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Experimental Performance Evaluation of R152a to replace R134a in Vapour Compression Refrigeration System

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ABSTRACT: *The performance of heat transfer is one of the most important research areas in the field of thermal engineering. There are a large number of refrigerants, which are used to transfer heat from low temperature reservoir to high temperature reservoir by using vapour compression refrigeration system. There are various obstacles faced in working of different refrigerants due to their environmental impact (CFC, HCFC), toxicity (NH_3), flammability (HC) and high* pressure (CO_2); which makes them more hazardous than other working fluids according to safety and environmental issues. *Experimentation is conducted to observe the performance of Hydro-fluorocarbon (HFC) refrigerants (R134a and R152a) in vapour compression refrigeration. Value of average refrigerating effect for R152a is about 57% more than that of R134a . Average pressure ratio for R152a was 18.92% higher than that of R134a. In this result, R152a has emerged as the most energy efficient refrigerant among both the investigated refrigerants being the one that exhibited the lowest power consumption per ton of refrigeration with the average value of 13.23% less than that of R134a.The COP of R152a obtain is higher than R134a by 3.769% .As a result, R152a could be used as a drop-in replacement for R134a in vapour compression refrigeration system. R152a offers the best desirable environmental requirements; zero Ozone Depleting Potential (ODP) and 120 Global Warming Potential (GWP).*

Keywords: *Hydro -fluorocarbon,COP, ODP, GWP, R134a, R152a*

I. INTRODUCTION

The first mechanically produced cooling system was developed in England in 1834. The process later becameknown as vapour compression. After availability of electricity automatic refrigeration system was developed in 1897. Basically a refrigeration or air conditioning is nothing more than a heat pump whose job is to remove heat from a lower temperature source and reject heat to high temperature sink. The Vapor Compression Refrigeration Cycle is a process that cools an enclosed space to a temperature lower than the surroundings. To accomplish this, heat must be removed from the enclosed space and dissipated into the surroundings. However, heat tends to flow from an area of high temperature to that of a lower temperature.

During the cycle refrigerant circulates continuously through four stages. The first stage is called Evaporation and it is here that the refrigerant cools the enclosed space by absorbing heat. Next, during the Compression stage, the pressure of the refrigerant is increased, which raises the temperature above that of the surroundings. As this hot refrigerant moves through the next stage, Condensation, the natural direction of heat flow allows the release of energy into the surrounding air. Finally, during the Expansion phase, the refrigerant temperature is lowered by what is called the auto refrigeration effect. This cold refrigerant then begins The Evaporation stage again, removing more heat from the enclosed space. Each of the four stages will now be revisited in detail, explaining the physical changes that occur in the refrigerant and the devices used to accomplish these changes. A visual representation of the cycle is displayed below with the explanation of each stage.

1.1 Refrigeration System: Working Principle and Construction

Refrigeration system is based upon the Clausius statement of second law of thermodynamics. This statement shows, "It is impossible to construct a device which, operating in a cycle, will produce no affect other than the transfer of heat from a cooler to a hotter body.

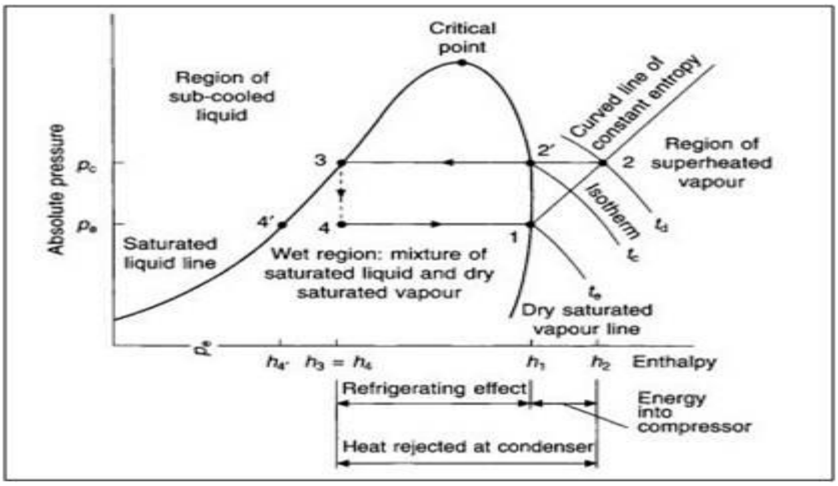


Figure 1: p-h Diagram for the Ideal Vapor Compression Refrigeration Cycle.

The vapour compression refrigeration system is illustrated on 2-property diagrams. Figure 1 and 2 shows p-h and T-s diagram for ideal vapour compression cycle.

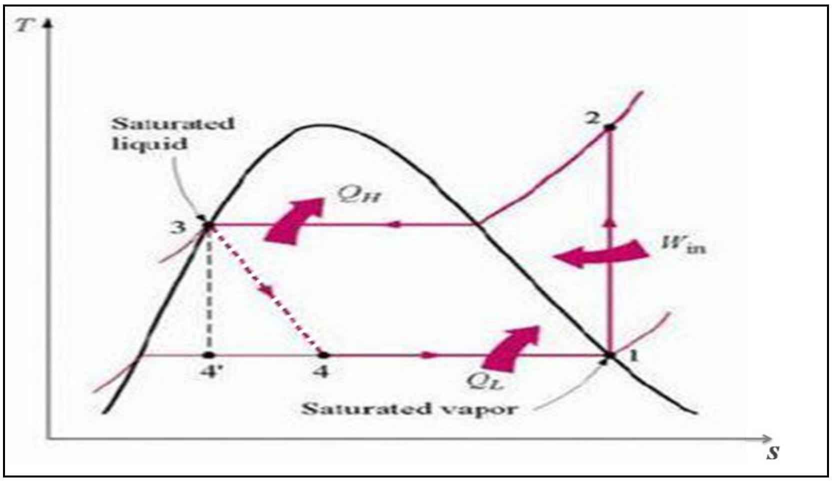


Figure 2: T-S Diagram for the Ideal Vapor Compression Refrigeration Cycle

Process 1 – 2: Isentropic compression in compressor.
Process 2 –3: Constant pressure heat rejection in condenser.
Process 3 – 4: Isenthalpic expansion in expansion device.
Process 4 –1: Constant pressure heat absorption in evaporator.

A vapor compression cycle is used in most water cooler, refrigerator and deep freezers. In this cycle, a circulating refrigerant such as R134a enters a compressor as low pressure vapor. The vapor is compressed and exits the compressor as high-pressure superheated vapor. The superheated vapor travels under pressure through coils or tubes comprising "the condenser", which are passively cooled by exposure to air in the room. The condenser cools the vapor, which liquefies. As the refrigerant leaves the condenser, this liquid refrigerant is forced through a metering or throttling device, also known as an expansion device (capillary tube) to an area of much lower pressure. The sudden decrease in pressure results in explosive-like flash evaporation of a portion (typically about one third) of the liquid. The latent heat absorbed by this flash evaporation is drawn mostly from adjacent still-liquid refrigerant, a phenomenon known as "auto-refrigeration". This cold and partially vaporized refrigerant continues through the coils or tubes of the evaporator unit. The evaporator coil is soldered on to the walls of the storage tank of the water cooler, generally on the outside surface of the walls. The tank may be galvanized steel or stainless steel sheets. The water level in the tank is maintained by a float valve. In this water cooler, the machine will have to run for a long time to bring down the temperature of the mass of water in the storage tank. When the water is drawn from the cooler and equal amount of fresh water is allowed in the tank, the temperature will rise up slowly and the machine starts again. As such there is always a reservoir of cold water all the time. Refrigerant leaves the evaporator, now fully vaporized and slightly heated, and returns to the compressor inlet to continue the cycle.[1]

1.2 Factors Affecting the Performance of Vapour Compression Refrigeration System

From the literature survey it is observed that following factors affect the performance of vapour compression refrigeration system.

i. Properties of working fluid.
ii. Mixture proportions of different refrigerants.
iii. Suction pressure.
iv. Discharge pressure.
v. Pressure ratio.
vi. Amount of charge filled.
vii. Dimensions of capillary tube

1.3 REFRIGERANTs

The working fluid used to transfer the heat from low temperature reservoir to high temperature reservoir is called refrigerant. There are different types of refrigerant which are described as followings. *CFC:* They are molecules composed of carbon, chlorine and fluorine. They are stable, allowing them to reach the stratosphere without too many problems. It contributes to the destruction of the ozone layer. These are R11, R12, R113, R500, R502 etc. *HCFC*: They are molecules composed of carbon, chlorine, fluorine and hydrogen. They are less stable than CFCs, destroy ozone and to a lesser extent. These are R22, R123, R124, R401a etc. *HFC:* They are molecules composed of carbon, fluorine and hydrogen. They do not contain chlorine and therefore do not participate in the destruction of the ozone layer. This is known as substitution substance. Restrictions on this family of gas are currently limited. Within the European Union, the HFC will be banned from air conditioners for cars from 2011.These are R134a.

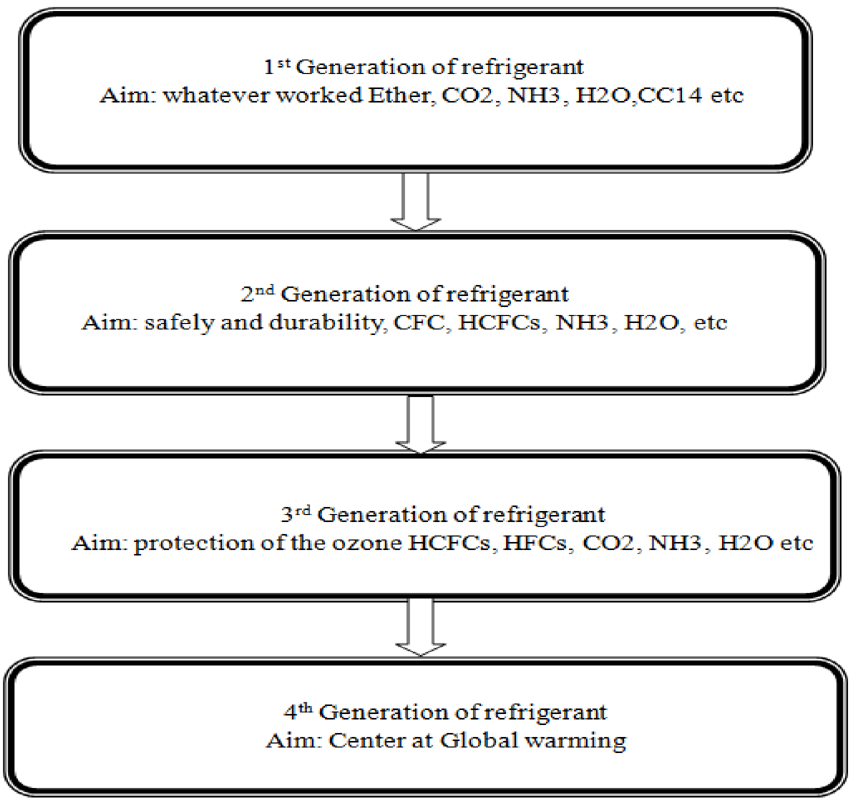


Figure 3: The Generation of Refrigerants

In the process of searching for new alternative, since no single component refrigerant matches, hence refrigerant blends as alternative was recommended, because by mixing two or more refrigerants a new working fluid with the desired characteristic can be developed. Problem with blend of refrigerantsis that not all of the properties can match the original refrigerant under all conditions. R12 for example will rarely match the pressure at all point in the desired temperature range. What is more common is that the blend will match in one region and the pressure differs elsewhere. The mixture of refrigerants could be Azeotropic, in which two or more refrigerants with similar boiling point acts as a single fluid. The components of the mixture will not separate under normal operating conditions and can be charged as a vapour or liquid.An example of these blends is 50/50, which is the mixture of R32 and R134a. The near Azeotrope mixture consist of two or more refrigerants with different boiling points, when in liquid or vapour state, act as one component. When changing from vapour to liquid or liquid to vapour, the individual refrigerant evaporates or condenses at different temperatures. The mixture has a temperature glide of less than 10 and should be charged in the liquid state to assume proper mixture, and the Zoetrope which is a mixture made up of two or more refrigerants with different boiling points, they are charged in the liquid state.

1. Mixture of refrigerants: They can be classified according to the type of fluorinated components they contain. They are also distinguished by the fact that some mixtures are:

a. Zeotropic: in a state change (condensation, evaporation), the temperature varies. These are R404a, R407a and R410a etc.
b. Azeotropes: they behave like pure, with no change in temperature during the change of state. These are R500, R502 and R507a etc.

2. Ammonia (NH3) or R717 : Fluid inorganic thermodynamically is an excellent refrigerant for evaporation temperatures between - 35 °C to 2 °C. But it is a fluid dangerous toxic and flammable, so it is generally used in industrial refrigeration.

3. Hydrocarbons (HC) as R290, R600a: This is primarily propane (R290), butane (R600) and isobutene (R600a). These fluids have good thermodynamic properties, but are dangerous because of their flammability. The world of the cold has always been wary of these fluids, even if they have reappeared recently in refrigerators and insulating foams. Their future use in air conditioning seems unlikely, given the cost of setting both mechanical and electrical safety.

4. Carbon dioxide (CO2) or R744: This is inorganic, non-toxic, non flammable, but inefficient in thermodynamics. Its use would involve high pressure and special compressors. Currently, specialists in air conditioning and refrigeration are interested again by:

a. Its low environmental impact (ODP = 0, GWP = 1);
b. The low specific volume resulting in facilities with low volume (small leak);
c. It has the distinction of having a low critical temperature at 31 °C at a pressure of 73.6 bars.

5. HFC-152a: It is almost a straight drop-in substitute for R-134a. The molecule is similar to R-134a except that two hydrogen atoms are substituted for two fluorine atoms. It has similar operating characteristics to R-134a but cools even better. An environmental benefit of HFC-152a is that it has a global warming rating of 120, which is 10 times less than R-134a, but still a lot higher than CO2. That is why HFC-152a is currently used in many aerosol products as a propellant. Its main drawback is that it is slightly flammable.

6. HFO-1234yf: Another new refrigerant that is being considered is HFO-1234yf. Developed jointly by Honeywell and DuPont, it is being promoted as a possible drop-in replacement for R-134a in both new vehicles and older vehicles, should that become necessary in the future. HFO-1234yf has thermal characteristics that are very similar to R-134a, so no major modifications to the A/C system are necessary. Better yet, HFO-1234yf has a global warming potential of only 4, compared to 1200 for R-134a, allowing it to meet the European requirements for a GWP of less than 150.

D. Criteria For Retrofitting:

When considering a refrigeration system/air conditioning retrofit, the following factors must be considered.

i. Expected remaining life-time of existing equipment;
ii. Refrigerant leak history of equipment and the value of leak rate;

iii. Effects and cost of retrofit with current technology;
iv. Alternative refrigerant cost;
v. Availability of alternative refrigerant in the present and future.

E. Mathematical Relations:

a. Heat rejection in condenser
$Q_r = m_{cw} x\ C_{pw}\ x \Delta\ T$

b. Heat abstraction in evaporator
$Q_a = m_{ew} x\ C_{pw}\ x \Delta\ T_{ew}$

c. Work input in compressor

W_{in} = Energy meter reading

d. Coefficient of performance

$COP = Q_a / W_{in}$

LITERATURE REVIEW

R. Cabello, E. Torrella and J. Navarro-Esbri [1], have analyzed the performance of a vapour compression refrigeration system using three different working fluids (R134a, R407c and R22). The operating variables are the evaporating pressure, condensing pressure and degree of superheating at the compressor inlet. They analyzed that the power consumption decreases when compression ratio increases with R22 than using the other working fluids.

B.O. Bolaji et al[2] investigated experimentally the performances of three ozone friendly Hydrofluorocarbon (HFC) refrigerants R12, R152a and R134a. R152a refrigerant found as a drop in replacement for R134a in vapour compression system.

B.O. Bolaji[3] discussed the process of selecting environmental-friendly refrigerants that have zero ozone depletion potential and low global warming potential. R23 and R32 from methane derivatives and R152a, R143a, R134a and R125 from ethane derivatives are the emerging refrigerants that are non toxic, have low flammability and environmental-friendly. These refrigerants need theoretical and experimental analysis to investigate their performance in the system.

James M. Calm [4], has studied the emission and environmental impacts of R11, R123, R134a due to leakage from centrifugal chiller system. He also investigated the total impact in form of TEWI and change in system efficiency or performance due to charge loss. He also summarized the methods to reduce the refrigerant losses by the system like design modifications, improvement in preventive maintenance techniques, use of purge system for refrigerant vapour recovery, servicing and lubricant changing in system.

Samira Benhadid-Dib and Ahmed Benzaoui [5], have showed that the uses of halogenated refrigerants are harmful for environment and the use of "natural" refrigerants become a possible solution. Here natural refrigerants are used as an alternative solution to replace halogenated refrigerants. The solution to the environmental impacts of refrigerant gases by a gas which contains no chlorine no fluorine and does not reject any CO2 emissions in the atmosphere. The researchers showed that emissions have bad effects on our environment. They also concerned by a contribution to the reduction of greenhouse gases and by the replacement of the polluting cooling fluids (HCFC).

Eric Granryd [6], has enlisted the different hydrocarbons as working medium in refrigeration system. He studied the different safety standards related to these refrigerants. He showed the properties of hydrocarbons (i.e. no ODP and negligible GWP) that make them interesting refrigeratingalternatives for energy efficient and environmentally friendly. But safety precautions due to flammability must be seriously taken into account.

Y. S. Lee and C. C. Su [7], have studied the performance of VCRS with isobutene and compare the results with R12 and R22. They used R600a about 150 g and set the refrigeration temperature about 4 °C and -10 °C to maintain the situation of cold storage and freezing applications. They used 0.7 mm internal diameter and 4 to 4.5 m length of capillary tube for cold storage applications and 0.6 mm internal diameter and 4.5 to 5 m length of capillary tube for freezing applications.

They observed that the COP lies between 1.2 and 4.5 in cold storage applications and between 0.8 and 3.5 in freezing applications. They also observed that the system with two capillary tubes in parallel performs better in the cold storage and air conditioning applications, whereas that with a single tube is suitable in the freezing applications.

Mao-Gang He, Tie-Chen Li, Zhi-Gang Liu and Ying Zhang [8], have analyzed that the R152a/R125 mixture in the composition of 0.85 mass fraction of R152a has a similar refrigeration performance with the existing refrigerant R12.Experimental research on the main refrigeration performances of domestic refrigerators was conducted, under the different proportions and charge amounts, when R152a/R125 is used to substitute R12 as a __drop-in'' refrigerant. The experimental results indicate that R152a/R125 can be used to replace R12 as a new generation refrigerant of domestic refrigerators, because of its well environmentally acceptable properties and its favorable refrigeration performances.

Ki-Jung Park, Taebeom Seo and Dongsoo Jung [9], have analyzed performances of two pure hydrocarbons and seven mixtures composed of propylene, propane, R152a, and dimethylether were measured to substitute for R22 in residential air-conditioners and heat pumps at the evaporation and condensation temperatures of 7 °C and 45 °C, respectively. Test results show that the coefficient of performance of these mixtures is up to 5.7% higher than that of R22. Whereas propane showed 11.5% reduction in capacity, most of the fluids had a similar capacity to that of R22. For these fluids, compressor-discharge temperatures were reduced by 11–17 °C. For all fluids tested, the amount of charge was reduced by up to 55% as compared to R22. Overall, these fluids provide good performances with reasonable energy savings without any environmental problem and thus can be used as long-term alternatives for residential air-conditioning and heat-pumping applications.

A.Baskaran, and P.Koshy Mathews [10], A performance analysis on a vapour compression refrigeration system with various eco-friendly refrigerants of HFC152a, HFC32, HC290, HC1270, HC600a and RE170 were done and their results were compared with R134a as possible alternative replacement. The results showed that the alternative refrigerants investigated in the analysis RE170, R152a and R600a have a slightly higher performance coefficient (COP) than R134a for the condensation temperature of 50^0C and evaporating temperatures ranging between -30^0C and 10^0C.Refrigerant RE170 instead of R134a was found to be a replacement refrigerant among other alternatives.

K. Mani and V. Selladurai [11], have analyzed a vapour compression refrigeration system with the new R290/R600a refrigerant mixture as drop-in replacement was conducted and compared with R12 and R134a. The VCRS was initially designed to operate with R12.The results showed that the refrigerant R134a showed slightly lower COP than R12. The discharge temperature and discharge pressure of the R290/R600a mixture was very close to R12. The R290/R600a (68/32 by wt %) mixture can be considered as a drop-in replacement refrigerant for R12 and R134a.

A.S. Dalkilic and S. Wongwises [12], have studied the performance on a VCRS with refrigerant mixtures based on R134a, R152a, R32, R290, R1270, R600 and R600a was done for various ratios and their results are compared with R12, R22 and R134a as possible alternative replacements. The results showed that all of the alternative refrigerants investigated in the analysis have a slightly lower COP than R12, R22, and R134a for the condensation temperature of 50 °C and evaporating temperatures ranging between −30 °C and 10 °C. Refrigerant blends of R290/R600a (40/60 by wt. %) instead of R12 and R290/R1270 (20/80 by wt. %) instead of R22 are found to be replacement refrigerants among other alternatives.

Vincenzo La Rocca and Giuseppe Panno [13], have analyzed and compared the performance of a vapour compression refrigerating unit operating with R22, and with three new HFC fluids, substituting the former according to Regulation No 2037/2000. Here the plant working efficiency was first tested with R22 and then with three new HFC fluids: R417a,R422a and R422d. It is analyzed that the performance with the new tested fluids did not result as efficient as when using R22.

Vincenzo La Rocca and Giuseppe Panno [14], have analyzed and compared the performance of a vapour compression refrigerating unit operating with R22, and with three new HFC fluids, substituting the former according to Regulation No 2037/2000. Here the plant working efficiency was first tested with R22 and then with three new HFC fluids: R417a, R422a and R422d. It is analyzed that the performance with the new tested fluids did not result as efficient as when using R22.

Minxia Li, Chaobin Dang and Eiji Hihara [15], have investigated that Hfo1234yf has been proposed for mobile air-conditioners due to its low GWP and performance comparable to that of R134a. However, its performance is inferior to that of R410a. This makes it difficult to be applied to residential air-conditioners.

II. EXPERIMENTAL SETUP OF VAPOUR COMPRESSION REFRIGERATION SYSTEM

The main loop of the system under study was composed of five basic components, i.e., a compressor, an evaporator, a condenser, capillary tubes and a liquid line filter–drier, as shown in Fig. 4. A three-phase, 220 V, reciprocating compressor originally designed for R134a systems was used. The input power of the compressor within the system varied between 230 and 300 W. The major ingredient of the compressor lubricant was POE. A silica gel drier filter was used to absorb the moisture. Compact forced air cooled type condenser was used for their good heat transfer performances. Capillary tubes of different internal diameters were used to find the optimum operating points of the system. Evaporator section was made by shell and tube type by copper tubes and stainless steel tank. For minimizing the heat loss, the evaporator tank was well insulated by puff. The refrigerants used were R134a, R152a. Some other measuring and controlling components were used in the system, that were, an electrical switch, an energy meter, a voltmeter, an ampere meter, a digital thermostat for controlling the evaporator temperature, bourdon tube type low pressure gauge and high pressure gauge, Pt 100 type thermocouples and indicator and gas flow

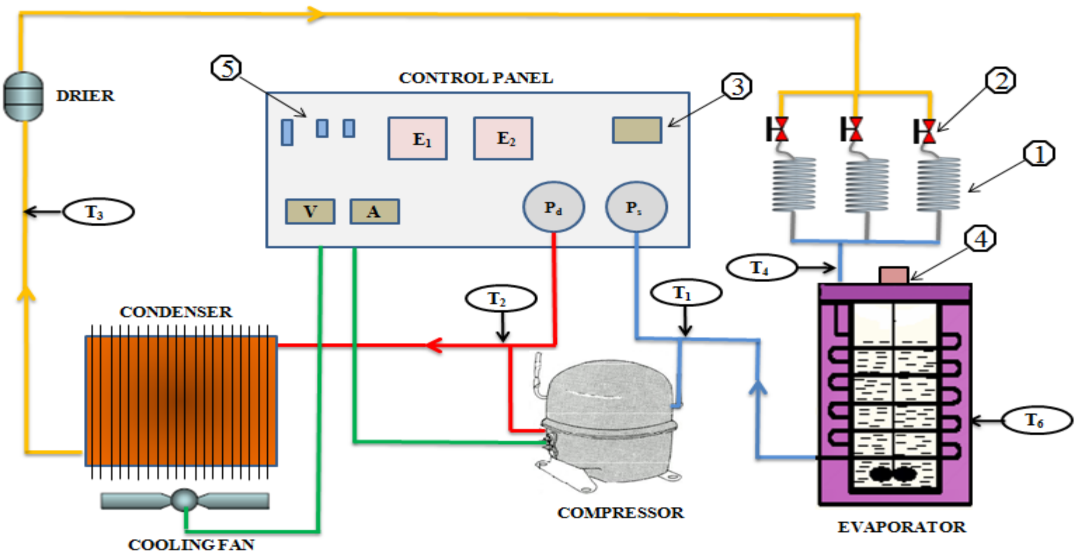


Figure 4: Schematic diagram of Test rig

Figure 5: Experimental setup.

Table 1: Description of setup components

COMPRESSOR	EMERSON COPELAND MADE KCE444HAG, HERMETICALLY SEALED,
EVAPORATOR	INNER STAINLESS STEEL TANK INSULATED BY SUPERLON
CONDENSER	279 MM ×254 MM × 76 MM
EXPANSION DEVICE	CAPILLARY TUBES OF DIAMETER 1.27 MM, 1.12 MM,0.91 MM
DRIER	DANFOSS MADE POE TYPE
DISCHARGE PRESSURE GAUGE	RANGE 0 TO 300 LB/IN^2
SUCTION PRESSURE GAUGE	RANGE -30 TO 150 LB/IN^2
THERMOCOUPLE	PT 100 (RANGE -50° C TO 1200° C)
CONDENSER FAN MOTOR	1/83 HP AC SYNCHRONOUS MOTOR
GAS CHARGING LINE	6.34 MM DIAMETER LINE WITH BRASS VALVE
VOLTMETER	RANGE 0-300 V
AMMETER	RANGE 0-10 A
DIMMER	RANGE 0-260 VOLTS
ENERGY METER	ELECTRONIC, RANGE 0-20 A
MINIATURE CIRCUIT BREAKER	ANCHOR MADE 10 KA 240/415 V~50HZ
TEMPERATURE INDICATOR	'PT 100' TYPE, RANGE 0-750°C (IRON–CONSTANTAN)
HEATER	1 KW, 240/415 V~50HZ

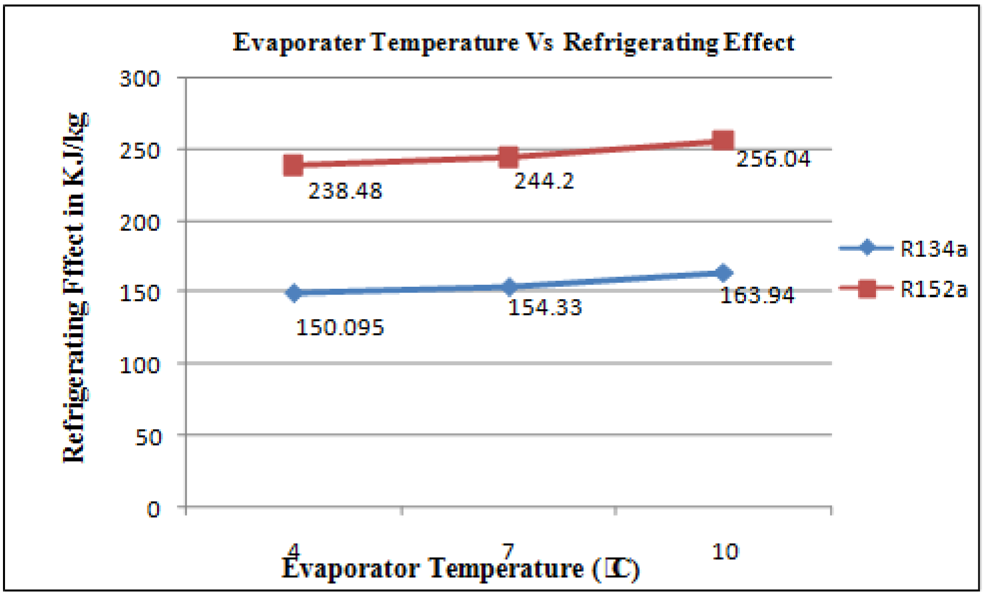
III. EXPERIMENTAL PROCEDURE

The objective of the study is to compare the refrigeration performance of different refrigerants in terms of COP .'Pt 100' type thermocouples were used to measure the temperatures and pressures were measured using calibrated pressure gauges. The thermocouples have been located in the pockets on the surface of the tubes and sensor is calibrated to reduce experimental uncertainties. The ranges of equipment used in the experimental test setup are showed in Table 1. The temperatures and pressures of the refrigerant and initial water temperatures are measured at various locations in the experimental setup as shown in Fig.4. The compressor energy consumption is measured using an energy meter. Three manual type expansion devices are used to regulate the mass flow rate of refrigerant and to set pressure difference. The refrigerant is charged after the system had been evacuated. The working fluids are R134a, R152a. Drop-in experiments are carried out without any modifications to the experimental apparatus. The experiment is started with R134a to set up the base reference for further comparisons with the other two refrigerants. The thermal load of the system is changed with an external electrically heated unit.

IV. RESULTS AND DISCUSSIONS

1. Refrigerating Effect

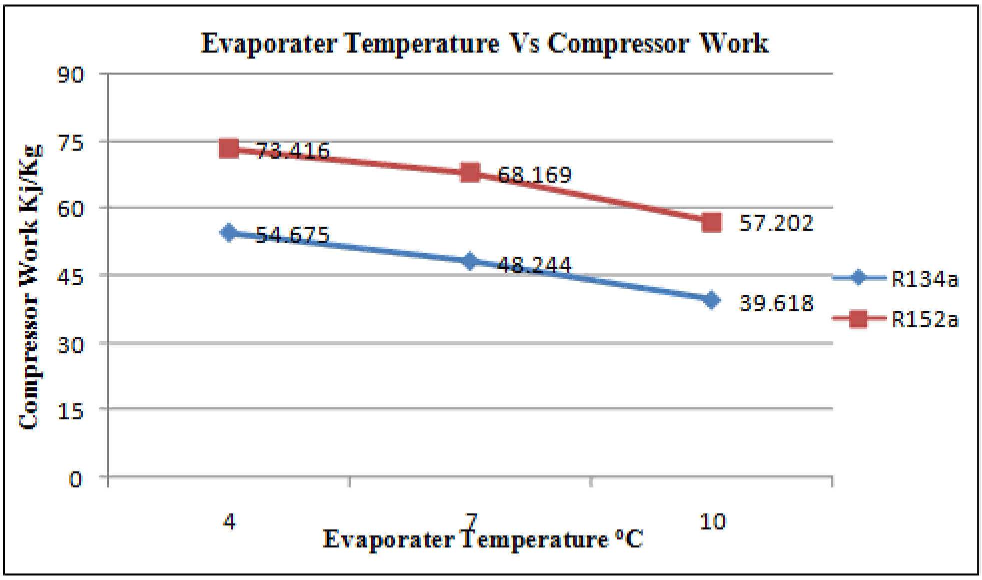
The refrigerating effects of R134a and its potential alternative R152a at varying evaporating temperature for condensing temperature of 51^0C are shown in Graph 2. As shown in the figure, refrigerating effect increases as the evaporating temperature increases for both refrigerants. This is due to the increase in latent heat value of the refrigerant. A very high latent heat value is desirable since the mass flow rate per unit of capacity is less. When the latent value is high, the efficiency and capacity of the compressor are greatly increased. This decreases the power consumption and also reduces the compressor displacement requirements that permit the use of smaller and more compact equipment. It is clearly shown in Figure that R152a exhibited higher refrigerating effect than R134a. Therefore, very low mass of refrigerant will be required for the same capacity and compressor size. A.Baskaran and P.Koshy Mathews obtained average values of 229.76 kJ/Kg and 137.28 kJ/Kg at 50^{0}C condenser temperature.[13] Whereas experiment performed by Bukola Olalekan Bolaji, Zhongjie Huan and Francis Olusesi Borokinni at constant condenser temperature had highest average values of 244.7 kJ/kg and 136.1 kJ/kg for R152a and R134a respectively.[3] The refrigerating effect highest average value of (246.24 kJ/kg) was obtained using R152a compare with (156.12 kJ/kg) of R134a at condensing temperature of 51^{0}C.



Graph1.Variation of Refrigerating Effect with varying Evaporator Temperature for R152a and R134a

2. Compressor Work

Graph 2 shows the variation of the compressor Work with evaporating temperature for R134a and its alternative refrigerant R152a at condensing temperature of 51^{0}C.

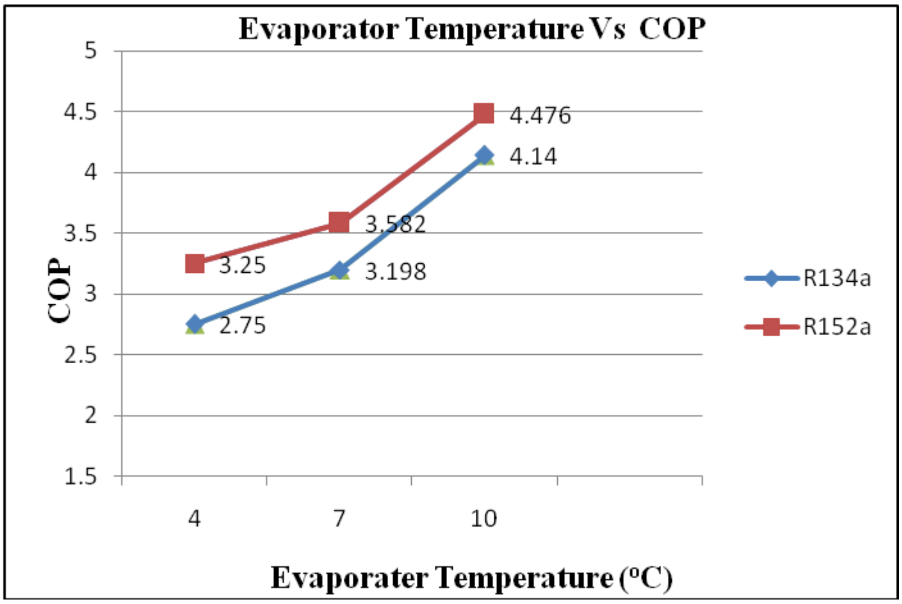


Graph 2: Variation of Refrigerating Effect with varying Evaporator Temperature for R152a and R134a.

The graph shows that the compression Work decreases as the evaporating temperature increases. This is due to the fact that when the temperature of the evaporator increases the suction temperature also increases. At high suction temperature, the vaporizing pressure is high and therefore the density of suction vapour entering the compressor is high. Hence the mass of refrigerant circulated through the compressor per unit time increases with the increases in suction temperature for a given piston displacement. The increase in the mass of refrigerant circulated decreases the work of compression. The R152a exhibited higher compressor Work than R134a (Graph 2) and it is 39.46% higher than the compressor work for R134a.

3. Coefficient of Performance

The coefficient of performance (COP) of a refrigeration cycle reflects the cycle performance and is the major criterion for selecting a new refrigerant as a substitute. The COPs for R134a and R152a refrigerants at varying evaporator temperature for condensing temperature of 51 ^{0}C are shown in Graph 3. COP increases with increase in evaporator temperature.



Graph 3: Variation of Coefficient of Performance (COP) with varying Evaporator Temperature for R152a and R134a.

V. CONCLUSION

In this study, an ideal vapor-compression system is used for the performance analysis of alternative new refrigerant R152a substitute for R134a in a vapour compression refrigeration system at varying evaporating temperature and condensing temperature of 51^{o}C. The following conclusions can be drawn from the analysis and discussion of the results:

1. Out of the two refrigerants investigated, R152a offers the best desirable environmental requirements; it has zero Ozone Depletion Potential (ODP) and 120 Global Warming Potential (GWP) which is lesser ten times that of R134a.
2. R134a exhibited lower compressor energy input than R152a, but R152a exhibited significantly high refrigerating effect, which is a form of compensation for its high compressor energy input.
3. R152a has the higher COP. The average COPs obtained for R152a were 3.769% higher than that of R134a.
4. R152a refrigerant has approximately the same performance with R134a, therefore, R152a is considered as a good drop-in substitute for R134a in vapour compression refrigeration system. The best performance was obtained from the use of R152a in the system.

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