Performance and energy saving analysis of a refrigerator using hydrocarbon mixture (HC-R134a) as working fluid

M N Mohtar\textsuperscript{1}, H Nasution\textsuperscript{2} and A A Aziz\textsuperscript{2}
\textsuperscript{1}Department of Mechanical Engineering Faculty, Faculty of Mechanical Engineering Universiti Teknologi Malaysia, Skudai, 81310 Johor Bahru, Johor, Malaysia
\textsuperscript{2}Automotive Development Centre, Universiti Teknologi Malaysia, Skudai, 81310 Johor Bahru, Johor, Malaysia

E-mail: henry@fkm.utm.my

Abstract. The use of hydrocarbon mixture as a working fluid in a refrigerator system is rarely explored. Almost all domestic refrigerators use hydrofluorocarbon R134a (HFC-R134a) as refrigerants. In this study, hydrocarbon gas (HC-R134a) is used as the alternative refrigerant to replace HFC-R134a. It has a composition of R290 (56\%), R600a (54.39\%) and additive (0.1\%wt) blended for the trials. The experiments were conducted with 105 g and 52.5 g refrigerant mass charge, subjected to internal heat load of 0, 1, 2, 3 and 4 kg respectively. The study investigates the coefficient of performance of the refrigerator (COPR) and energy consumption. The results show that the use of HC-R134a as the replaceable refrigerant can save energy ranging from 2.04\% to 7.09\%, as compared to the conventional HFC-R134a refrigerant. Naturally, the COPR improvement and temperature distribution using HC-R134a are much better than HFC-R134a

1. Introduction
The refrigerator releasing to the environment will eventually have an impact on the ozone depletion and indirectly enhances global warming. Montreal Protocol [1] was formed in 1987 with the purpose to phase-out the use of CFCs and the formulation of new environmentally-friendly. The importance of the stratospheric ozone layer is to absorb ultraviolet radiation produced by the sun and to protect human and other living creatures from this exposure [2]. Kyoto Protocol [3] comes into existence in 1997 to gather efforts to curb greenhouse warming. One of the objectives of this protocol is the requirement to phase out all substances that promote greenhouse warming such as HFCs. Over several decades there were global consensus and effort expedited to promote awareness on this global warming issue and to strategize ways to formulate solutions.

Hydrocarbon mixture is the combination of two or more hydrocarbon refrigerants by blending. Hydrocarbon mixture can be categorized in two i.e. azeotrope and zeotrope. Azeotrope can be defined as a stable mixture of refrigerants and its vapour and liquid phase retain identical compositions over a wide-range temperature [4]. Basically, azeotropic refrigerant mixtures blended from two or more refrigerants with similar boiling points respectively. Zeotrope or non azeotrope phase change process is non-isothermal, and the composition does not remain constant due to temperature lead and composition shift [5]. Non azeotrope refrigerant mixtures (NARMs) consist of two or more refrigerants with different boiling points for each refrigerant.
A sample of the hydrocarbon mixture was provided for to the researchers by a local chemical company for trial. The hydrocarbon mixture is an alternative drop-in for HFC-R134a and R12 with a code name OS-12a and is also referred as HC-R134a [6]. The mixture is a non-zeotrope refrigerant mixture (NARMs), since R290 present in the mixture is of lower boiling point, the other constituent, iso-butane (R600a), is of higher boiling point. In addition, R290 is having higher pressure and smaller suction vapour volume, whereas R600a is of lower pressure and high suction vapour volume [7]. The percentage of hydrocarbon mixture is 56% of Propane, 54.39% of isobutane and 0.1%wt of additive. The primary objective of this study is to investigate the performance of a refrigerator on an instrumented test rig as well as energy consumption using the prescribed hydrocarbon as working fluid. A refrigerator for trial has a volume capacity of 153 litres.

2. Experimental setup

2.1. Test rig design

Figure 1 shows the positions of the power meter, flow meter and pressure gauge setup. The refrigerant will flow from the condenser at high pressure and temperature. The flow meter is installed between the condenser and a drier to measure the mass flow rate of refrigerant which also circulate in whole of the refrigeration system. The refrigerant will pass through the evaporator to the compressor and will be at low pressure and temperature. The pressure line in the evaporator pressure is located between the evaporator and compressor tubing and is installed the low-pressure gauge at that region. As obvious, the refrigerant will be at high pressure and temperature between compressor and condenser. The components installed are fitted with pressure gauges at the respective locations. Power meter is installed just before the refrigerator for input power measurement. Figure 2 shows the eight points in which the temperatures are monitored in the refrigeration circuit.

![Figure 1. Monitoring panels fitted onto the experimental set-up.](image-url)
2.2. Mass charging of the alternative refrigerant

The information gathered from the supplier, indicated that the mass charge of HC-R134a (OS-12) is only half of that of HFC-R134a. Although, the mass charge is half, its pressure is almost similar to that produced by HFC-R134a when subjected to similar working conditions. Thus for the experiment undertaken the quantity of the mass charge for HFC-R124a is 105g meanwhile mass charging for HC-R134a is 52.5g. Figure 3 illustrates the technique of charging the refrigerants into the refrigeration circuit.

![Figure 2. Temperature probes fitted onto the refrigerator during trials.](image)

**Figure 2.** Temperature probes fitted onto the refrigerator during trials.

![Figure 3. Refrigerant being charged into the refrigerator.](image)

**Figure 3.** Refrigerant being charged into the refrigerator.
2.3. Experiment procedures
Table 1 is the manipulated variables for the COPR and energy consumption meanwhile the constant variables for these experiments are thermostat setting, mass of refrigerant and duration of experiment. The load being used in this study is water. For the thermostat, it should be set at 3 for both experiments.

| Parameter | Range of variation |
|-----------|--------------------|
| Type of refrigerant | HFC-R134a with mass charging 105.9 g |
| | HC-R134a with mass charging 52.5 g |
| Mass of water as load for COPR experiment | 0 kg, 1 kg, 2 kg |
| Mass of water for energy consumption experiment | 0 kg, 1 kg 2 kg, 3 kg, 4 kg |

3. Performance and energy analysis

3.1. Coefficient of performance for refrigerator
The efficiency of a refrigerator is expressed in terms of its coefficient of performance, denoted by COPR [8]. Equation (1) is COPR equation for a typical refrigerator.

\[
\text{COPR} = \frac{h_2 - h_4}{h_2 - h_1} = \frac{Q_L}{W_{\text{net, in}}}
\]

where:

- \(Q_L\) is latent heat or cooling capacity (kJ/kg),
- \(W_{\text{net, in}}\) is compressor work net (kJ/kg),
- \(h_1\) is enthalpy at after expansion valve (kJ/kg)
- \(h_2\) is enthalpy at after compressor (kJ/kg) and
- \(h_4\) is enthalpy at after condenser (kJ/kg). The higher the value to more efficient the refrigerator becomes.

3.2. Energy Consumption
Basically, the energy consumed by refrigerator is measured by the power meter. Eq. 2 is the energy consumption equation used when the refrigerator is tested for 24 hours.

\[
\text{Power per day (kWh/day)} = \text{Final power reading} - \text{Initial power reading}
\]

3.3. Energy Saving
The compressor work basically the current supply consumed and is to operate the refrigerator for cooling the freezer and food compartment. The type of refrigerant will also has an effect on the energy consumed by the compressor as well as the energy saving which can be gained. Eq. 3 is the energy saving formula in calculating the energy saving.

\[
\text{Energy saving} = \frac{\text{Energy by HFC} - \text{Energy by HC}}{\text{Energy by HFC}} \times 100\%
\]
4. Result and discussion

4.1. Coefficient of performance for refrigerator (COPₚ)

Figure 4 shows the trend of COPR for each load which is generally dissimilar, and they do not look linear. At load 0 kg (refer Figure 4a), the COPR of HFC-R134a dramatically dropped from 3.06 to 2.20 and then gradually touches 1.83. Meanwhile the COPR for HC-R134a gradually drop from 2.7 to 1.80. In the freezer food compartment, there is only air present and it has a small heat capacity as there is no load. HFC-R134a at -2°C seems quite high to absorb heat from the freezer and food compartment which is the latent heat, Qₐ. However the compressor work input, Wₚₑₙ, is in the lowest at beginning of the cooling process. 

At load 1 kg, the distances between two lines are afar, when evaporator temperature is from -2°C to -14°C. The gap will get closer when the evaporator temperature is from -16°C to -20°C. When the evaporator temperature is at -14°C, the COPR of HFC-R134a dropped dramatically from 2.11 to 1.98. At load 2 kg, the evaporator temperature is from -2°C to -6°C, while the distance between two lines (of these refrigerants) is quite afar where the evaporator temperature is from -8°C to -12°C, i.e. the distance is too close to each other. When evaporator temperature at -14°C, these two lines will start to drift for a steady length until -20°C. However, for all loads tested, it shows that the COPR of HC-R134a is higher than the COPR of HFC-R134a.

4.2. Temperature distribution in the freezer

Figure 5 shows the temperature distribution against time. It shows that when a freezer is in the HC-R134a mode, the temperature distribution is quite similar to that of HFC-R134a for all loads. At 0 kg, HC-R134a has the tendency to generate the lower of the two temperatures which is at -8.88°C compared with HFC-R134a is -8.22°C. At 1 kg, the lowest temperature is at -9.72°C when in HC-R134a mode as compared to HFC-R134a mode, which generate -9.58°C. At 2 kg, the lowest temperature produced by HC-R134 is -5.88°C but the lower of the two is by HFC-R134a, which is -8.12°C. When the compressor influence in the temperature drop of the freezer, obtained that the compressor stop early at minute 47, 86 and 76 when using HC- R134a at 0 kg, 1 kg and 2 kg respectively compared using HFC-R134a. Besides that, HC-R134a recorded higher number of compressor fluctuation (on/off) with 4, 2 and 3 cycles at 0 kg, 1 kg and 2 kg respectively, as compared to HFC-R134a. At load 0 kg, the compressor stopped early i.e. at the 56th minute and yielded two fluctuation of compressor (on/off) which is at 1 kg and 2 kg load settings. The compressor will continue to influence in the freezer temperature until 120th minute, when using HFC-R134a without any cyclic variation of the compressor (on/off).

4.3. Power Consumption by Load Quantity Effect

The energy consumption increased proportionally to the mass flow rate of water, as much of the energy needed by the compressor is rejected as latent heat, Qₐ from the mass flow rate of the refrigerant. Figure 6 shows that on the basis of the load quantity effect, HFC-R134a demonstrate higher energy consumption than HC-R134a for all of the water mass flow rate. Table 2 on the other hand shows the result of energy saving for HC-R134a with varying mass of water in the freezer on a daily basis.

| Mass of water (kg) | 0    | 1    | 2    | 3    | 4    |
|-------------------|------|------|------|------|------|
| Energy saving (%) per day | 7.09 | 3.05 | 4.44 | 5.52 | 2.04 |
Figure 4. COP against evaporator temperature with varying load.

From table 2, the highest energy saving that can be achieved is 5.52 percent per day when the mass of water in the freezer is 3 kg. However, the energy saving can be considered to fluctuate from 2.04 percent to 7.09 percent per day to measure for one-unit refrigerator. In general, using HC-R134a as refrigerant can save energy of a domestic refrigerator ranging from 2.04 percent (at 4 kg of water as load) up to 7.09 percent (zero load) per day while the timing of the compressor is set to on/off mode.
5. Conclusion
Based on the experimental investigation, the hydrocarbon mixture of HC-R134a has shown to improve COPR when used in a typical domestic refrigerator at ambient condition. The improved COPR for the refrigerator can be interpreted as utilizing minimum energy by the compressor yet yielding maximum latent heat, $Q_L$ which the heat is rejected thus lowering the freezer and food compartment temperatures. The hydrocarbon mixture, HC-R134a can be considered as one of the many solutions in overcoming this problem, as it has shown to save energy consumption by as much as 2 to 7 percent, from high to low load. Hydrocarbon mixture of HC-R134a can be an alternative refrigerant to replace the existing HFC-R134a in domestic refrigerator units.

Acknowledgements
The research work is supported partially by the Knowledge Transfer Program (KTP), Vote No. R.J130000.7809.4L509 and the Automotive Development Centre (ADC), Universiti Teknologi Malaysia (UTM). The assistance of the technicians involved, their guidance and assistance are gratefully acknowledged.
References

[1] Montreal Protocol. Montreal protocol on substances that deplete the ozone layer. 1987.

[2] Wongwises S, Chimres N 2005 Energy conversion and management 46 85-100

[3] Breidenich C, Magraw D, Rowley A, Rubin J W 1998 American Journal of International Law 315-31

[4] Khurmi R S, Gupta J K 2005 A textbook of Refrigeration and Air Conditioning Eurasia Publishing House)

[5] Rajapaksha L 2007 Energy conversion and Management 48 539-45

[6] Dahlan A A 2012 Fakultei Kejuruteraan Mekanikal: UTM – Malaysia

[7] Arora C P 2003 Refrigeration and Air Conditioning (New Delhi: Tata McGraw-Hill Publishing Company)

[8] Cengel Y A, Boles M A, Thermodynamics, An Engineering Approach Sixth Edition (SI Units). Mc Graw Hill, Singapore; 2007.