

Effects of evaporator load on vapour compression refrigeration system using eco friendly hydrocarbon refrigerants with sub cooling

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The main objective is to study the effect of evaporator load on performance of vapour compression refrigeration system with eco friendly refrigerants with and without sub-cooling. Mixture of Propane (R290) and Isobutene (R600a) is used as alternate refrigerant to Hydro Fluorocarbon (HFC) and Chlorofluorocarbon (CFC) compounds in this analysis. Performance analysis is investigated at different loads in evaporator. Hydrocarbon mixture (HCM) is an alternative refrigerant for HFC and CFC compounds due to their lower Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP). Computational analysis is carried out to study the performance of the proposed mixture and also compared with conventional refrigerants R12 and R134a with respect to condensing temperature. In order to operate the refrigeration system at economical mode, the evaporator is loaded at various load conditions like 25%, 50%, 75% and 100%. Various performance parameters like discharge temperature, compressor input power, heat rejected in the condenser, refrigeration effect and Coefficient of Performance (COP) are investigated at various loads in the evaporator. The analysis is carried out for condensing temperature from 30°C to 65°C and evaporator is maintained at -10°C. As per computational analysis, discharge temperature and pressure ratio of HCM is about 3.9-7.4%, 16.4-24.9% lower than R134a and about 2.8-9.4%, 5.5-8.6% lower than R12. Volumetric efficiency of HCM is about 1.8-6.5%, 2% higher than R134a and R12 respectively. From the experimental load analysis, 75% load in the evaporator gave better results in terms of higher refrigeration effect and COP, lower discharge temperature and low compressor input power consumption as compared to other loads. Heat rejection rate for 75% load is moderate with 50% load. COP is about 8.5-24%, 2.9-11.9%, 1.9-5.5% higher than 25%, 50% and 100% loads respectively. Under sub cooling analysis in 3°C, 4°C and 5°C, the COP of the 75% load is about 1.1-9.3%, 2.5-13.4% and 2.5-14.5% higher than 50% load respectively. Based on computational analysis HCM could be used as an eco friendly refrigerant in the refrigeration system. The experimental results show that 75% load of evaporator having the feature of economic mode to operate the refrigeration system.

Keywords: Evaporator load, HCM, Sub-cooling, COP.

Introduction

The process of removal of heat from the substance by using refrigerant is termed as refrigeration. 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 in both household and industries. 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 HFCs used as refrigerants¹¹. Based on the ecological condition and healthiness, alternative refrigerants and identification of economical mode of operation 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. Hence an alternative refrigerant is a solution for this problem with respect to GWP. 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, lower GWP and reduction in weight of the system due to lower density. New refrigerants also should execute the other properties like easy availability, cheap and an eco friendly nature.

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The traditional refrigerators are packed with materials by over load or under load conditions. Overloading will cause more heat should be extracted from the evaporator unit, similarly under loading leads to use of larger quantity of refrigeration effect for small quantity of material. This becomes in uneven load distribution as per the design. The usage of refrigeration will not be an economical mode at that situation. Hence the load on evaporator unit is playing an important role in the performance of the refrigeration system.

Literature review

Hydrocarbons having the similar thermodynamics characteristics and better heat transfer rate as compared to other refrigerants⁵. Their impact towards the environmental is also very low as comparing HFC and CFC due to very low GWP and zero ODP. The only problem is flammability and that can be avoided by implementing the safety precautions. Based on the assessment on alternatives in domestic refrigerators by Mohanraj *et al*⁹ R152a was recommended in the place of R134a. From their results, R152a have the better uniqueness like zero ODP, 9% low operating pressure, 7-9% higher COP, higher energy efficiency as compared to R134a. The investigation on domestic refrigerators with LPG as a refrigerant in the ratio of 60% propane and 40% commercial butane was carried out⁶ and their result shows that, when the capillary tube length of 5 m and LPG charge of 60 g, the higher volumetric cooling capacity and lower freezer air temperature were obtained as compared to R134a. The mixture of R290 and R600a was considered as an alternative to R134a in domestic refrigerators. This HCM⁸ is composed of 45.2% of R290 & 54.8% of R600a and the refrigerator was charged with refrigerant mass of 40, 50, 60 and 70 g. Hydrocarbon mixture of propane, butane and isobutene was investigated by Hammad *et al*⁷ and proposed that the mixture can be used in domestic refrigerator to replace R12.

R290 and R600a with each 50% is used as a refrigerant instead of R134a in a domestic refrigerator of 440 liters capacity³. The mass of the refrigerant charge is varied from 60g to 120g. From their results 90g of the refrigerant mixture shows best performance behavior. The performance of domestic refrigerator was evaluated through R152a and R32 as refrigerants¹. The experimental result gives that R152a offers lowest energy consumption, COP value about 4.7% higher than R134a. The performance of R152a closely follows R134a. Hydrocarbon (HC) blends and HFC134a mixture was

used as a refrigerant in domestic refrigerator¹⁰. Their result shows that the HFC134a and 9% of HC blend mixture gave better performance as compared to R12 in terms of energy consumption. Energy consumption test and no load pull-down test on commercial refrigerators capacity of 299 and 465 liters were analysed by Dongsoo Jung *et al*⁴. Mixture of R290/R600a was used in their experiment and the range of mass fraction of propane is (0.2-0.6). The effect of sub-cooling on the performance of domestic refrigerator was studied with refrigerants like R32, R152a, R143a and R134a². R152a and R134a were giving the close results to R12 with degree of sub-cooling from 2°C to 10°C. From their discussion, the increase in degree of sub-cooling, reduces the pressure ratio, increases in mass flow rate of the refrigerant and COP of the system.

From the literature review, HCM is considered as an eco friendly refrigerant to use in the refrigerating system due to their advantageous possessions and HCM of 50% of Propane and 50% of Isobutene by mass fraction has introduced in this present analysis. This research work mainly focuses on behavior of performance parameters of refrigerator with respect to various evaporator loads. The significant outcome of this experimental observations and discussions are detailed in the following titles.

Materials and methods

Refrigeration system

The conventional vapour 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 whole system. Isentropic compression of refrigerant is carried in the compressor and work input to the compressor (W_{comp}) is calculated by

$$W_{\text{comp}} = m_r (h_2 - h_1) \quad \text{é} \quad (1)$$

In actual condition, the isentropic efficiency (η_{isent}) and compressor efficiency (η_{comp}) are to be accounted; the actual work input ($W_{\text{comp-act}}$) given to the compressor is given by

$$W_{\text{comp-act}} = W_{\text{comp}} / \eta_{\text{isent}} \eta_{\text{comp}} \quad \text{é} \quad (2)$$

Based on Yeunyongkul *et al*¹², isentropic and compressor efficiency is given by

Table 1δ Physical properties of refrigerants

Refrigerant	Chemical Name	Formula	Natural	Boiling Point (°C)	Flammability limit	ODP	GWP
R12	DichloroDifluoro Methane	CCl_2F_2	No	-29.80	Non Flammable	1	8500
R134a	TetraFluoroethane	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

$$\eta_{\text{isent}} = 0.73 - 0.1\text{CR} - 0.026\text{CR}^2 + 0.0017\text{CR}^3 \quad \text{é} \quad (3)$$

$$\eta_{\text{comp}} = 1.1\eta_v \quad \text{é} \quad (4)$$

In high pressure side of the refrigeration system, discharge temperature of the refrigerant to be condensed which is carried by air cooled condenser. The heat rejected by the condenser (Q_{cond}) to the environment is given by

$$Q_{\text{cond}} = m_r (h_2 - h_3) \quad \text{é} \quad (5)$$

Throttling process 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 (P_r) is obtained by the following relation.

$$P_r = P_{\text{cond}} / P_{\text{evap}} \quad \text{é} \quad (6)$$

Volumetric efficiency (η_v)⁹ of the compressor is calculated by

$$\eta_v = 1 - C ((P_r)^{1/n} - 1) \quad \text{é} \quad (7)$$

The performance of the refrigerator unit is expressed in terms of COP and is ratio between the refrigerating effect and work input to the compressor. It is expressed as

$$(\text{COP})_R = \text{Refrigeration Effect} / W_{\text{comp-act}} \quad \text{é} \quad (8)$$

The required refrigeration effect is achieved in the evaporator and is given by

$$\text{Refrigerated Effect} = m_r (h_1 - h_4) \quad \text{é} \quad (9)$$

Table1 given in this paper represents the physical properties of conventional refrigerants like R12, R134a and hydrocarbon refrigerants. This shows that hydrocarbon refrigerants having similar characteristics

have the feasibility to use an alternate refrigerant for R12 and R134a in refrigeration system. The GWP and ODP values are considerably very low for hydrocarbon refrigerant mixture and this leads to green environmental condition.

Computational analysis

Computational analysis for CFC, HFC and HCM are carried out by accounting the various performance characteristics. Variation of saturated pressure with respect to temperature range from -30 to 70°C is analysed. Pure R290 have high pressure value and it cannot be used as pure refrigerant in the refrigerator. R600a is having low pressure value, so it also not possible to use as pure refrigerant. In order to get the similar characteristics of R12 and R134a, the mixture of R290 and R600a is proposed as a refrigerant in the analysis. A mixture of R290 and R600a each 50% by mass fraction is considered in this analysis. Saturation pressure of the proposed HCM is found to be very close to the saturation pressure of conventional refrigerants R12 and R134a.

The effect of thermal conductivity and vapour density with wide range of temperature (-30°C to 70°C) has been studied. These result shows that HCM having better thermal conductivity as compared to R134a and R12, which is used to make better heat transfer through refrigerant in the refrigeration cycle. In this comparison study, R290 holds the highest thermal conductivity among the investigated refrigerants. The analysis on vapour density represents that the proposed HCM is lower than the R134a and R12. The highest and lowest vapour density is obtained for R12 and R600 respectively.

Effect of condensing temperature

The comparison of pressure ratio with condensing temperature ranges from 30 to 65°C is plotted in Fig. 1a. This shows that R600 and R290 having the highest and lowest values respectively. The pressure ratio of the proposed HCM is about 16.4-24.9% and 5.5-8.6% less

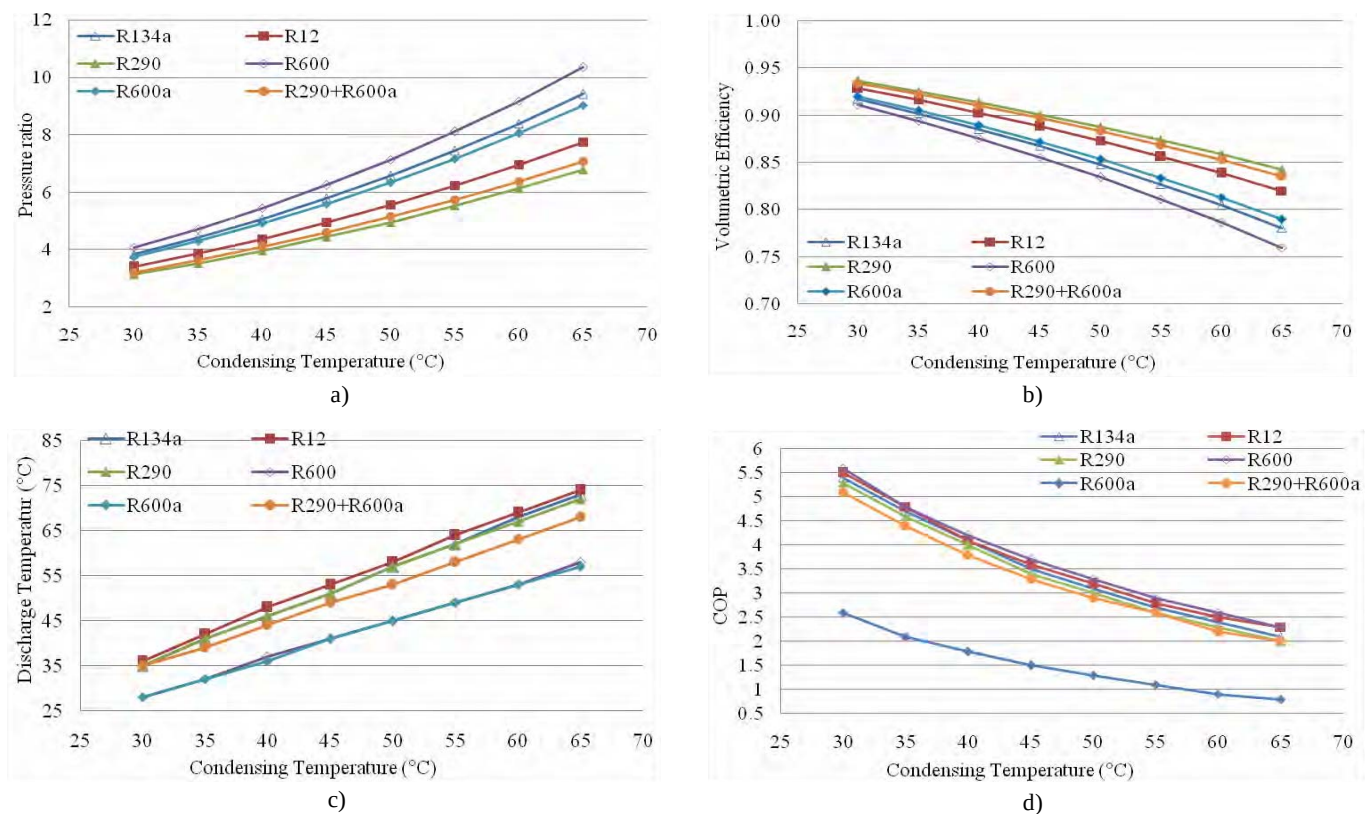


Fig. 10 For the same condensing temperature, computational analysis of: a) Pressure ratio; b) Volumetric efficiency; c) Discharge temperature; and d) COP

than R134a and R12 respectively. The reduction in the pressure ratio will lead to increase in volumetric efficiency of the compressor. Fig. 1b shows that the volumetric efficiency of the proposed HCM which is having highest value about 1.8-6.5% and 2% higher than R134a and R12 respectively for the wide range of condensing temperature. Hence, the mixture of hydrocarbons can be used as an alternate to conventional refrigerants.

Fig. 1c represents the variation of compressor discharge temperature with condensing temperature. Whenever the condensing temperature increases, the linear increment in the discharge temperature occurs for all the refrigerants. R134a and R12 are located in the higher temperature zone in the graph. Over this range of condensing temperature, HCM is about 3.9-7.4%, 2.8-9.4% less than that of R134a and R12 respectively. Even the discharge temperature is low; R600 and R600a could not be used as pure refrigerants in the refrigeration system due to their higher pressure ratio and lower volumetric efficiency.

COP variation is shown in Fig. 1d. As seen from this, COP of R134a and R12 are having 4.76% and 13.04% higher than the proposed refrigerant due to their thermodynamic properties. From the computational

analysis with reference to condensing temperature, it is concluded that comparing to CFC and HFC, HCM can be used as an alternate refrigerants because of its more desirable characteristics like better saturation pressure range, low pressure ratio, high volumetric efficiency, lower discharge temperature, low GWP and zero ODP. Even though the COP of the proposed mixture is less, it fulfills the needs of the global standards.

Refrigeration cycle with sub-cooling

Refrigeration cycle processes are plotted in p-h diagram with sub-cooling shown in Fig. 2. Sub-cooling is the process of making the refrigerant temperature less than that of the saturation temperature at constant pressure process. Degree of sub-cooling is obtained by the following relation, which gives the temperature difference between the saturation temperature of the liquid refrigerant and the temperature of the liquid refrigerant before throttling process.

$$\text{Degree of sub-cooling } (\Delta T)_{\text{sub}} = (T_3 - T_{3d}) \quad \text{é} \quad (10)$$

$$(\text{COP})_R = \frac{\text{Refrigeration Effect WSC}}{W_{\text{comp-act}}} \quad \text{é} \quad (11)$$

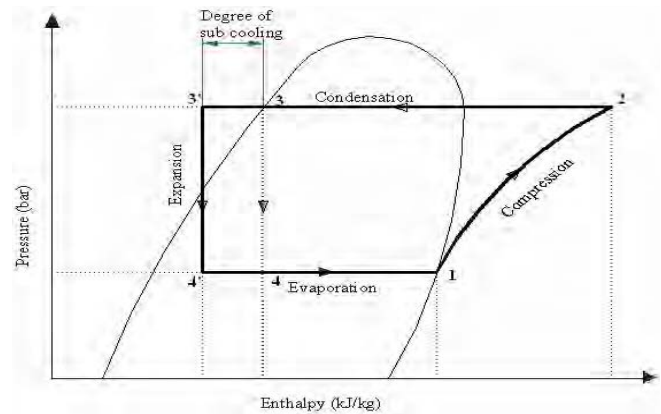
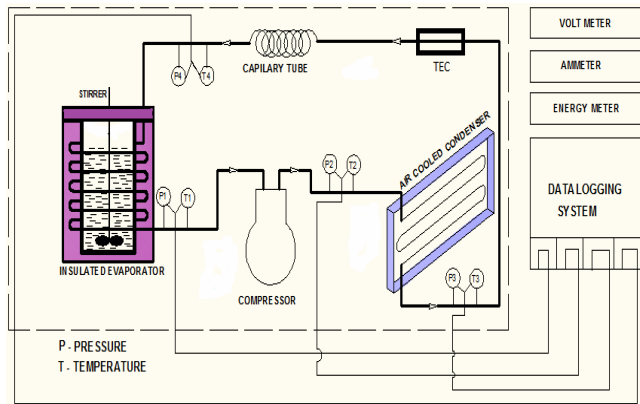


Fig. 2δ Experimental refrigeration system and p-h diagram of refrigeration cycle with sub-cooling

Table 2δ Measured variables with its uncertainties

Component	Range	Accuracy
Temperature sensor	-100°C to 100°C	±0.1°C
Pressure Gauge	0-300 psi	±1 psi
Pressure Gauge	0-150 psi	±1 psi

Nomenclature

C	Clearance ratio(-)	P_{evap}	Evaporator pressure (bar)
CR	Compression ratio	T_1	Compressor inlet temperature (°C)
h_1, h_2	Enthalpy at compressor inlet & outlet (kJkg ⁻¹)	T_2	Compressor outlet temperature (°C)
h_3	Enthalpy at condenser outlet (kJkg ⁻¹)	T_3	Condenser outlet temperature (°C)
h_4	Enthalpy at evaporator inlet (kJkg ⁻¹)	$T_{3\delta}$	Condenser outlet temperature WSC (°C)
m_r	Mass flow rate of refrigerant (kg sec ⁻¹)	T_4	Evaporator inlet temperature (°C)
P_1, P_2	Compressor inlet & outlet pressure (bar)	$T_{4\delta}$	Evaporator inlet temperature WSC (°C)
P_3	Condenser outlet pressure (bar)	<i>Subscripts</i>	
P_4	Evaporator inlet pressure (bar)	n-Polytropic index (-)	
P_{cond}	Condenser pressure (bar)	R-Refrigerator	

The refrigeration effect with sub-cooling (WSC) is given by

$$\text{Refrigerated Effect WSC} = m_r (h_1 - h_{4\delta}) \quad \epsilon \quad (12)$$

The effect of sub cooling on COP for wide range of condensing temperature is computationally analyzed with 5°C of sub cooling. A significant enhancement in COP is attained for all kind of refrigerants. The COP enhancement for HCM is achieved about 5.5-9% and the increment in condensing temperature leads to the decrease in COP. At lower condensing temperature, highest and lowest COP is achieved for R12 and R600a respectively.

Experimental detail

Mixture of R290 and R600a is charged as a refrigerant with 50% each by mass in the refrigerator. Hermetically sealed compressor (1phase, (220-240) V, 50 Hz, 2850 rpm) is used and power consumed by the compressor is noted by using energy meter (750 rev/

kWh). Air cooled condenser is placed after the compressor to reduce the temperature of the refrigerant and vapour state 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. 2) is prearranged with measuring instruments. Voltmeter (0-300) V and Ammeter (0-15) A are used to monitor the voltage and current flow in the system. The temperatures at compressor inlet & outlet, condenser inlet & outlet, evaporator inlet & outlet are measured by using thermocouples. Temperature measurements at various points were obtained by using RTD type thermocouples. Pressure gauges are used to measure the pressure at low pressure side (evaporator outlet, compressor inlet) and high pressure side (compressor outlet, condenser inlet & outlet). Table 2 represents measured variables

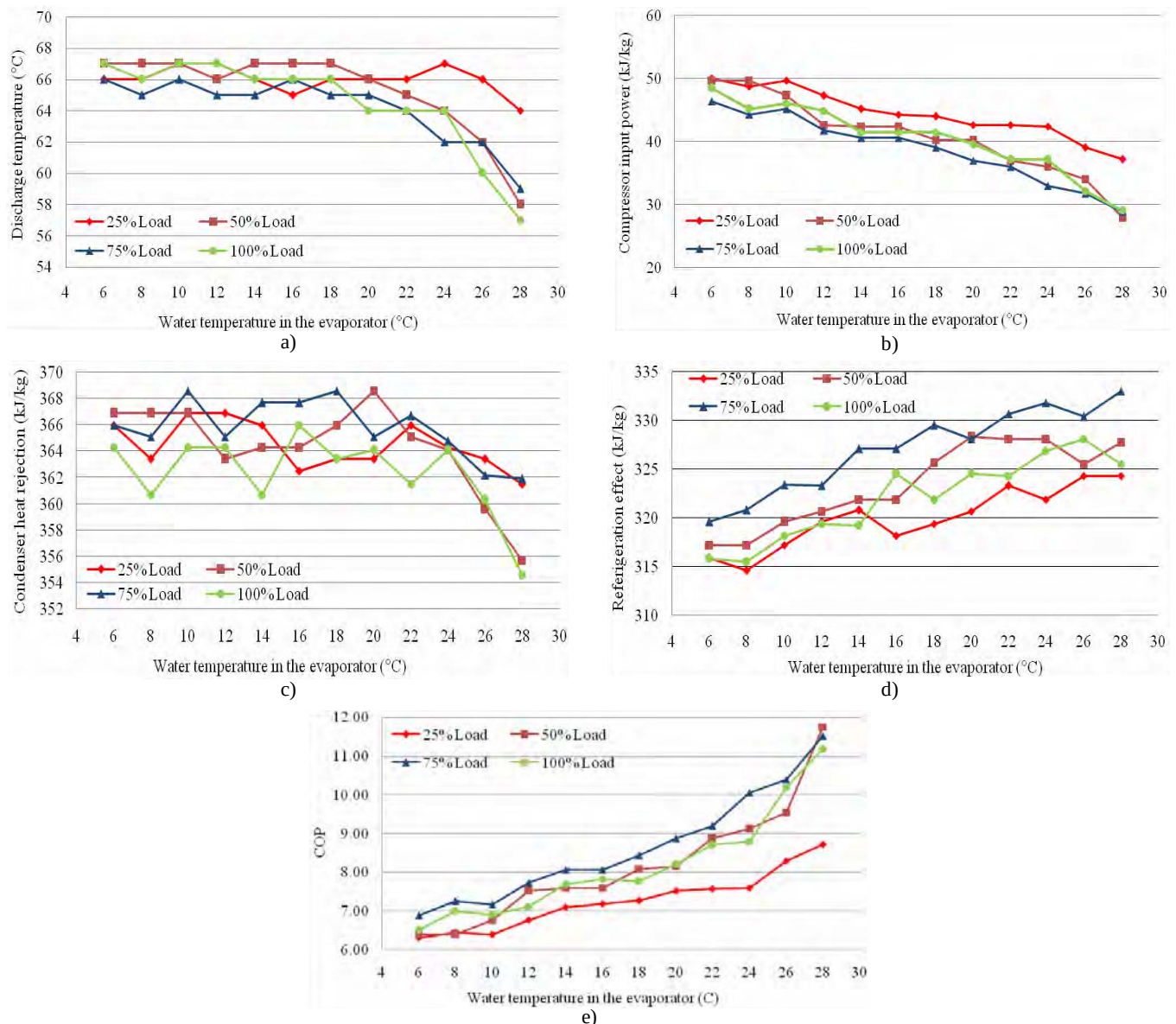


Fig. 3d For the same water temperature in evaporator, effects of: a) Discharge temperature; b) Compressor input power; c) Condenser heat rejection; d) Refrigeration effect; and e) COP

with its uncertainties. Data logging system is incorporated with the experimental set up. In this study, 25%, 50%, 75% and 100% of loads are considered in the evaporator 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 in the evaporator based on the load values. Cycling test (on/off) is performed for each load in the evaporator. For each load, 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. The mass flow rate of refrigerant is considered as 1 kg/sec for this analysis. Minimum temperature of

water in the evaporator is limited up to 6°C in order to avoid the ice formation.

In this experimental study sub-cooling is obtained by Thermo Electric Cooler (TEC) which is working on the principle of Peltier effect. Whenever DC power supply is applied at the junction of dissimilar materials, heat absorption will takes place. This heat absorption is used to produce cooling effect in the sub-cooler.

Results and discussion

Based on the loads like 25%, 50%, 75% and 100% of water in the evaporator, the behavior of refrigeration system is analysed by considering the following parameters: compressor discharge temperature,

compressor input power, COP, condenser heat rejection and refrigeration effect. The above values are calculated by unit mass flow rate of the refrigerant in the system.

The discharge temperature influences the stability of the lubricants and life span of the compressor. Fig. 3a represents the discharge temperatures of various load values and is found that for 75% load is lower than that of loads 25%, 75% and 100%. Load of 75% in evaporator has lower impact on compressor components and stability of lubricants. Highest temperature is attained in full load condition and leads to change in characteristics of the lubricating oil in the compressor. For better operation of compressor, 75% load on the evaporator will be suitable one.

Variation of compressor input power with respect to water temperature in the evaporator is plotted in Fig. 3b. For reaching the minimum temperature of water, 25% of load consumes more power as compared to other loads. For the load of 75%, compressor consumes minimum amount of power about 43.13kJ/kg. The result shows that the economic mode operation of the compressor is obtained in 75% load because power requirement for 75% load is about 7.4-22.3%, 2.1-10.9% less than 25% and 50% load respectively. The variation in condenser heat rejection rate is plotted in Fig. 3c. Based on various loads maximum and better heat rejection is obtained in the load of 75%. Phase change effect of the refrigerant is reached very quickly in that same load of operation. 25% and 100% loads having lower heat rejection rate from the condenser. When the load is in 50%, the heat rejection is maintained as medium between the higher and lower ranges.

Water temperature in the evaporator is assessed from 28°C to 6°C. The highest and lowest refrigeration effect is to be found in 75% and 25% loads respectively. The variation in the refrigeration effect is shown in Fig. 3d. The refrigeration effect for 75% load is about 1.1-3.1%, 0.7-2.4% greater than 25% and 100% loads respectively. Ultimately the COP of 75% load condition having highest among the other loads. The variation in COP is shown in Fig. 3e. The COP is about 8.5-24%, 2.9-11.9%, 1.9-5.5% higher than 25%, 50% and 100% loads respectively.

Effect of sub-cooling

TEC is incorporated (Fig. 2) within the experimental arrangement to produce the cooling effect after air cooled condenser. At various load conditions the refrigeration effect is monitored with different degree of sub-cooling

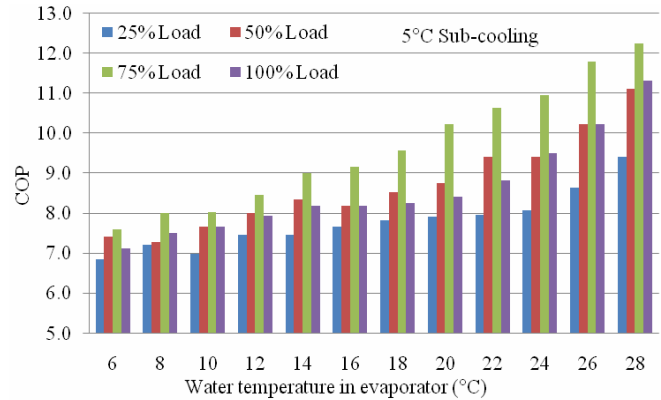


Fig. 4d Effects of sub cooling on COP with water temperature in evaporator for 5°C sub cooling

such as 3°C, 4°C and 5°C. The variation of COP with sub-cooling is analysed with water temperature in the evaporator. The percentage enhancement of COP with sub cooling is about 2.44%, 3.23% and 4.00% were achieved at 3°C, 4°C and 5°C (Fig. 4) degree of sub-cooling respectively for minimum temperature of water in evaporator. The experimental values of COP with sub cooling are well agreed with the computational values.

Conclusions

A Computational analysis was performed with respect to condensing temperature for CFC, HFC and HCM. Based on this analysis, HCM is used as a refrigerant in vapour compression refrigeration system and experimental analysis is carried out at different load values in the evaporator. Computational analysis and experimental investigation on vapour compression refrigeration system provides the following conclusions.

- Due to higher and lower operating pressure of R290 and R600 could not be used as a refrigerant in pure form.
- HCM provide more desirable uniqueness like zero ODP, lower GWP, lower pressure ratio, higher volumetric efficiency, lower discharge temperature and higher thermal conductivity with respect to condensing temperature.
- Refrigeration effect and COP are enhanced by sub cooling effect. Simulation analysis shows that 5.5-9% of COP enhancement was obtained for HCM.
- In experimental analysis based on the load in evaporator, 75% load in evaporator has better performance as compared to other loads like 25%, 50% and 100%.

- At 75% load in evaporator, discharge temperature and the compressor input power are low.
- The power requirement for 75% load is about 7.4-22.3%, 2.1-10.9% less than 25% and 50% loads respectively.
- Better condensation performance at 75% of load.
- The refrigeration effect for 75% load is about 1.1-3.1%, 0.7-2.4% greater than 25% and 100% loads respectively.
- COP is about 8.5-24%, 2.9-11.9%, 1.9-5.5% higher than 25%, 50% and 100% loads respectively.
- The effect of sub cooling on refrigeration system was analysed experimentally at various degree of sub-cooling.
- The percentage enhancement of COP with sub cooling is about 2.44%, 3.23% and 4.00% were achieved at 3°C, 4°C and 5°C degree of sub-cooling respectively.

At the out said mixture of R290 & R600a each 50% is recommended as refrigerant and leads to reduction in the GWP & ODP. By considering all kind of performance parameters, 75% of load condition is better mode of operation for any refrigeration system and the proposed HCM refrigerant enhances the performance of the refrigeration system with sub cooling.

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