure ratio at different evaporating temperature and offering lowest pressure ratio as compared to R134a and R12. Lowest pressure ratio leads to increment in the volumetric efficiency which is plotted in Fig. 9 and shows that HCM2 having highest volumetric efficiency.

The compressor performance and life time could be increased by maintaining at that pressure ratio for the refrigerants.

Fig. 10 indicates variation of discharge temperature at different evaporating temperatures. Whenever the evaporator temperature lowered, the discharge temperature is increased for all the refrigerants. R12 and

R134a and R600 and R600a are having highest and lowest discharge temperature respectively in this group of refrigerants. As compared to conventional refrigerants, HCMs yields better results about 11.76%, 15.09% lower than R134a and R12 respectively.

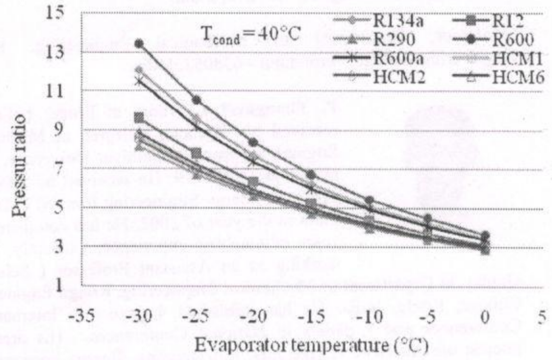

Fig. 8. Pressure ratio vs evaporator temperature

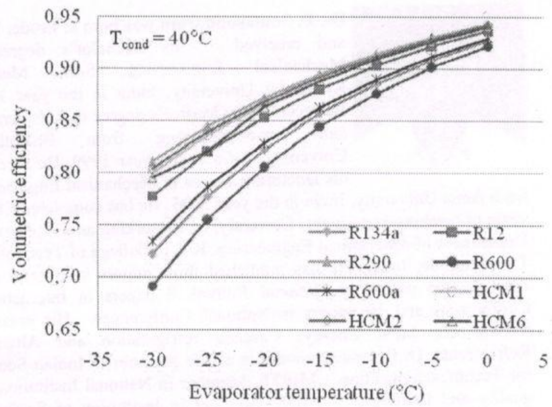

Fig. 9. Volumetric efficiency vs evaporator temperature

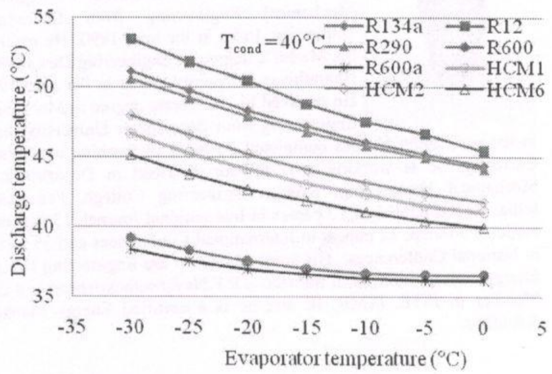

Fig. 10. Discharge temperature vs evaporator temperature

Better heat rejection rate is also achieved for the HCMs about 57.63% and 46.82% higher than to the conventional refrigerants like R12 and R134a respectively. Even though R600 having the highest heat rejection rate, the other thermodynamic properties of R600 is not feasible. The variation in condenser heat rejection is shown in Fig. 11. In this group of refrigerant analysis, R12 and R134a offered higher COP values as compared to HCMs. The effect of COP variation is plotted in Fig. 12.

Even though small reduction in the COP of HCMs, they offers higher condenser heat rejection rate, lower discharge temperature, higher volumetric efficiency and lower pressure ratio. According to GWP and ODP, HCMs are having the lowest value as compared to R12 and R134a.

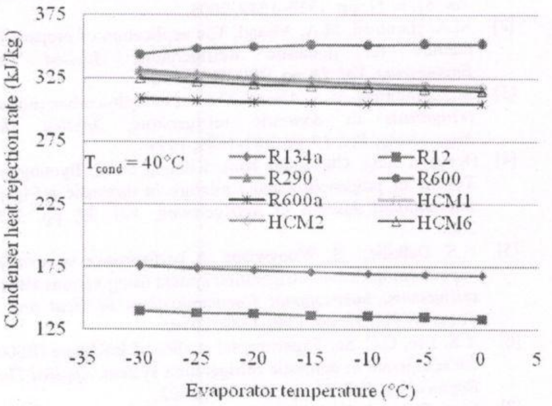

Fig. 11. Condenser heat rejection rate vs evaporator temperature

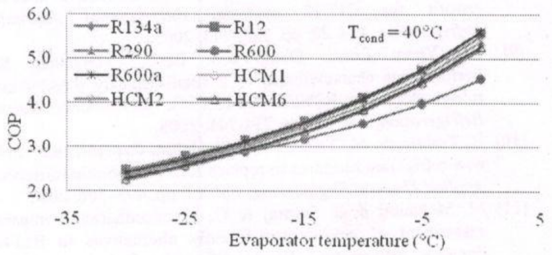

Fig. 12. COP vs evaporator temperature

V. Conclusion

Based on the above computational analysis of HCMs can be employ as alternate to R12 and R134a, the following conclusions are noted:

- HCMs are eco friendly refrigerants due to zero ODP and negligible GWP.
- Among the three HCMs, HCM2 offers lowest pressure ratio and highest volumetric efficiency.
- Pressure ratio of HCMs is about 6.37 % and 17.11 % lower than R12 and R134a respectively.
- Due low pressure ratio of HCMs, the volumetric efficiency is enhanced about 1.06% and 2.12% higher than R12 and R134a respectively.
- Discharge temperatures of the HCMs are comparatively lower than R12 and R134a about 11.11 % and 8.57 % respectively.
- Because of better heat transfer characteristics of hydrocarbons, the condenser heat rejection rate is

improved about 57.86% and 46.49% greater than R12 and R134 respectively.

- COP values of HCMs are approaching very close to R12 &R134a.
- Based on the mass fraction of R290 and R600a, HCM1 & HCM2 could be used as an alternate to R12 and R134a in refrigeration systems.

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