Performance Investigation of Domestic Refrigerator Using Pure Hydrocarbons and Blends of Hydrocarbons as Refrigerants

M. A. Sattar, R. Saidur, and H. H. Masjuki

Abstract**—**A domestic refrigerator designed to work with R-134a was used as a test unit to asses the possibility of using hydrocarbons and their blends as refrigerants. Pure butane, isobutene and mixture of propane, butane and isobutene were used as refrigerants. The performance of the refrigerator using hydrocarbons as refrigerants was investigated and compared with the performance of refrigerator when R-134a was used as refrigerant. The effect of condenser temperature and evaporator temperature on COP, refrigerating effect, condenser duty, work of compression and heat rejection ratio were investigated. The energy consumption of the refrigerator during experiment with hydrocarbons and R-134a was measured. The results show that the compressor consumed 3% and 2% less energy than that of HFC-134a at 28°C ambient temperature when iso-butane and butane was used as refrigerants respectively. The energy consumption and COP of hydrocarbons and their blends shows that hydrocarbon can be used as refrigerant in the domestic refrigerator. The COP and other result obtained in this experiment show a positive indication of using HC as refrigerants in domestic refrigerator.

Keywords**—**Hydrocarbons, Butane, Iso-butane, Heat rejection ratio, Energy consumption.

I. INTRODUCTION

NATURAL ice was harvested, distributed and used in both commercial and home applications in the mid-1800s to refrigerate food. The idea that cold could be produced by the forced evaporation of a volatile liquid under reduced pressure had been previously pursued by Willam Cullen in the eighteenth century. These same volatile liquids could be condensed from a vapor state by application of cooling and compression was also known by the 1800s. Combining these two ideas led to the development of what would ultimately become the dominant means of cooling, the vapor compression refrigerating system. Since the invention of the vapor compression refrigeration system in the middle of the 18th century and its commercial application at the end of the 18th century, the application of refrigeration has entered many fields. The application includes the preservation of food and medicine, air-conditioning for comfort and industrial processing (Donald and Nagengast, 1994).

Chlorofluorocarbons (CFCs) and hydrochloro-fluorocarbons (HCFCs) have many suitable properties, for example, nonflammability, low toxicity and material compatibility that have led to their common widespread use by both consumers and industries around the world, especially as refrigerants in air conditioning and refrigerating systems. Results from many researches show that this ozone layer is being depleted. The general consensus for the cause of this event is that free chlorine radicals remove ozone from the atmosphere, and later, chlorine atoms continue to convert more ozone to oxygen. The presence of chlorine in the stratosphere is the result of the migration of chlorine containing chemicals. The chlorofluorocarbons (CFCs) and hydrochloro-fluorocarbons (HCFCs) are a large class of chemicals that behave in this manner. (Radermacher and Kim, 1996, Akash and Said, 2003).

Since the discovery of the depletion of the earth's ozone layer caused mainly by CFC and HCFC and as a result of the 1992 United Nations Environment Program meeting, the phase out of CFC-11 and CFC-12, used mainly in conventional refrigeration and air conditioning equipment, was expected by 1996 (Lee and Su, 2002). The thermo physical properties of HFC-134a are very similar to those of CFC-12 and are also non-toxic environmentally safe refrigerant; the American Household Appliances Manufacturers have recommended HFC-134a as a potential replacement for CFC-12 in domestic refrigerators. However, while the ozone depletion potentials (ODPs) of HFC-134a relative to CFC-11 are very low ($<5.10^{-4}$), the global warming potentials (GWPs) are extremely high (GWP 1300) and also expensive. For this reason, the production and use of HFC-134a will be terminated in the near future (Tashtoush *et al.*, 2002, Sekhar *et al.*, 2005, Somchai and Nares, 2005).

Scientist and researcher are searching the environment benign refrigerant for the domestic refrigerator and freezer. Hydrocarbon especially propane, butane and isobutene are proposed as an environment benign refrigerant. Hydrocarbons are free from ozone depletion potential and have negligible global warming potential. Lee and Su (2002) conducted an

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M.A.Sattar, is with the University of Malaya, Kuala Lumpur Malaysia (corresponding author phone: 0060-162-481723; fax: +60379675317; e-mail: sattar106@ yahoo.com).

R. Saidur is with the Departent of Mechanical Engineering, University of Malaya, Kuala Lumpur Malaysia (e-mail: saidur@um.edu.my).

H.H. Masjuki is with the Departent of Mechanical Engineering, University of Malaya, Kuala Lumpur Malaysia (e-mail: masjuki@um.edu.my).

experiment study on the use of isobutene as refrigerant in domestic refrigerator. The performance was comparable with those of CFC-12 and HCFC-22 was used as refrigerant. Akash and Said (2003) studied the performance of LPG from local market (30%propane, 55% n-butane and 15% isobutene by mass) as an alternative refrigerant for CFC-12 in domestic refrigerator with masses of 50g, 80g and 100g. The result showed that a mass charge of 80g gave the best performance. Devotta *et al.,* (2001) selected HFC-134a, HC-290, R-407C, R-410A, and three blends of HFC-32, HFC-134a and HFC-125 and found that HFC-134a offers the highest COP, but its capacity is the lowest and requires much larger compressors. The characteristics of HC-290 are very close to those of HCFC-22, and compressors require very little modification. Therefore, HC-290 is a potential candidate provided the risk concerns are mitigated as had been accomplished for refrigerators. Sekhar *et al.,* (2004) investigated an experiment to retrofit a CFC12 system to eco-friendly system using of HCFC134a/HC290/HC600a without changing the mineral oil and found that the new mixture could reduce the energy consumption by 4 to 11% and improve the actual COP by 3 to 8% from that of CFC12. Sekhar *et al.,* (2005) also investigated refrigerant mixture of HCFC134a/HC in two low temperature system (domestic refrigerator and deep freezer) and two medium temperature system (vending machine and walk in cooler) and found that the HCFC134a/HC mixture that contains 9% HC blend (by weight) has better performance resulting in 10-30% and 5-15% less energy consumption (than CFC) in medium and low temperature system respectively.

Hydrocarbons (HCs) are an environmentally sound alternative for CFCs and HFCs. HCs as a refrigerant have been known and used since the beginning of this century. The development of the inert CFCs in the 1930s put the HC technology in the background. CFCs have been applied since then in numerous refrigeration equipments (United Nations Environment Programme, 1991). There is currently little information on the application of hydrocarbon as refrigerant in the refrigerator without modification of the components. In this experiment a domestic refrigerator designed to work with HFC-134a were investigated without modification. The experiments were conducted with pure Butane, Iso-butane, HFC-134a and the mixture of propane, butane and isobutene.

II. EXPERIMENTAL SETUP AND TEST PROCEDURE

This section provides a description of the facilities developed for conducting experimental work on a domestic refrigerator. The technique of charging and evacuation of the system is also discussed here. Experimental data collection was carried out at ECL (Energy Conservations Laboratory), Mechanical Engineering Department, University of Malaya (UM). The schematic diagram of the test unit and apparatus is shown in the Fig. 1.

A. Experimental Methodology

The temperature of the refrigerant inlet/outlet of each component of the refrigerator was measured with copper-constantan thermocouples (T type). The thermocouple sensors fitted at inlet and outlet of the compressor, condenser, and evaporator are shown in Fig. 1.

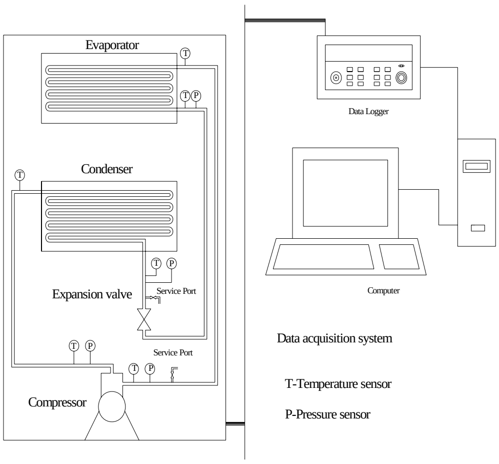

Fig. 1 Schematic diagram of the test unit and apparatus

Thermocouples/Temperature sensors were interfaced with a HP data logger via a PC through the GPIB cable for data storage. Temperature measurement is necessary to find out the enthalpy in and out of each component of the system to investigate the performance. The inlet and outlet pressure of refrigerant for each of the component is also necessary to find out their enthalpy at corresponding state. The pressure transducer was fitted at the inlet and outlet of the compressor and expansion valve as shown in Fig. 1.The pressure transducers were fitted with the T-joint and then brazed with the tube to measure the pressure at desired position. The range of the pressure transducer is -1 to + 39 bars. The pressure transducers have also been interfaced with computer via data logger to store data. A service port was installed at the inlet of expansion valve and compressor for charging and recovering the refrigerant. The location of the service port is shown in Fig. 1. The evacuation has also been carried out through this service port. A power meter was connected with compressor to measure the power and energy consumption.

B. System Evacuation

Moisture combines in varying degree with most of the commonly used refrigerants and reacts with the lubricating oil and with other materials in the system, producing highly corrosive compound. The resulting chemical reaction often produces pitting and other damage on the valves seals, bearing journal, cylinder wall and other polished surface of the system. It may cause the deterioration of the lubricating oil and the formation of sludge that can gum up valves, clog oil passages, score bearing surface and produce other effect that reduce the life of the system. Moisture in the system may exist in solution or as free water. Free water can freeze into the ice crystals inside the metering device and in the evaporator tubes of system that operate below the freezing point of the water. This reaction is called freeze up. When freeze up occurs, the formation of ice within the orifice of the metering device temporarily stops the flow of the liquid refrigerant (Dossat and Horan, 2002).

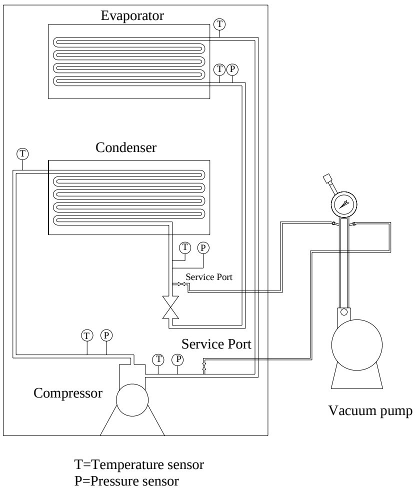

Fig. 2 Schematic diagram of the evacuation system

To get rid of the detrimental effect of moisture Yellow jacket 4cfm vacuum pump was used to evacuate the system. This supervac system evacuates the system fast and better which is deep enough to get rid of contaminant that could cause system failure. The evacuation system which is shown in the Fig. 2 consists of a vacuum pump, a pressure gauge and hoses. The hoses were connected with the service port to remove the moisture from the system as shown in the Fig. 2. When the pump is turned on the internal the pressure gauge shows the pressure inside the refrigerator system.

C. System Charging

Yellow jacket digital electronic charging scale has been used to charge HCs, their blends and HFC-134a into the system. This is an automatic digital charging system that can charge the desired amount accurately and automatically. The mechanism of the charging is shown in the Fig. 3.

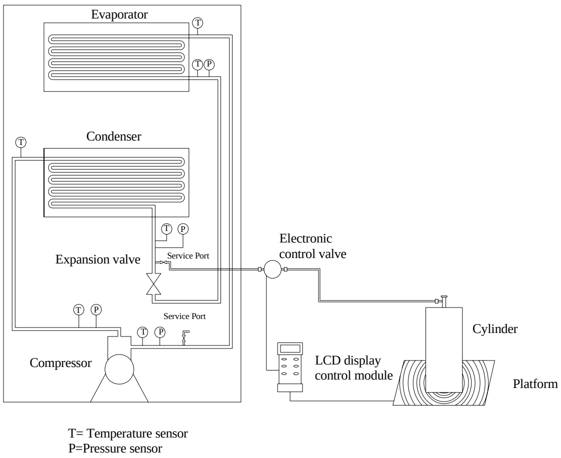

Fig. 3 Schematic diagram of the charging system

The charging system consists of a platform, an LCD, an electronic controlled valve and charging hose. The refrigerant cylinder was placed on the platform which measures the weight of the cylinder. The LCD displays the weight and also acts as a control panel. One charging hose was connected with the outlet of the cylinder and inlet of the electronic valve and another one was connected with the outlet of electronic valve and inlet of the service port. Using this charging system refrigerants were charged into the system according to desired amount.

D. Test Unit

The test unit was a Samsung refrigerator and designed to work with R-134a refrigerant. The refrigerator's performance with no load and closed door condition has been investigated. The specification of the refrigerator is shown in Table I.

TABLE I
TECHNICAL SPECIFICATIONS OF REFRIGERATOR FREEZER TEST UNIT

SPECIFICATIONS	
Freezer Capacity (liter)	80
Fresh Food Compartment Capacity (liter)	220
Power Rating (W)	160
Current rating (A)	0.9
Voltage (V)	220
Frequency (Hz)	50
No of door	2
Refrigerant type	134a(CF3CH2F)
Defrost system	Auto Defrost

E. Test Procedure

The system was evacuated with the help of vacuum pump to remove the moisture and charged with the help of charging system. The pressure transducers and thermocouples fitted with the system were connected with the data logger. The data logger was interfaced with the computer and software has been installed to operate the data logger from the computer and to store the data. The data logger was set to scan the data from the temperature sensor and pressure sensor at an interval of 15 minutes within 24 hours. A power meter was connected with the refrigerator and interfaced with the computer and power meter software was installed. The power meter stores the instantaneous power and cumulative energy consumption of the refrigerator at an interval of one minute within 24 hours in the computer. The pressures and temperatures of the refrigerants from the data logger were used to determine the enthalpy of the refrigerant with the help of REFPROP7 software. All equipments and test unit was installed inside the environment control chamber where the temperature and humidity was controlled. The dehumidifier has been used to maintain desired level of humidity at the control chamber. The unit can maintain humidity from 60% to 90% with an accuracy of ±5%. The humidity has been maintained at 60% RH for all experimental work. The temperature inside the chamber was maintained at 25°C and 28°C. When the temperature and humidity inside the chamber was at steady state, the experiments were started. The experiment has been conducted on the domestic refrigerator at no load and closed door conditions.

III. RESULTS AND DISCUSSIONS

The comparison of the performance parameter of the refrigerants and energy consumption by the refrigerator is discussed in this section. The comparison of energy consumption and performance is given below for each of the refrigerants.

A. Energy Consumption by the Compressor

The energy consumption by the compressor during 24 hours was measured and stored in computer. The test was carried out at 25°C and 28°C ambient temperatures. The refrigerator consumes more energy at 28°C ambient temperature than at 25°C ambient temperature for all refrigerants as shown in the Table II. The energy consumption by the refrigerator is presented in the Table II.

TABLE II
ENERGY CONSUMPTION BY COMPRESSOR AT 25°C AND 28°C AMBIENT TEMPERATURE

Refrigerant used	Room temperature, 25°C	Room temperature, 28°C
	Energy consumption, kWh/day	Energy consumption, kWh/day
HFC134a	2.077	2.254
Isobutane	2.131	2.183
Butane	2.197	2.199
M1	2.626	2.758
M2	2.515	2.579

The compressor consumes 2% and 3% less energy when Butane and Iso-butane was used than that of HFC-134a at 28°C as shown in the Table II. The compressor consumes 22% and 14% more energy than that of HFC-134a when mixture 1 and mixture 2 was used as refrigerant at 28°C.

B. Effect of Evaporator and Condenser Temperature on Co-efficient of Performance

The COP of the domestic refrigerator using R-134a as a refrigerant was considered as benchmark and the COP of butane, iso-butane and their blend were compared. The COP versus evaporator temperature is plotted at 25°C and 28°C ambient temperatures in the same graph. The results displayed in Figs. 4 and 5 show a progressive increase in COP as the evaporating temperature increases. The COP of the domestic refrigerator is plotted against condenser temperature of the refrigerator and shown in Figs. 6 and 7. The result displayed in Figs. 6 and 7 shows that COP increases as the temperature of the condenser decrease. The COP of the refrigerator when isobutene and butane was used is better than that of R-134a. This is because the enthalpy of the isobutene and butane is higher than that of the R-134a at same condition.

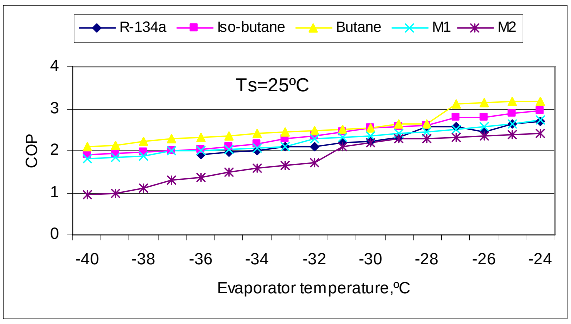

Fig. 4 Effect of evaporator temperature on COP at 25°C ambient temperature

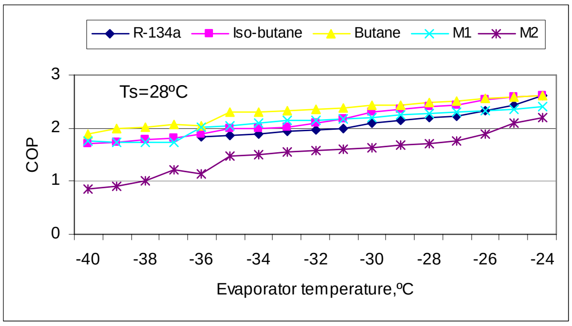

Fig. 5 Effect of evaporator temperature on COP at 28°C ambient temperature

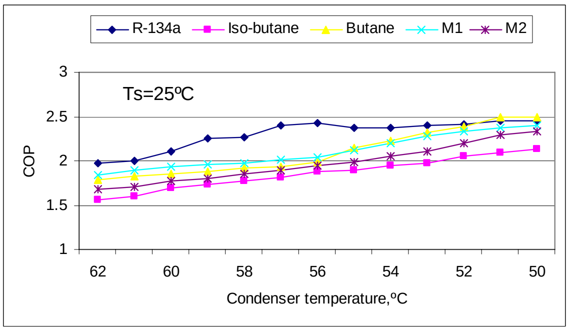

Fig. 6 Effect of condenser temperature on COP at 25°C ambient temperature

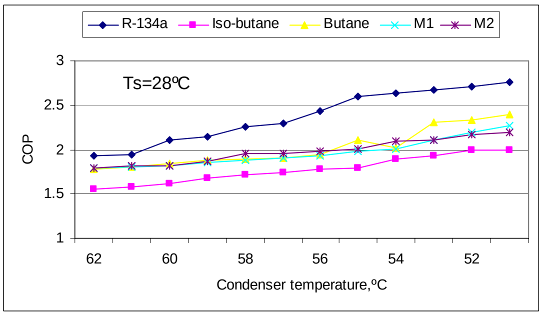

Fig. 7 Effect of condenser temperature on COP at 28°C ambient temperature

C. Effect of Evaporator Temperature on Refrigerating Effect and Compressor Work

The refrigerating effect is the main purposes of the refrigeration system. The liquid refrigerant at low pressure side enters the evaporator. As the liquid refrigerant passes through the evaporator coil, it continually absorbs heat through the coil walls, from the medium being cooled. During this, the refrigerant continues to boil and evaporate. Finally the entire refrigerants have evaporated and only vapor refrigerant remains in the evaporator coil. The liquid refrigerant still colder than the medium being cooled, therefore the vapor refrigerants continue to absorb heat. The refrigerating effect versus evaporator temperature is shown in Figs. 8 and 9. The Figures show that the refrigerating effect increases as the temperature of the evaporator decreases. The refrigerant effect when pure butane, isobutene and their blends were used is higher than that of R-134a because the enthalpy of the pure HCs and their blends are higher than that of HFC134a at same condition.

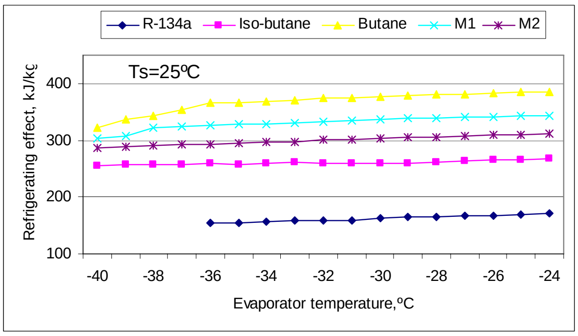

Fig. 8 Effect of evaporator temperature on refrigerating effect at 25°C ambient temperature

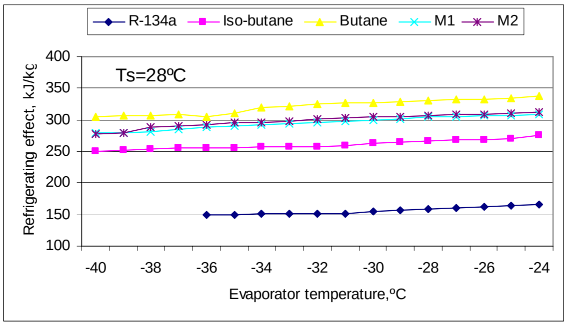

Fig. 9 Effect of evaporator temperature on refrigerating effect at 28°C ambient temperature

The evaporator temperature versus work of compression is shown in Figs. 10 and 11. The Figures show that the work of compression increases as the temperature of the evaporator decreases. This is due to the fact that when the temperature of the evaporator decreases the suction temperature also decreases. At low suction temperature, the vaporizing pressure is low and therefore the density of suction vapor entering the compressor is low. Hence the mass of refrigerant circulated through the compressor per unit time decreases with the decreases in suction temperature for a given piston displacement. The decreases in the mass of refrigerant circulated increases in work of compression. The work of compression when HCs and their blends are used is higher than that of R-134a as shown in Figs. 10 and 11.

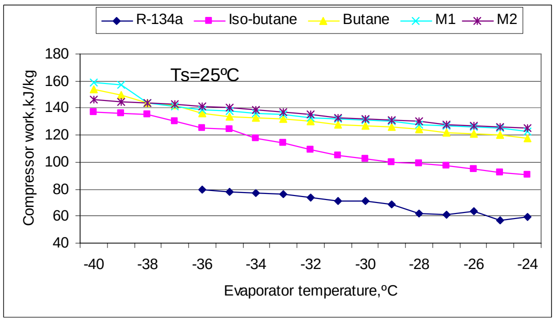

Fig. 10 Effect of evaporator temperature on compressor work at 25°C ambient temperature

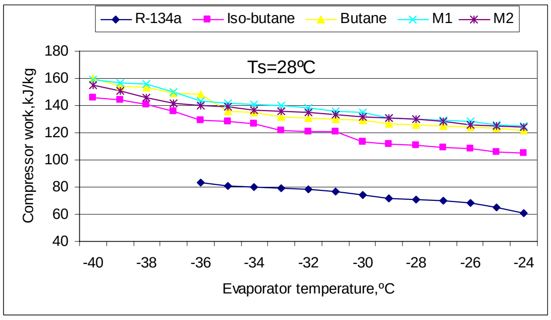

Fig. 11 Effect of evaporator temperature on compressor work at 28°C ambient temperature

D. Effect of Evaporator Temperature on Condenser Duty for Different Refrigerants

The evaporator temperature versus condenser duty is shown in Figs. 12 and 13. The Figures show that the condenser duty increases as the temperature of the evaporator decreases. As work of compression increases the heat added to the hot refrigerant during compression increases so the condenser requires more heat to remove. It is found from the Figs. 12 and 13 that the condenser duty when butane, isobutene and their blends were used is better then that of HFC-134a.

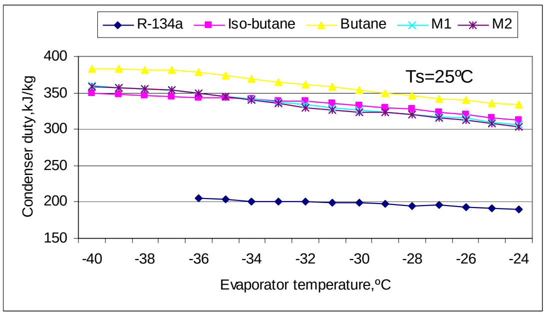

Fig. 12 Effect of evaporator temperature on condenser duty at 25°C ambient temperature

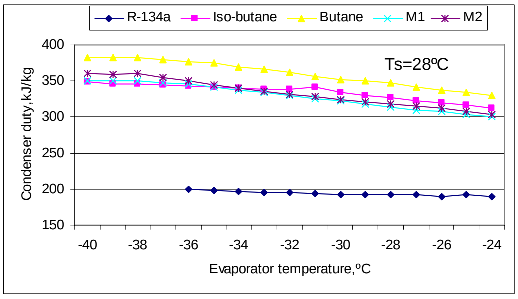

Fig. 13 Effect of evaporator temperature on condenser duty at 28°C ambient temperature

E. Heat Rejection Ratio for Different Refrigerant

The condenser must reject both the energy absorbed by the evaporator and the heat of compression added by the compressor. A term often used to relate the rate of heat flow at the condenser to that of the evaporator is the heat-rejection ratio. Heat rejection ratio at the condenser temperature is shown in Figs. 14 and 15. The heat rejection in the condenser depends on the refrigerating effect and the work done by the compressor. The hot vapor refrigerant consists of the heat absorbed by the evaporator and the heat of compression added by the mechanical energy of the compressor motor. It is found from Figs. 14 and 15 that the heat rejection ratio for butane, iso-butane and their blends is better than that of HFC-134a.

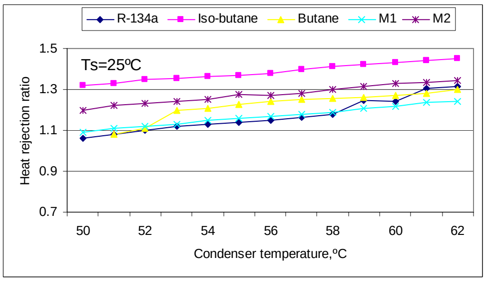

Fig. 14 Effect of condenser temperature on heat rejection ratio at 25°C ambient temperature

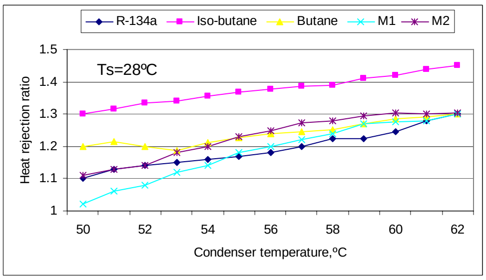

Fig. 15 Effect of condenser temperature on heat rejection ratio at 28°C ambient temperature

IV. CONCLUSION

This project invested an ozone friendly, energy efficient, user friendly, safe and cost-effective alternative refrigerant for HFC134a in domestic refrigeration systems. After the successful investigation on the performance of HCs and blends of HCs as refrigerants the following conclusions can be drawn based on the results obtained.

- The co-efficient of performance for the HCs and blends of HCs is comparable with the co-efficient of performance of HFC134a.
- The energy consumption of the pure HCs and blends of HCs is about similar to the energy consumption of refrigerator when HFC134a is used as refrigerant. The compressor consumes 2% and 3% less energy when Butane and Iso-butane was used than that of HFC-134a at 28°C ambient temperature.
- HCs and mixture of HCs offer lowest inlet refrigerant temperature of evaporator. So for the low temperature application HCs and blends of HCs is better than HFC-134a.
- The domestic refrigerator was charged with 140g of HFC134a and 70g of HCs and blends of HCs. This is an indication of better performance of HCs as refrigerants.
- The experiment was performed on the domestic refrigerator purchased from the market, the components of the refrigerator was not changed or modified. This indicates the possibility of using HCs as an alternative of HFc-134a in the existing refrigerator system.

Chemical and thermodynamics properties of hydrocarbon meet the requirement of a good refrigerant. Some standards allow the use HCs as refrigerant if small amount of refrigerant is used. The final conclusion is that butane and isobutene can be used in the existing refrigerator-freezer without modification of the components.

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