Experimental Investigation on the Performance of Domestic Refrigerator Using Isobutane and Mixture of Propane, Butane and Isobutene

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Abstract

This paper presents an experimental investigation on the performance of a domestic refrigerator using pure isobutane and mixture of propane, butane and isobutene as a refrigerant. The experiment was conducted with a refrigerator designed to work with HFC-134a under the same no load condition at a surrounding temperature of 25°C and 28°C. The refrigeration capacity, the compressor power, the coefficient of performance (COP), condenser duty and heat rejection ratio were investigated. The compressor consumes 2.08kWh/day and 2.25kWh/day when R-134a was used as refrigerant at 25°C and 28°C ambient temperature but when iso-butane was used it consumed 2.131kWh/day and 2.183kWh/day at same condition. Where as the compressor consumed 2.625kWh/day and 2.758kWh/day when mixture of 70% Propane, 25% Butane and 5% Iso-butane was used and 2.515kWh/day and 2.579kWh/day when mixture of 50% Propane, 40% Butane and 10% Iso-butane was used at 25°C and 28°C ambient temperatures respectively. It can be stated that the performance of iso-butane is comparable with the performance of the HFC134a. The result shows a better performance of iso-butane than HFC134a. The results support the possibility of using iso-butane as an alternative to HFC134a in domestic refrigerators without modification of the components.

1. Introduction

Stratospheric ozone absorbs the sun's high-energy ultraviolet rays and protects both humans and other living things from exposure to ultraviolet radiation. 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. These chemicals 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 [1,2].

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, is expected by 1996 and that of HCFCs is expected after 2030 [3]. Many corporations have been forced to find alternative chemicals to CFCs and HCFCs for the refrigeration system. 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 [4-6].

The use of natural fluids as refrigerant has attracted renewed interest during the last decades. Hydrocarbon belongs to this group of natural fluids. A number of hydrocarbons have suitable properties as refrigerant. Standards for the use of hydrocarbons have changed over the years, reflecting a change of view. Hydrocarbon refrigerant were accepted before the introduction of CFC and HCFC-fluids [7]. The short atmospheric live times of hydrocarbons take their GWPs close to zero. Moreover hydrocarbons provide zero ozone depletion potential, low toxicity, chemical stability, together with suitable thermodynamic, physical and chemical properties. The only disadvantage is that hydrocarbons are flammable if careless and unexpected leakage occurs. It is safer in smaller application [8].

The United Nations Environmental Program (UNEP) has carried out a program*" study into the possibility for the conversion of domestic and small commercial refrigeration appliances with refrigerants based on hydrocarbons".* Under this program SWISSCONTACT-SMEP has carried out the Survey in Indonesia and Costa Rica. The list of the price of hydrocarbon and other refrigerant as obtained by the SWISSCONTACT-SMEP is given in Table 1.

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Table 1 Price of the refrigerants

Refrigerant	Price in Indonesia (US$/kg)	Price in Costa Rica US$/kg)
CFC12	11	2.51-4.72
R11	7.76	**N/A**
HFC R134a	30.17	16.1
LPG	1.72	0.51
HC	13 - 21	6.24
Propane	7 - 25	**N/A**

(Source: United Nations Environment Program, 1991)

So from the above information it is evident that the price of hydrocarbon is less than the price of HFC and CFC (United Nations Environment Program, 1991).

This experiment has investigated the performance of refrigerator using hydrocarbon as refrigerant. A refrigerator designed to work with R-134a is retrofitted with pure iso-butane and mixture of propane, n-butane and iso-butane. The component of the domestic refrigerator remains unchanged during this experiment. The co-efficient of performance, power consumption of the compressor etc were investigated. The performance of the refrigerator using R-143a is considered as a baseline and then the performance of the refrigerator using Hydrocarbon and their mixture is compared.

2. Experimental setup and test procedure

This section provides a description of the facilities developed for conducting experimental test on a 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), ME, UM. The schematic diagram of the test unit and apparatus is shown in Figure 1.

2.1. Experimental setup and apparatus

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 Figure 1. Thermocouples/Temperature sensors were interfaced with a HP data logger via a PC through the GPIB cable for data storage. Temperature is necessary to find out the enthalpy in and out of each component of the system to investigate the performance.

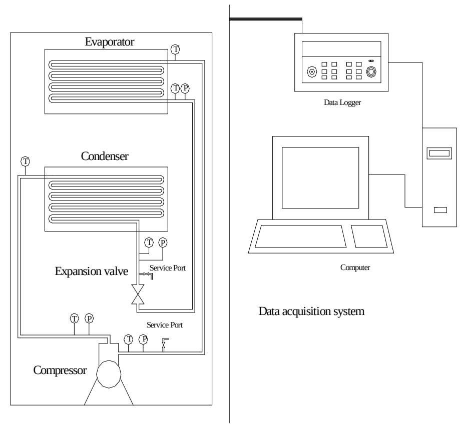

Figure 1 Schematic diagram of the test unit and apparatus

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 Figure 1. The pressure transducer is fitted with the T-joint and then brazed with the tube to measure the pressure at desired position as mentioned before. 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 is installed at the inlet of expansion valve and compressor for charging and recovering the refrigerant. The location of the service port is shown in Figure 1 as well. 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.

2.1.1. System evacuation

Moisture combines in varying degree with most of the commonly used refrigerants. This moisture 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.

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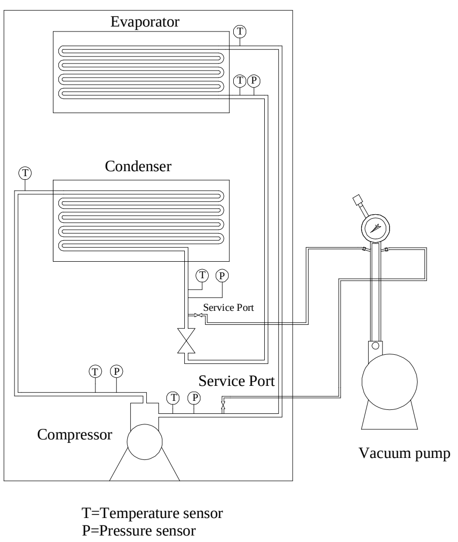

Figure 2 Schematic diagram of the evacuation system

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 Figure 2 consists of a vacuum pump, a pressure gauge and hoses. The hoses are connected with the service port as shown in the Figure 2 to remove the moisture from the system. When the pump is turned on the internal the pressure gauge shows the pressure inside the refrigerator system.

2.1.2 System charging

Yellow jacket digital electronic charging scale has been used to charge the system. This is an automatic digital charging system that can charge the desired amount accurately. The mechanism of the charging is shown in the Figure 3.

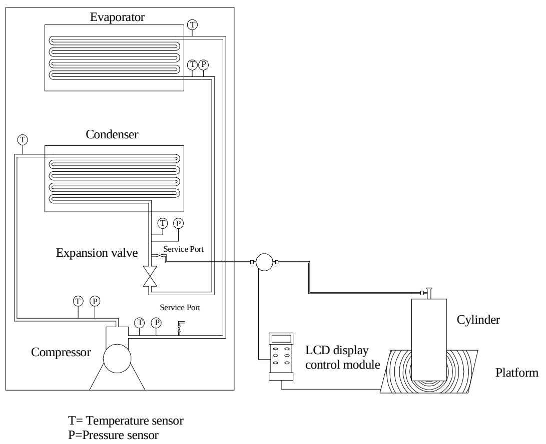

Figure 3 Schematic diagram of the charging system

The charging system consists of a platform, an LCD, an electronic controlled valve and charging hose. The refrigerant cylinder is 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 is connected with the outlet of the cylinder and inlet of the electronic valve and another one is connected with the outlet of electronic valve and inlet of the service port. Using this charging system, the refrigerant is charged into the system according to desired amount.

2.1.3. Test unit

The test unit is 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 refrigerator is fitted with the thermocouple and pressure transducers as shown in Figure 1. The specification of the refrigerator is shown in Table 2.

Table 2 Technical specifications of refrigerator freezer test unit

Specifications	**Values**
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

2. 2. Test procedure

The system was evacuated with the help of vacuum pump to remove the moisture. The system was charged with the help of charging system. The pressure transducers and thermocouples 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. The output of these sensors was stored in the computer. The data logger was set to scan the data from the temperature sensor and

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pressure sensor at an interval of 15 minutes within 24 hours. A power meter was connected with the refrigerator and interfaced with the computer. Power meter software was installed in the computer to operate from the computer. The power meter stores the power consumption of the refrigerator at an interval of one minute. The power consumption of the refrigerator within 24 hours was stored in the computer. The pressures and temperatures from the data logger was used to determine the enthalpy of the refrigerant. REFPROP7 software was used to find the enthalpy of the refrigerant. All equipment and test unit was placed inside the environment control chamber. The temperature and humidity inside the chamber 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 work. The temperature inside the chamber is 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.

3. Results and discussions

This chapter covers the discussion and comparison of the result of the refrigerant used in this experiment. The comparison of power consumption, performance is given below for each of the refrigerant used in this experiment.

3.1. Energy consumption by the compressor when different refrigerants were used.

The total energy consumption of all refrigerants is presented in Table 3. It has been found that the refrigerator consumes more energy at 28°C ambient temperature than at 25°C ambient temperature for all refrigerants. The compressor consumes more energy when blends of hydrocarbons were used. The comparison of energy consumption is made considering the HFC-134a as benchmark and presented in the last two columns of Table 3. The negative and positive sign indicates the decrease and increase of energy consumption from the benchmark respectively. From the Table 3 it is obvious that the energy consumption of the HC refrigerants is more or less same as that of HFC-134a.

Table 3 Energy consumption by compressor at 25°C and 28°C ambient temperature.

Refrigerant used	Energy consumption, kWh/day		Percentage fluctuations	
	Room temp., 25°C	Room temp. 28°C	Room temp. 25°C	Room temp. 28°C
HFC134a	2.077	2.254		
Isobutane	2.131	2.183	+2.53	-3.25
M1	2.626	2.758	+20.90	+18.27
M2	2.515	2.579	+17.41	+12.60

(The positive and negative sign indicates the increase and decrease of energy consumption from the base case)

From the Table 3 it is evident that the energy consumption of the compressor at 28 °C is always higher than that of at 25°C. Conduction heat transfer plays an important role of electricity consumption in refrigerator. Saidur *et. al*., [10] mentioned that most of the thermal load on a refrigerator is conduction through the refrigerator wall. ASHRAE [11] shows that about 60–70% of the total refrigerator load comes by conduction through the cabinet walls. This conduction load is proportional to the difference between the ambient temperature and the internal compartment/freezer temperature. The higher the difference, the higher is the load imposed on a refrigerator. For this reason, the temperature of air around a refrigerator is a significant determinant of energy consumption. Since compressor efficiency also declines as the ambient temperature rises, a refrigerator’s electricity use is very sensitive to the ambient temperature. Saidur *et. al*., [10] found that energy consumption increases 47Wh for Model E and 53 Wh for Model S for each degree increase in room temperature. Meier *et al*., [12] showed that energy consumption increased 120 Wh for each degree increase in temperature. Here in this experiment the compressor consumes 8%, 3%, 5% and 4% more energy at 28°C than at 25°C when R-134a, Iso-butane, M1, and M2 was used respectively.

3.2. Effect of evaporator temperature on co-efficient of performance

The COP of the domestic refrigerator using R-134a as a refrigerant is calculated to compare with other refrigerant used in this experiment. The COP is plotted against inlet refrigerant temperature of the evaporator. The COP against inlet refrigerant temperature of the evaporator is plotted at 25°C and 28°C ambient temperatures in the same graph. The result displayed in Figures 4 and 5, shows a progressive increase as the evaporating temperature increases. The COP is the ratio of the refrigerating effect to the compressor work. The refrigerating effect decreases with the decreases of evaporating temperature where as the compressor duty increases with the decreases of evaporating temperature. Therefore, the COP decreases with the decreases of evaporating temperature. The COP at 25°C is slightly higher than that at 28°C for all refrigerants. This is due to the fact that the compressor efficiency decreases with the increase of ambient temperature [10] which ultimately affects the co-efficient of performance.

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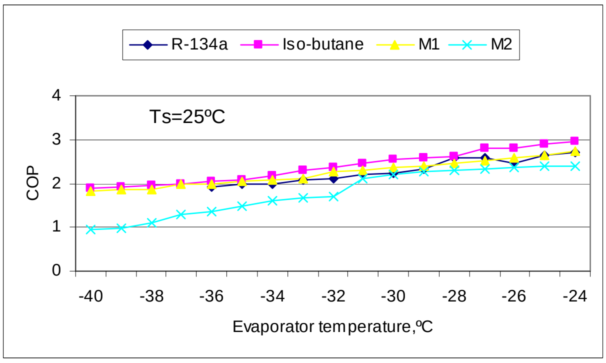

Figure 4 Effect of inlet refrigerant on co-efficient of performance

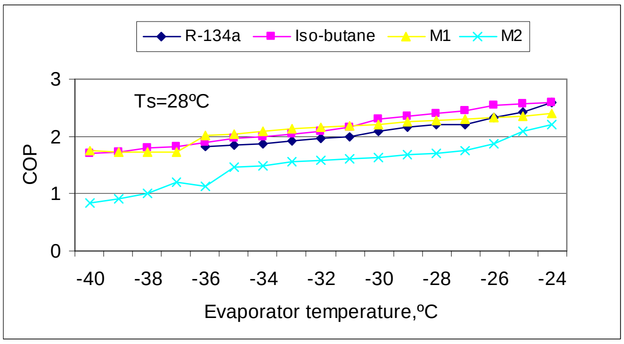

Figure 5 Effect of inlet refrigerant on co-efficient of performance

3.3. Effect of evaporator temperature on refrigerating effect and work of compression.

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 vapour refrigerant remains in the evaporator coil. The liquid refrigerant still colder than the medium being cooled, therefore the vapor refrigerant continues to absorb heat. The refrigerating effect is difference of the enthalpy of inlet and outlet refrigerant of the evaporator. The refrigerating effect and inlet refrigerant temperature is shown in Figures 6-7. From the Figures it is evident that the refrigerating effect increases with the increases of evaporating temperature. This can be explained that if the evaporating temperature increases the heat transfer between the refrigerant entered into the evaporator tubes and the medium being cooled also increases which ultimately increase the refrigerating effect.

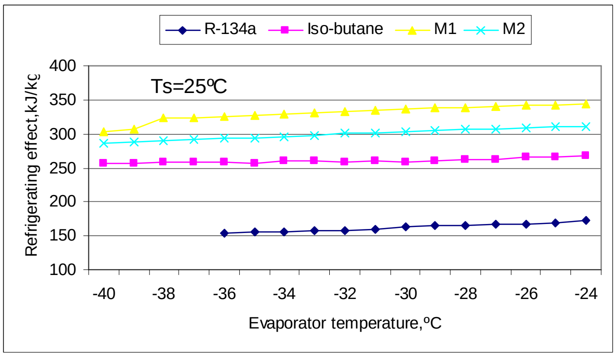

Figure 6 refrigerating effect versus inlet evaporator temperature

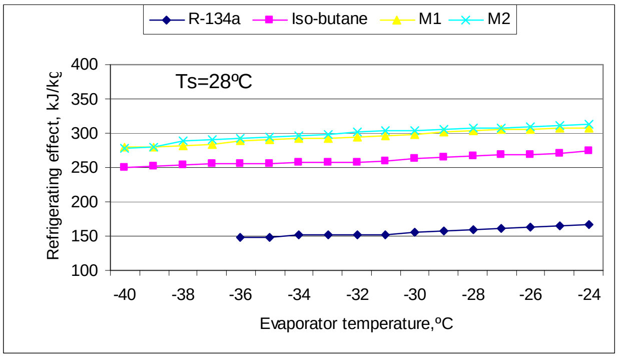

Figure 7 refrigerating effect versus inlet evaporator temperature

The refrigerant effect when pure butane, isobutene and their blends are used is higher than R-134a because the value of enthalpy of the pure HCs and their blend are higher than that of HFC134a.

A refrigerant compressor compresses the vapor refrigerant from the evaporator and raises its pressure so that the corresponding saturation temperature is higher than that of the cooling medium. The work of compression is the difference of the enthalpy of inlet and outlet refrigerant. The work of compression and inlet refrigerant temperature is shown in Figures 8-9. 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.

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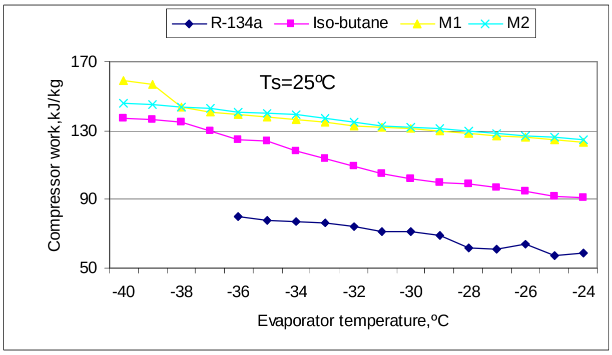

Figure 8 effect of evaporator temperature on work of compression for R-134a

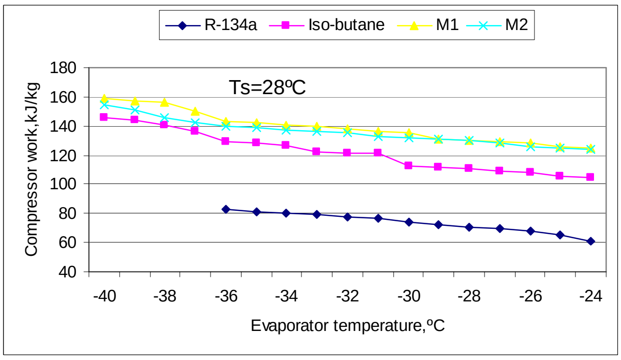

Figure 9 effect of evaporator temperature on work of compression for R-134a

The work of compression when HCs and their blends are used is higher than that of R-134a as shown in Figure 8-9.

3.4. Effect of evaporator temperature on condenser duty

The function of the condenser is to remove heat of the hot vapor refrigerant discharged from the compressor. Heat is added to the hot refrigerant during evaporation in the evaporator and by the compressor during work of compression. The heat from the hot refrigerant is removed by transferring heat to the wall of thee condenser tubes and then from the tubes to the condensing medium. The condenser duty and evaporator temperature is sown in Figures 10-11. The Figure show that the condenser duty increases as the temperature of the evaporator decreases. If the temperature of the evaporator decreases the work of compression increases that is explained in the previous section. As work of compression increases the heat added to the hot refrigerant during compression increases so the condenser requires more heat to remove.

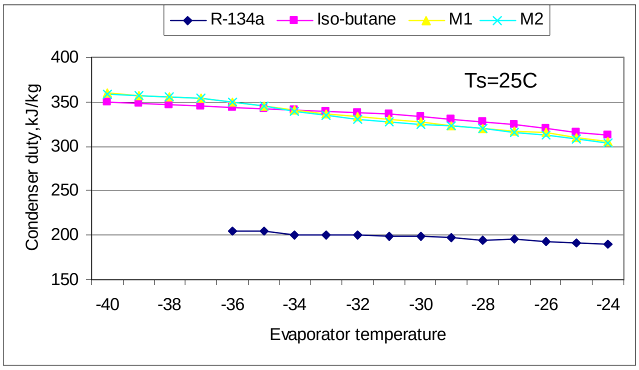

Figure 10 effect of evaporator temperature on condenser duty

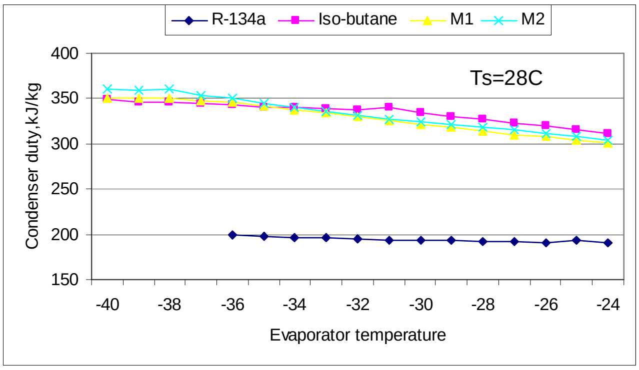

Figure 11 effect of evaporator temperature on condenser duty

3.5. 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 pf the evaporator is the heat-rejection ratio. Heat rejection ratio at the condenser temperature is shown in Figures 12-13.

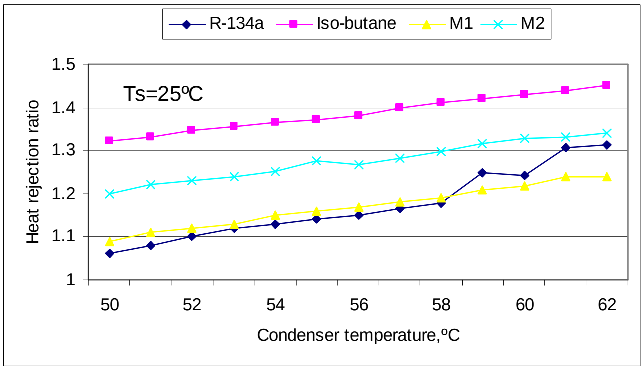

Figure 12 Heat rejection ratio at different condensing temperature

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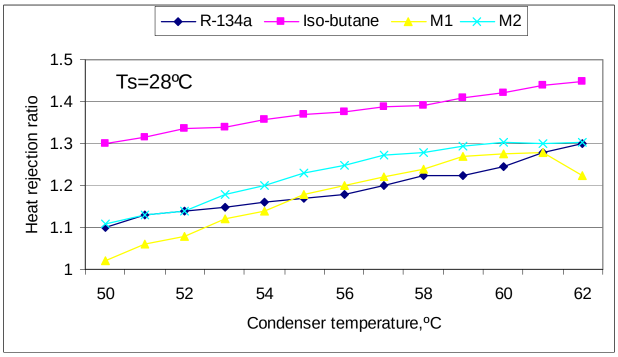

Figure 13 Heat rejection ratio at different condensing temperature

The heat rejection in the condenser depends on the refrigerating effect and the work done by the compressor. The condenser removes the heat of the hot vapor refrigerant discharged from 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.

4. Conclusions

This project investigated an ozone friendly, energy efficient, user friendly, safe and cost-effective alternative refrigerant for HFC134a in domestic refrigeration systems. A domestic refrigerator was used as a test unit to investigate experimentally the possibility of using HC as refrigerant. After the successful investigation on the performance of HC as refrigerant the following conclusion can be drawn based on the result obtained.

- The co-efficient of performance for the HC and blend of HCs is comparable with the co-efficient of performance of HFC134a.
- The energy consumption of the pure HC and blends of HCs is about similar to that of HFC134a.
- HCs and mixture of HCs offer lowest inlet refrigerant temperature of evaporator. So for the low temperature application HC and blend of HCs is better than HFC134a.
- The domestic refrigerator was charged with 140gm of HFC134a where as 70gms of HCs and blend of HCs was used to carry out the experiment. This is an indication of better performance of the HC as refrigerant.
- 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 in the existing refrigerator system without modification of the components.

The use of Hydrocarbon as refrigerant already started in some European countries. Their chemical and thermodynamics properties meet the requirement of a good refrigerant except flammability. Hydrocarbons are environmentally friendly. They have zero Ozone Depletion Potential (ODP) and negligible Global Warming Potential (GWP). Hydrocarbon is cheaper than the R-134a which is being used in the refrigerator at present. Hydrocarbon is also easily available. Some standards allow the use HC as refrigerant if small amount of refrigerant is used. So there is no alternative way but to use the HC as refrigerant mitigating the adverse effect of HC.

Acknowledgements

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