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EXPERIMENTAL ANALYSIS OF PERFORMANCE OF VAPOUR COMPRESSION REFRIGERATION SYSTEMS USING VARIOUS ALTERNATIVE REFRIGERANTS

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Abstract

The industrial revolution increased the utilization of the new technological products in our daily life which has led to the consumption of more energy. The gap between supply and demand of electrical energy is increasing every year. The proven reserves of fossil fuel in India are not very large. It has also urged there search the energy conservation devices and to develop new techniques to utilize the existing limited resource efficiently. In India about 80% of the domestic refrigerators working under simple vapour compression system use R134a as the refrigerant. The major concern of using R134a in domestic refrigeration system is that, it has a high global warming potential of 1300, which causes many harmful effects on the environment. Therefore the use of R134a must be replaced. In this research an attempt also has been made to investigate the performance and exergy analysis of alternate refrigerants (hydrocarbon refrigerants). The alternate refrigerants selected are combination of Propane (R290), Butane (R600) and Iso-butane (R600a). Propane and Butane are used in the ratio (R290/R600– 79/21 by weight %), Propane and Iso-butane (R290/R600a–68/32 by weight %) and LPG. The refrigeration system variables considered for the investigation are evaporating temperature, condensing temperature and mass of the refrigerant. For these studies an experimental set-up has been built up. The working ranges of all the selected parameters are fixed by conducting trial runs. The performance analysis of a vapour compression refrigeration system was done with both HFC and HC compressor. The results revealed that HC compressor gave better coefficient of performance than HFC compressor. LPG shows higher COP at higher evaporating temperatures than R134a. During exergy analysis, the selected alternate environment friendly hydrocarbon refrigerants exhibited better exergy efficiency compared to the exergy efficiency of R134a. Exergy loss was lower with the selected alternate environment friendly hydrocarbon refrigerants compared to the Exergy loss of R134a.

Index Terms— Alternate Refrigerants, Energy Conversion, Exergy, Performance, Refrigerants.

I. INTRODUCTION

With the phasing out of CFC12 and HFC134a, existing refrigeration and air-conditioning appliances will have to be replaced with new appliances or retrofitted with alternative refrigerants. Current research focuses on the development of new refrigerants to retrofit the existing CFC12 and HFC134a systems. Various alternative refrigerants are available to retrofit the conventional systems, but each one has its own merits and demerits. Previous researchers have studied the performance of various alternative refrigerants and their mixtures. A comprehensive survey of the previous study on the performance of alternative refrigerants and their mixtures in refrigeration and air conditioning system is presented.

Objectives of Present Work

This research focuses on investigation of environmental friendly HC refrigerant mixtures as a substitute to R134a in a vapour compression refrigeration system. The objectives of the present research work are:

i. To identify environmental friendly HC refrigerant mixtures for a vapour compression refrigeration system as a drop-in substitute for R134a.

ii. To study theoretically the performance of a vapour compression refrigeration system with environment friendly HC refrigerant mixtures and their performance comparison with R134a.

iii. To develop mathematical model using design of experiments to predict the performance of the refrigerants.

iv. To investigate the performance of the selected refrigerant experimentally with HFC and HC compressors.

v. To investigate the exergy analysis of the selected refrigerant experimentally.

Approaches of Present Work

The present work has been carried out to investigate the performance and exergy analysis of the selected alternative refrigerants in a vapour compression refrigeration system. The various parameters considered for the study are the condensing temperature, evaporating temperature and mass of the refrigerant. For conducting this study an experimental setup has been built up. The working range of all the required parameters is fixed by conducting trial runs.

II. SYSTEM DEVELOPMENT

Selection of Refrigerant Mixture

From the literatures that have been published, it is learnt that mixture of hydrocarbon (HC) refrigerants is a promising substitute for R134a, as hydrocarbon refrigerants have GWP less than 10 compared to GWP of 1300 for R134a. Also it is clear that adding HC to R134a would make it compatible with mineral oil and would avoid the usage of hygroscopic Polyoilester oil. In this chapter the various factors that are considered for selection of suitable HC refrigerants as substitute to R134a are discussed.

Hydrocarbon mixture preparation and handling procedure is also discussed.

Refrigerant Mixture Properties

From previously literatures it has been found that the important factors that determine the performance of alternate refrigerants used are the vapour pressure, liquid density, vapour density, liquid viscosity and vapour viscosity of the refrigerants. Hence, for the present research work, the above said properties of the refrigerant mixtures used were obtained from the software REFPROP 7.0 for operating temperature from -30ºC to 20ºC. The HC mixtures of refrigerants,Propane/Butane-R290/R600, Propane/Isobutene- R290/R600a and Propane/Butane/isobutene-LPG are mixtures proposed as alternate refrigerants for R134a. These refrigerant mixtures can be retrofitted with the existing vapour compression refrigeration system.

It has been reported that, there is no single refrigerant or mixture available to satisfy both the ozone depletion potential and global warming potential issues. The use of mixtures of refrigerants has proved to be an excellent substitute for the refrigerant R134a. When some hydrocarbon refrigerants are mixed, the mixture of hydrocarbon can have properties similar to that of R134a. Graph 2.1 shows the variation of vapour pressure with saturation temperature of the alternate refrigerants considered for experimentation.

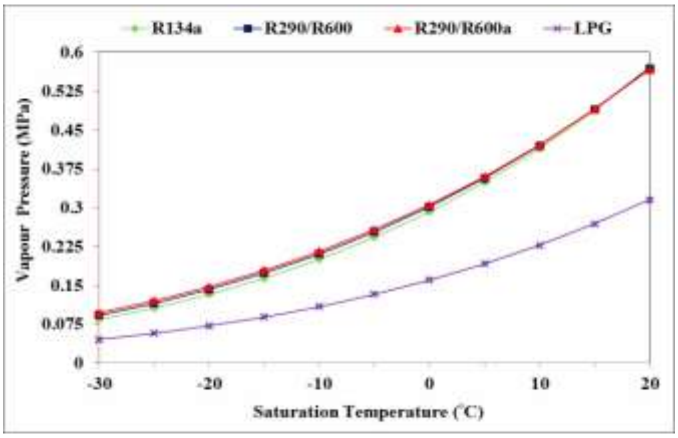
Table 2.1: Properties of Refrigerant used for Study

Name of Refrigerant	**R134a**	**R290**	**R600**	**R600a**
Latent Heat (kJ/kg)	216.87	421.1	386	364.4
Molecular Weight (g/mol)	102	44.10	58.13	58.12
Boiling Point (ºC)	-26.1	-42.1	-0.56	-11.67
Freezing Point (ºC)	-104	-188	-139	-160
Critical Temperature (ºC)	101.06	96.8	153	135
Critical Pressure (MPa)	4.06	4.25	3.8	3.64
ODP	0	0	0	0
GWP	1300	<10	<10	<10
Flammability	Low	High	High	High

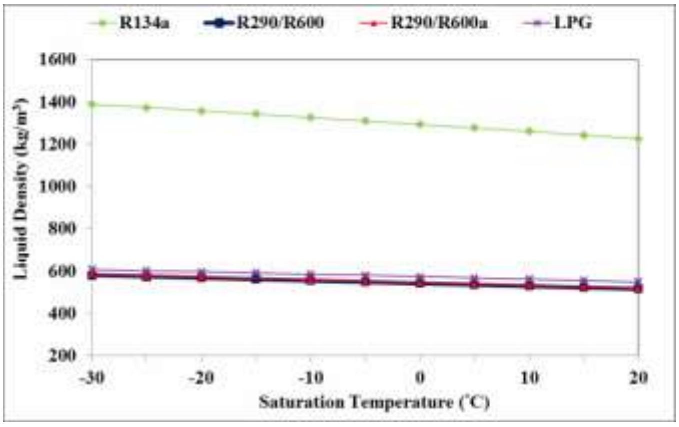
From the Graph 2.1 it can be said that:

i. At concentration equal to 79% by weight of propane and 21% by weight of butane for propane/butane

iii. The saturated vapour pressure for LPG mixture is lower than that of R134a.



Graph 2.1: Variation of Vapour Pressure with Saturation Temperature



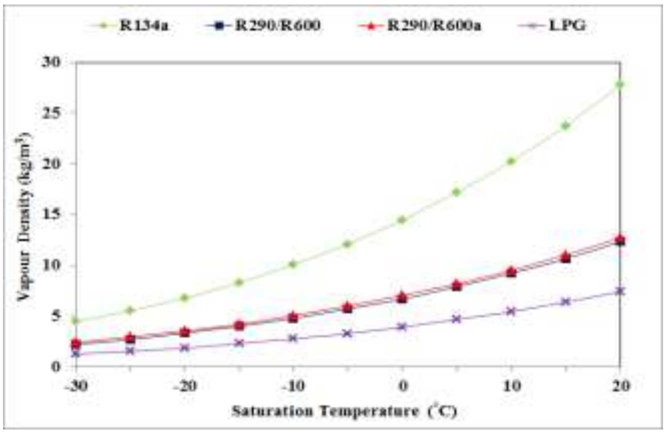
Graph 2.2: Variation of Liquid Density with Saturation Temperature

Graph 2.2 shows the variation of liquid density with saturation temperature for the hydrocarbon refrigerant mixtures and R134a. It has been observed that R134a has more density than HC mixtures. Hence, the quantity of charge required reduces when HC refrigerants are used. It was found that among the selected refrigerant mixtures the liquid density of propane/isobutane and propane/butane was found to be minimum which was lower than that of R134a. It is also observed that the liquid density of LPG is slightly higher than that of propane/ isobutane and propane/butane mixture. In vapour compression refrigeration system, it is necessary to study the vapour density of refrigerants used. The work of compression increases with increase in fluid density. The variation in vapour density of the refrigerants considered with respect to saturation temperature is plotted in Graph 2.3. From the Graph 2.3 it was observed that R134a

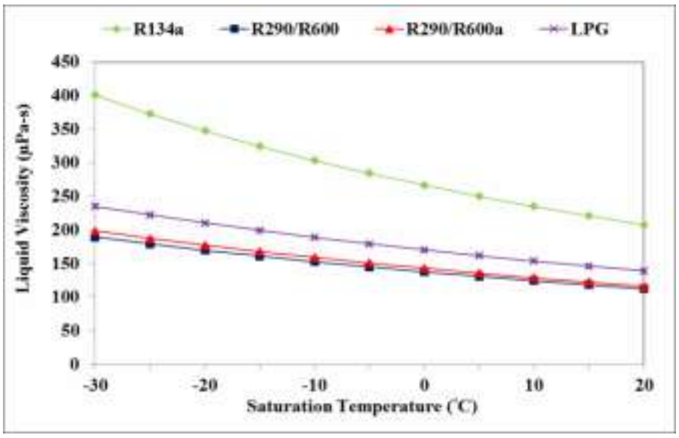
mixture, the saturated vapour pressure of the

hydrocarbon mixture is very close to the saturation vapour pressure of R134a.

ii. At concentration equal to 68% by weight of propane and 32% of isobutane for propane/isobutane mixture, the saturated vapour pressure of the hydrocarbon mixture is very close to the saturation vapour pressure of R134a. has higher vapour density than the selected hydrocarbon refrigerant mixtures.



Graph 2.3: Variation of Vapour Density with Saturation Temperature

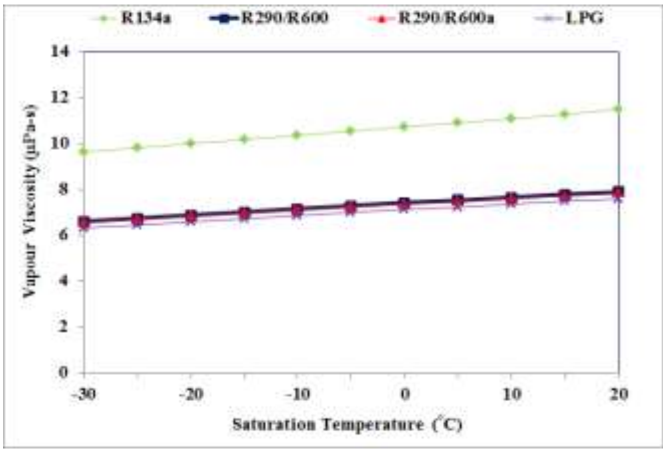


zeotropic in nature, their preparation, handling and charging are very complicated. The three hydrocarbon refrigerants (R290, R600 and R600a) were purchased in separate cylinders, neatly labeled indicating their name and the quantity of refrigerant contained in it. To keep concentration shifts within 2% the guideline is that, the liquid charge in the refrigerant mixture cylinder should not fall below 10% volume at any time while charging the system. Hence, the prepared mixture quantity was always maintained sufficiently high to satisfy the above condition.

Before charging, the system was cleaned and flushed with nitrogen gas to eliminate the presence of air and impurities. Then, they were evacuated to 0.1 millibar. The refrigerant gas cylinders were kept in a low temperature ice bath while filling the refrigerant into the system, from the refrigerant cylinder. This is done to avoid pressure build up in the cylinder during charging. The system was first filled with the required quantities of R600 or R600a and then R290 was filled. This is because R600/R600a has lower vapour pressure than R290. To maintain the required mass percentage in the total quantity, the required mass of R600/600a was calculated and filled and then R290 was filled.

Graph 2.4: Variation of Liquid Viscosity with Saturation Temperature

The flow characteristics of refrigerants inside the capillary tubes are also influenced greatly by viscosity. For this reason, the liquid and vapour viscosity of refrigerants were calculated and plotted in Graph 2.4 and 2.5 respectively. These plots show that the viscosity of HC mixtures is less compared to the viscosity of R134a. Hence better thermodynamic transport properties could be expected with the HC refrigerant mixtures.



Graph 2.5: Variation of Vapour Viscosity with Saturation Temperature

The refrigerant mixtures R290/R600, R290/R600a and LPG are considered for analysis in this research. Since they are This work aims at finding alternate environmental friendly refrigerants to be used as a substitute for R134a in a vapour compression refrigeration system, without retrofitting the existing system. The alternate hydrocarbon refrigerant mixtures considered are propane/butane (R290/R600), propane/isobutane (R290/R600a) and LPG.

The mixtures of hydrocarbon refrigerants propane/butane and propane/isobutane have similar properties as that of R134a. LPG has lower vapour pressure than R134a and the other hydrocarbon mixtures selected for this research. The density of hydrocarbon refrigerant mixtures was lower than the density of R134a. Due to lower density of the hydrocarbon refrigerants, the charge quantity required by the hydrocarbon refrigerant mixtures is less compared to R134a.

Experimental Investigations

The performance of R134a and the selected hydrocarbon refrigerant mixtures was experimentally studied as substitute for R134a in a vapour compression refrigeration system. The experimental setup, procedure and the values obtained of various parameters by using HFC and HC compressors are discussed in this section.

Experimental Set up

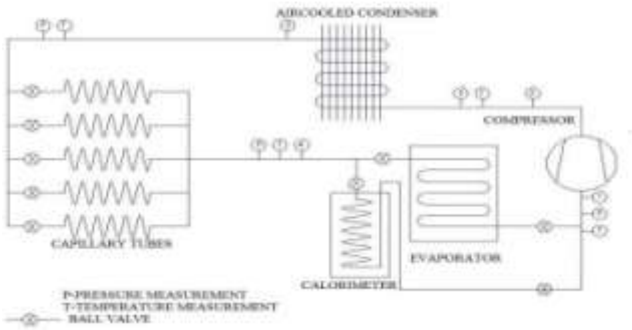


Figure 2.1: Schematic Line Diagram of Experimental Set-up

An experimental setup was developed to facilitate the study on the performance and exergy analysis of a vapour compression refrigeration system with selected refrigerants. The line diagram of the experimental setup used for this study is shown in Figure 2.1. The experimental setup consists of 200 liter domestic refrigerator, which is working under simple vapour compression refrigeration system.

The vapour compression refrigeration system experimental setup consists of a hermetically sealed reciprocating compressor, a wire mesh air cooled condenser, a drier, five capillary tubes of different lengths with ball valves and an evaporator. Five capillary tubes of 0.78mm diameter and with different lengths (3, 3.5, 4, 4.5 and 5 m) were provided. To estimate the refrigeration effect and actual COP of the system, the evaporator similar to the one used in the refrigerator was kept in a calorimeter of 10 liters capacity filled with brine solution as secondary refrigerant. The calorimeter was insulated with PUF to reduce the ambient heat infiltration. A heater is provided inside the calorimeter, to vary the heat load. Four ball valves were fixed in the circuit between the capillary tube outlet and compressor suction to divert the refrigerant flow to either one of the evaporator (in the refrigerator cabin or calorimeter). Another five ball valves were fixed at the capillary tube inlet for choosing different capillary tube length.

The refrigerator was instrumented with four compound pressure gauges with an accuracy of ±1 psi at the inlet and outlet of the compressor for measuring the suction and discharge pressures and at the inlet and outlet of the capillary tubes. The experiment has been conducted using in the refrigerator at constant temperature condition. All the temperatures were measured with an accuracy of ± 0.1ºC. Temperature sensors PT100 were placed at the compressor outlet, condenser outlet, evaporator inlet and inlet of the compressor to measure the temperature. The power consumption of the compressor was measured by using an energy meter with 0.01kWh accuracy. As there was leakage in the visual section it was removed.

Experimental Procedure

The vapour compression refrigeration experimental setup was first charged with R134a and tested in the intended various conditions with HFC compressor. During experimentation with R134a, 3.5m capillary tube length, which is normally used in the domestic refrigerator, was used. The actual refrigeration effect and COP of the refrigerator were calculated as per the procedure followed by Sekhar and Lal (2004). The energy consumption of the compressor was measured using energy meter. All the experimental observations were made after attaining steady state conditions. After completing the baseline reference test with R134a, the refrigerant was recovered from the system and then, the system was charged with hydrocarbon refrigerant mixtures.

A 4.5m capillary tube was taken for the experimentation with hydrocarbon refrigerant mixtures. The system was charged with various mass percentages (25%, 50%, 75% and 100%) of R290/R600, R290/R600a and LPG refrigerant mixtures and tests were done with HFC and HC compressor. Since, the mixtures were zeotrope, the refrigerants were charged in liquid state and the charge quantity was ensured with the help of electronic balance having an accuracy of ±0.01g. In order to reduce experimental uncertainties, experiments were repeated three times and average values were considered. The variation in experimental values from the average value was within ±5%. Temperatures and pressures at different locations were recorded at frequent intervals. Energy consumption during tests was measured by using a digital energy meter. The measured values used to study the performance characteristics of the experimental setup.

III. PERFORMANCE OF VAPOUR COMPRESSION SYSTEM WITH DIFFERENT PARAMETERS

Refrigerating Effect

Refrigerating effect of a vapour compression refrigeration system setup was studied using HFC and HC compressor. Refrigerating effect was better while using HC compressor than in the case of HFC compressor. The refrigerating effect of the refrigerant R290/R600 with HC compressor was from 3.11% to 11.51% higher than HFC compressor for the same operating conditions. Also, the refrigerating effect of the refrigerant R290/R600a with HC compressor was from 4.31% to 17.82% higher than HFC compressor. Similarly, the refrigerating effect of the refrigerant LPG with HC compressor was from 5.64% to 96.46% higher than HFC compressor.

Compressor Work

Compressor work of a vapour compression refrigeration system setup was studied using HFC and HC compressor. Compressor work was less while using HC compressor than in the case of HFC compressor. The Compressor work of the refrigerant R290/R600 with HC compressor was from 5.27% to 9.59% lesser than HFC compressor for the same operating conditions. Also, the Compressor work of the refrigerant R290/R600a with HC compressor was from 4.48% to 8.73% less than HFC compressor. Similarly, the Compressor work of the refrigerant LPG with HC compressor was from 1.58% to 12.24% less than HFC compressor.

Coefficient of Performance

Coefficient of performance of a vapour compression refrigeration system setup was studied using HFC and HC compressor. Coefficient of performance of the system was better while using HC compressor than in the case of HFC compressor. The Coefficient of performance of the refrigerant R290/R600 with HC compressor was from 9.36% to 21.15% higher than HFC compressor for the same operating conditions. Also, the Coefficient of performance of the refrigerant R290/R600a with HC compressor was from 9.71% to 25.88% higher than HFC compressor. Similarly, the COP of the refrigerant LPG with HC compressor was from 14.12% to 93.39% higher than HFC compressor.

Summary

i. From the experimental investigation it has been observed that the refrigerating effect of the selected refrigerant mixtures increases with increase in evaporator temperature.
ii. The refrigerating effect of the selected refrigerant mixtures decreases with increase in condensing temperature, because of the reduced refrigerant flow rate.
iii. The power consumed by the compressor was low with the refrigerant LPG in both the cases, i.e. with HFC compressor and also with HC compressor. This is because of the reduced mass flow rate of the refrigerant.
iv. The COP of all the HC refrigerants was more while using HC compressor than with HFC compressor.
v. All the selected alternative refrigerant mixtures showed a reduction in charge due to their low liquid densities.
vi. All the selected alternative refrigerant mixtures gave better performance with HC compressor, than with HFC compressor for the same operating conditions.

IV. CONCLUSIONS AND FUTURE SCOPE

Conclusions

High global warming potential is the main reason for the phase out of R134a from the refrigeration industry. Based on the research made, it is observed that the hydrocarbon blends of R290/R600, R290/R600a and LPG is found be a viable alternative to R134a in a vapour compression refrigeration system. Based on experimental investigations the following conclusions were drawn:

Performance Studies On Refrigeration System Using Hydrocarbon Refrigerants

i. Three different hydrocarbon refrigerant mixtures have been tested for use in a vapour compression refrigeration system. The selected alternative hydrocarbon refrigerant mixtures used in this research gave better performance in all aspects than that of R134a.
ii. Among the three alternative hydrocarbon refrigerant mixtures considered R290/R600 and R290/R600a were found to have higher COP than LPG refrigerant, as well as to R134a for all the operating conditions.

Experimental Investigations

i. The experimental study revealed that the refrigerating capacity and COP of the selected refrigerant mixtures increases with increase in evaporator temperatures.
ii. Depending on the evaporator temperatures the refrigerating effect of the refrigerant mixtures R290/R600 was from 11.07% to 89.09% and for R290/R600a was from 1.2% to 42.38% higher than that of R134a.
iii. The power consumed by the compressor with the refrigerants R290/R600, R290/R600a was lesser than that of R134a depending on the evaporator temperatures, due to higher latent heat of vaporization.
iv. LPG consumes less power than other selected hydrocarbon refrigerant mixtures, due to higher saturation temperature than other hydrocarbon refrigerants selected.
v. The refrigerant was charged with various mass charges and the results revealed that the COP was maximum with 60 grams of all the refrigerants taken for the study.
vi. All the refrigeration system using hydrocarbon refrigerant mixtures require less charge than that of the system using R134a due to their low liquid density of the hydrocarbon refrigerant mixtures.
vii. During the exergy analysis, it was found that the condenser and evaporator temperatures have considerable effects on COP and the exergy efficiency of the system.
viii. R290/R600, R290/R600a mixtures exhibit lower exergy loss at all range of operating conditions than R134a.
ix. LPG exhibits more exergy loss among the selected hydrocarbon mixtures.

Future Scope

i. Studies on hydrocarbon mixtures with subcooling arrangement can be carried out with the same experimental setup.
ii. The analysis can be further extended to different systems. The length of the capillary tube can be varied and also different geometries of capillary tube (straight, helical and serpentine shapes) can be varied and tested.
iii. The exergy analysis can be extended to other condensing temperatures also.
iv. The exergy analysis can be extended to various ambient temperatures.

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