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Part load performance analysis of vapour compression refrigeration system with hydrocarbon refrigerants

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The objective of this paper is to study the effect of evaporator load on performance of vapour compression refrigeration system with hydrocarbon refrigerants at different loads in evaporator. Hydrocarbon mixture (HCM) is an alternative refrigerant for hydro fluorocarbon (HFC) and chlorofluorocarbon (CFC) compounds due to their lower global warming potential (GWP) and zero ozone depletion potential (ODP). The impact on the environment is also reduced due usage of hydrocarbons as refrigerants. 50% of Propane (R290) and 50% of Isobutene (R600a) by mass fraction is used as a refrigerant in this analysis. Effects of condenser and evaporator temperature are computationally analysised. Various performance parameters like compressor input power, discharge temperature, heat rejected in the condenser, refrigeration effect and coefficient of performance are investigated at various loads of 25%, 50%, 75% and 100% in the evaporator. As compared to other loads, 75% load in the evaporator is economic mode to operate the system due to 3.81% reduction in compressor input power, 4.76 % reduction in discharge temperature, better condenser heat rejection rate and refrigeration effect.

Keywords: evaporator load, R290, R600a, discharge temperature, compressor input power, refrigeration effect.

Introduction

Energy demand for refrigeration systems is escalating, due to an increasing desire for comfort, necessity of food storage and medical applications. In industrial environment and household appliances, refrigerators are playing an important role to make the required lower temperature. Refrigerators are endorsed as more energy consuming devices. Whenever discussing the refrigerators, selection of an eco friendly 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 hydro fluorocarbons used as refrigerants[13]. Based on the ecological condition and healthiness, identification of new technology and alternative refrigerants are essential in the refrigeration system. Most of the domestic refrigerators are employed with R134a as refrigerant. The value of GWP of R134a is about 1300[10]. Hence an alternative refrigerant is the solution for this problem with respect to clean and green environmental conditions. Many research works are going around the world for alternate refrigerants.

In this regard, HCM can be used as refrigerant in a refrigerator which is having the properties like non toxic; zero ODP and GWP is about 20[10]. New refrigerants also should execute the other properties like easy availability, cheap and an eco friendly nature. Basically, most of the refrigerators are packed by over loaded or under loaded. In overloading, more heat should be extracted from the evaporator unit, since this leads to higher discharge temperature, higher power consumption in compressor. Even though refrigeration effect is high, the usage of refrigeration effect is less in under loading due to lesser quantity of material in the refrigeration system. This becomes in uneven load distribution in refrigeration system as per the design of the refrigeration system. The usage of refrigeration effect will not be an economical mode at those situations. Hence the load in evaporator unit is playing an important role on performance of refrigeration system in terms of coefficient of performance (COP).

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Akash *et al*[1] used a composition of 30% propane, 55% n-butane and 15% iso-butane in domestic refrigerator as a substitute for R12. Refrigerant mass charge of 80g has the better results and having similar characteristics of R12.

The liquefied petroleum gas (LPG)[2] could used as an alternate refrigerant in domestic refrigerator for replacement of R12. From the research work carried out by Bolaji[3], the performance of domestic refrigerator was evaluated through R152a and R32 as refrigerants. Their experimental work result gives that R152a offers lowest energy consumption, COP value about 4.7% higher than R134a. Ching-Song Jwo *et al*[4] conducted an investigation on domestic refrigerator of 440 liters capacity with R290 and R600a with each 50% as a refrigerant instead of R134a and better performance results were obtained. Dongsoo Jung *et al*[5] conducted an energy consumption test and no load pull-down test on commercial refrigerators. Mixture of R290/R600a was used in their experiment and the range of mass fraction of propane is about (0.2-0.6). Hydrocarbons[6] having the similar thermodynamics characteristics and better heat transfer rate as compared to other refrigerants. Hammad *et al*[7] discussed the performance analysis domestic refrigerator with different ratios of propane, butane and isobutene for alternative of R12. Fatouh *et al*[8] investigated LPG as a refrigerant in the ratio of 60% propane and 40% commercial butane in domestic refrigerators. Their result shows that, COP of the domestic refrigerator is enhanced with LPG about 7.6% as compared to R134a. Mohanraj *et al*[9] have discussed that the mixture of R290 and R600a is considered as an alternative to R134a in domestic refrigerators. Their results reported that, 60 g of HCM consumes about 11.1% lesser energy compared to that of R134a; the discharge temperature of HCM is about 8.5 to 13.4 K lower than that of R134a. The study on assessment of alternatives[10] in domestic refrigerators and R152a was recommended in the place of R134a. From the analysis, R152a have the better uniqueness like zero ODP, 9% low operating pressure, 7-9% higher COP, higher energy efficiency as compared to R134a. The performance study of direct cooled refrigerator[11] with different capillary tube lengths and various refrigerant mass charges by using HCM of R290/R600a (55/45) shows the better results. According to Sekar *et al*[12] hydrocarbon (HC) blend and HFC134a mixture was used as a refrigerant in domestic refrigerator.

From the literature review, HCM is suggested to use in the refrigerating system due their advantageous possessions and HCM of Propane and Isobutene each 50% by mass fraction has used in this study as a refrigerant. This research work mainly focuses on behavior of performance parameters of refrigerator with respect to various evaporator loads.

Experimental Section

Materials and Methods

The major components of vapour compression refrigeration system are compressor, condenser, expansion device and evaporator. Heat balance and energy balance[14, 15] of each component of the system will make the perfect energy assessment of the whole system. The required refrigeration effect is obtained in the evaporator and is given by

$$\text{Refrigeration Effect} = m_r (h_1 - h_4) \quad \text{é} \quad (1)$$

Isentropic compression of refrigerant is carried in the compressor. Compressor input power (P_{comp}) is calculated by

$$P_{comp} = m_r (h_2 - h_1) \quad \text{é} \quad (2)$$

Due to increase in pressure, discharge temperature of the refrigerant is also amplified. Refrigerant phase change is carried out in condenser by air cooled mode. Condenser heat rejection rate (Q_{cond}) to the environment is given by

$$Q_{cond} = m_r (h_2 - h_3) \quad \text{é} \quad (3)$$

Throttling process is carried out in the expansion device and the pressure of the refrigerant is reduced from P_{cond} to P_{evap}. Pressure ratio (P_r) is calculated by

$$\text{Pressure ratio } P_r = (P_{cond} / P_{evap}) \quad \text{é} \quad (4)$$

Volumetric efficiency (η_v) of the compressor is calculated by

$$\eta_v = 1 - C\,((P_r)^{1/n} - 1) \quad \text{é} \quad (5)$$

The performance of the refrigerator unit is expressed in terms of COP and is expressed as

$$(COP)_R = \text{Refrigerated Effect} / P_{comp}$$

$$= (h_1 - h_4) / (h_2 - h_1) \quad \text{é} \quad (6)$$

Table 1ð Thermo physical properties of refrigerants

Refrigerant	Chemical	Formula	Natural Name	Boiling Point (°C)	Flammability limit	ODP	GWP
R12	Dichloro Difluoro Methane	CCl_2F_2	No	-29.80	Non Flammable	1	8500
R134a	Tetra Fluroethane	CH_2FCF_3	No	-26.10	Non Flammable	0	1300
R290	Propane	C_3H_8	Yes	-42.20	2.1	0	20
R600	Butane	C_4H_{10}	Yes	-02.00	1.5	0	20
R600a	Isobutane	C_4H_{10}	Yes	-11.70	1.7	0	20

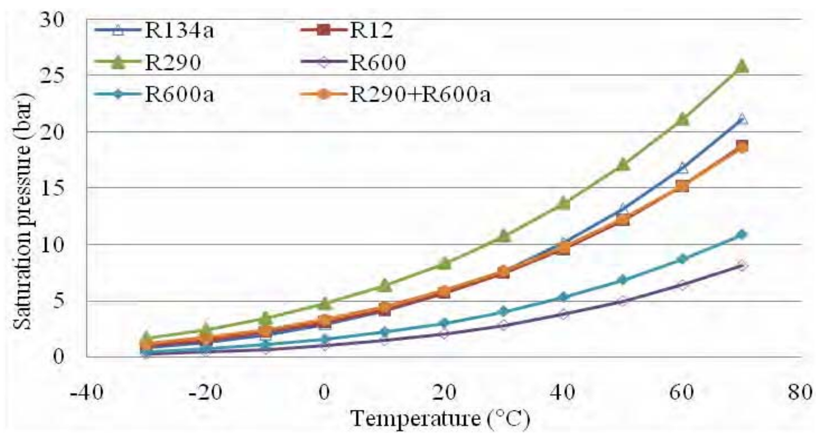

Fig.ð 1 Variation of saturation pressure with temperature

The comparison of thermo physical properties of conventional refrigerants like R12, R134a with hydrocarbon refrigerants are given in Table 1. This shows that hydrocarbon refrigerants having similar characteristic feasibility to use as an alternate refrigerants for R12 and R134a. The GWP and ODP values are considerably very low for the proposed refrigerant mixture and this leads to green environmental condition.

Computational analysis

The computational analysis of refrigeration cycle was completed by considering the following assumptions:

- The system is under steady state.
- Pressure losses in the system are neglected.
- Saturated vapour is entering into the compressor.
- Isentropic compression is performed in the compressor.
- Heat losses are neglected (system is insulated).

Variation of saturated pressure with respect to temperature is computed in Fig. 1. As compared to R134a and R12, R290 having higher saturation pressure and it cannot be used as pure refrigerant in the refrigeration system. R600a is placed on low pressure side, so it also not possible to as pure refrigerant. In order to get the similar characteristics to R12 and R134a, mixture of R290 and R600a is proposed as a refrigerant in the system. R290 and R600a are mixed 50% each by mass basis and it is positioned in between the higher and lower pressure range. The saturation pressure of the proposed mixture is very close to conventional refrigerants.

Effect of condensation temperature

The comparison of pressure ratio with condensing temperature shows that increase in condensing temperature leads to increase in the pressure ratio Fig. 2(a). For this analysis the evaporator temperature is assumed as -10°C and the variation of pressure ratio is calculated for wide range of condenser temperature about 30-65°C. This shows that R600 and R290 having the highest and lowest pressure ratio values respectively. The pressure ratio of the proposed mixture is about 16.4-24.9% and 5.5-8.6% less than R134a and R12 respectively. The reduction in the pressure ratio will lead to increase in volumetric efficiency of the compressor. The effect of pressure ratio on volumetric efficiency has been completed for wide range of condensing temperature

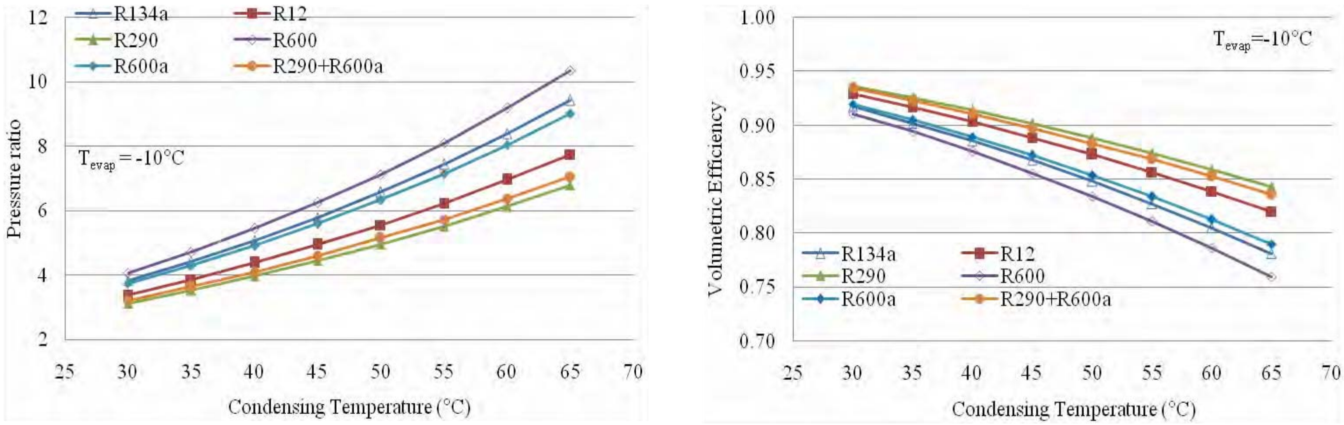

Fig. 2ð Computational analysis of: a) Pressure ratio b) Volumetric efficiency

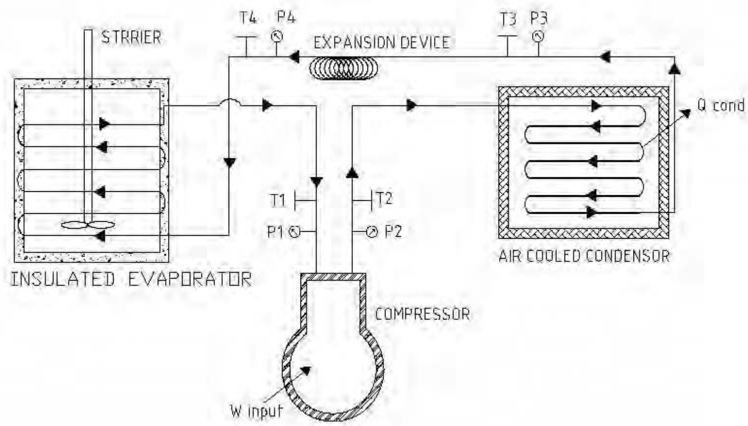

Fig. 3ð Experimental refrigeration system

Fig. 2(b). Compared to conventional refrigerants like R12 and R134a, HCM having the highest volumetric efficiency. The highest and lowest volumetric efficiency is obtained for R290 and R600 respectively. The volumetric efficiency of R600a is closer to R134a.

Experimental refrigeration system

Hydrocarbons mixture of R290 and R600a is charged as a refrigerant with 50% each (by mass) in the refrigerator. Hermetically sealed compressor (Single phase, 220-240 V, 50 Hz, 2850 rpm) is used and power consumed by the compressor is noted by using energy meter (750 rev/kWh). Saturated vapour refrigerant from the evaporator is compressed in the compressor. Air cooled condenser is placed after the compressor to reduce the temperature of the refrigerant and vapour phase is changed into liquid state. Then high pressure is reduced as low pressure by using a capillary tube. The evaporator section is well insulated by the insulating material (Glass wool) in order avoid the heat interaction between the evaporator and the environment. Stirring effect is produced by stirrer which is attached with the system to attain the uniform cooling effect. Experimental refrigeration system Fig. 3 is prearranged with measuring instruments like pressure measurement, temperature measurement. Data logging system is also incorporated with the refrigeration system in order to store the pressure and temperature at various places. Temperature is measured by using the thermocouples with accuracy of $\pm$0.1°C. Pressure gauges with the working range of (0-300 psi) and (0-150 psi) are used with accuracy of $\pm$1 psi.

In this investigation, 25%, 50%, 75% and 100% of loads are considered in the evaporator unit to identify the better performance of the refrigeration system. Water is used as a substance in the evaporator for experimental purposes and it is filled by based on the load values. Cycling test (on/off)[9] is performed for each load in the evaporator. For each load of operation, measurements like pressure & temperature at various points, energy meter reading are noted. An initial and final temperature of the water in the evaporator shows the refrigerated effect produced by the refrigeration system. Under

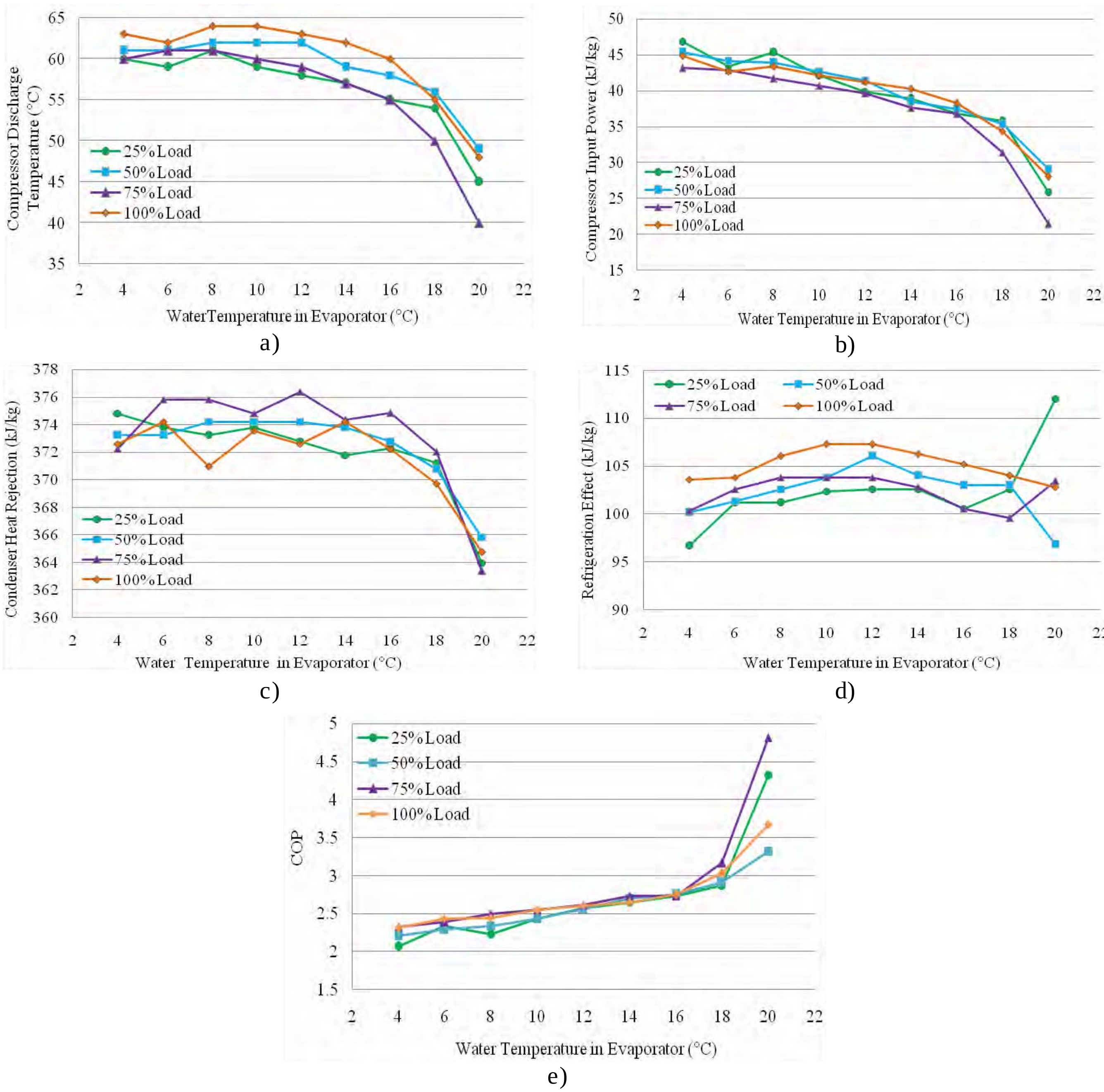

Fig. 4 ð for the same water temperature in evaporator, effects of: a) Compressor discharge temperature; b) Compressor input power; c) Condenser heat rejection rate; d) Refrigeration effect; and e) COP

steady conditions and for better results, the initial and final temperature of water is considered from 20°C to 4°C.

Results and Discussion

Based on the loads like 25%, 50%, 75% and 100% of water in the evaporator, the behavior of refrigerator is analysised by taking into account of the parameters like compressor discharge temperature, compressor input power, condenser heat rejection, refrigeration effect and COP. The calculations are calculated by unit mass flow rate of the refrigerant.

The discharge temperature influences the stability of the lubricants and life span of the compressor. Fig. 4(a) represents discharge temperature of 75% load is found to be lower than that of load 25%, 50%, and 100%. Load of 75% has lower impact on compressor components and stability of lubricants. Hence the same compressor and no change of lubrication oil can be applied for HCM operated refrigeration system[7]. Highest temperature is attained in full load condition and leads to change in characteristics of the lubricating oil in the compressor. Compared to 100% load, 4.7% reduction of discharge temperature is obtained in 75% load. For better performance of compressor, the evaporator can be loaded at 75%. The lowest discharge temperature is approached in 25% load of evaporator, but the other performance characteristics are not productive in this load of operation. Variation in power consumption by the compressor with respect to water temperature in the evaporator is plotted in Fig. 4(b). For reaching the minimum temperature of water 4°C, 25% of load consumes more power as compared to other loads. At 75% of load, compressor consumes minimum amount of power about 43.13kJ/kg. From these results, as compared to other loads the economic mode operation of the compressor is obtained in 75% load in the evaporator.

For making phase change of vapour refrigerant into liquid refrigerant, heat should be rejected to the surrounding which is carried out by an air cooled condenser. The variation in heat rejection rate in the air cooled condenser is plotted in Fig. 4(c). Based on various loads maximum and better heat rejection rate is obtained in the load of 75% and phase change effect on the refrigerant is reached very quickly in that same load of operation. 25% and 100% loads having lower heat rejection rate in the condenser. When the load is in 50%, the heat rejection rate is maintained as medium between the higher and lower ranges. The variation in the refrigeration effect is shown in Fig. 4(d). Water temperature in the evaporator is assessed from 20°C to 4°C. For attaining this cooling effect, 100% load gave the maximum cooling capacity about 3.15% higher than 75% load. The other loads are placed in the lower level. But in full load condition, compressor should operate in its maximum capacity that leads to shorter life time of compressor. 50% and 75% loads are produced almost same refrigeration effect with respect to minimum water temperature of 4°C. The lowest refrigeration effect is obtained in 25% load as compared to other loads.

Even refrigeration effect is high in 100% load as compared to 75% load; the power consumption for 100% load is not favorable. Hence, maximum COP of the system is reached in 75% and 100% load conditions. The COP for 25% and 50% loads are having lower than the remaining loads. The variation in COP is shown in Fig.4e and COP value is maintained in the range of 2.00 to 2.32 in low temperature values. By considering the other performance parameters, 75% load gave 3.81% reduction in compressor input power and 4.76% reduction in discharge temperature. For 100% load, refrigeration effect is 3.15% greater than 75% load condition. But considering the lifespan of the compressor and better performance of vapour compression refrigeration system, 75% load on the evaporator is recommended.

Conclusions

Hydrocarbon mixture of Propane and Iso-butane each 50% could be used as a refrigerant in vapour compression refrigeration systems. Computational analysis and experimental performance evaluation of the refrigeration system are carried out at various loading conditions. Based on the load values in the evaporator, the significance of various performance parameters is studied. During the test, experimental results show that 75% of load has better performance as compared to other load values. The following point gives the significance of 75% of load condition in the refrigeration system.

- Power consumption is reduced about 3.81% when compared to 100% load.
- With reference to 25% and 50% loads, compressor power consumption is reduced about 4.85% and 7.88% respectively.
- The percentage reduction of discharge temperature is about 4.76% as compared to 100% load.
- Refrigeration Effect is 3.15% less than 100% load.
- Maximum value of COP is obtained when the system is loaded at 75% and 100%.
- Even COP is same in 100% with 75% load; the compressor discharge temperature and compressor input power consumption is high for 100% load.
- Better condenser heat rejection rate to the environment is achieved.

Hence the mixture of R290 and R600a is recommended as refrigerant and leads to reduction in the GWP and ODP. By considering all kinds of performance parameters, 75% of load in the evaporator is economic mode of operation for the refrigeration system and the performance of vapour compression refrigeration system can be enhanced by using HCM as a refrigerant.

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