PERFORMANCE ANALYSIS OF A RETROFITTED REFRIGERATOR USING ECO-FRIENDLY REFRIGERANT

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ABSTRACT

The use of refrigerants with a global warming potential (GWP) greater than 150 is banned in small and medium-sized refrigerators in accordance with the European F-Gas policy. Therefore, the suitability of retrofitting an existing refrigerator using a low GWP working fluid (R152a), as a replacement for the usual refrigerant (R134a) that is harmful to the environment, was investigated experimentally in this paper. In this study, close trend and similarities have been observed between the retrofit refrigerant (R152a) and the traditional refrigerant (R134a) in terms of their thermophysical properties. This has shown the compatibility of R152a with the components of the existing refrigerator. The two refrigerants met the pull-down time standard for the refrigerator, but the values of R152a were consistently lower than those of R134a. In addition, R152a consumed less energy with higher coefficient of performance and cooling capacity (12.2 and 14.6 %, respectively) than R134a. Due to the superior performance and the eco-friendly properties of R152a, it is recommended as a retrofit refrigerant for the existing small and medium-sized refrigerators.

Keywords: *eco-friendly refrigerant, refrigerator, F-Gas Policy, low-GWP, R152a, retrofitting*

Abbreviations

CFC - Chlorofluorocarbon
CO_2 - Carbon dioxide
COP - Coefficient of performance
CPP - Critical point pressure (kPa)
CPT - Critical point temperature (°C)
EU F-Gas - Fluorinated-Gas
EU - European Union
GHG - Greenhouse gas
GWP - Global warming potential
h - Enthalpy (kJ/kg)
h_1 - Specific enthalpy of the refrigerant at the compressor inlet (kJ/kg)
h_2 - Specific enthalpy of the refrigerant at the compressor outlet (kJ/kg)
h_3 - Specific enthalpy of the refrigerant at the condenser outlet (kJ/kg)
h_4 - Specific enthalpy of the refrigerant at the evaporator inlet (kJ/kg)
HCFC - Hydro-chlorofluorocarbon
HFC - Hydrofluorocarbon

ODP - Ozone depletion potential
ODS – Ozone-depleting substances
P - Pressure (kPa)
P_{actual} - Actual power consumption of compressor (kW)
P_{input} - Input power to compressor (kW)
R134a - 1,1,1,2-Tetrafluoroethane
R152a - 1,1-Difluoroethane
$\dot{m}$ - Mass flow rate of refrigerant (kg/s)
η_{comp} - Compressor efficiency

INTRODUCTION

Global warming is currently the most pressing environmental issue facing the world since ozone-depleting substances were phased out under the Montreal Protocol, and studies have revealed that the ozone hole has healed significantly [1 - 3]. Ozone-depleting substances (ODS) are grouped into classes. Class I is the group of chemicals with ozone depletion potential (ODP) greater than or equal to 0.2. This class mainly consists of chlorofluorocarbon (CFC) refrigerants, which have been completely banned for use globally since January 1, 2010 [4, 5]. Class II is the group of chemicals with ODP less than 0.2, which consists of hydrochlorofluorocarbons (HCFCs) refrigerants. As a result of the Montreal Protocol regulations, this group of halocarbon refrigerants has been phased out with usage reduction of 90.0 and 99.5 % in 2015 and 2020, respectively and will be fully phased out globally by 2030 [6].

The greenhouse effect is the main cause of global warming, and it is generated by increasing emission of greenhouse gases (GHGs) attributable to human activities. As the concentration of GHGs in the atmosphere rises, the amount of absorbed infrared radiation rises, resulting in long-term climate changes [7 - 9]. The global warming potential (GWP) is a metric that compares the amount of infrared radiation absorbed by a refrigerant to the effect of carbon dioxide, which has a GWP of 1 [10, 11]. As a result of the adoption of the Montreal Protocol's regulations banning the use of ODS, climate change or global warming became a serious environmental concern. This occurred as a result of the switch to HFC refrigerants, as a replacement for ozone-depleting refrigerants [12, 13]. Although the ODP of HFCs is zero (they have no influence and they are not involved in the destruction of the ozone layer), they are potent greenhouse gases with GWP thousands times higher compared to the GWP of carbon-dioxide because of their high infrared absorption properties and extended presence in the stratosphere [14 - 16].

Currently, the most prominent HFC refrigerant is R134a ($C_2H_2F_4$) with chemical name of 1,1,1,2-Tetrafluoroethane and due to its outstanding heat transport properties, it is now a widely used refrigerant in small and moderate-sized air conditioning and refrigeration applications [17]. Recent research [2] revealed that R134a is currently the most abundant of the HFC group of greenhouse gases in the atmosphere, with an approximately calculated content in the atmosphere of 77.9 ppt mole fraction in 2012. In addition, the contribution of R134a to climate forcing, which was negligible in 1995, increased to about 12 mW/m^2 in 2012 due to the huge increase in its use combined with its uncontrolled emission all that time [10]. The use of R134a in small and medium-sized refrigeration systems is completely banned in the European countries due to concerns over its high GWP of 1300 making it more than a thousand time more potent a greenhouse gas than CO_2. To reduce the HFC emissions, refrigerants with a global warming potential of no more than 150 are currently permitted for use in medium and small refrigeration systems [18, 19]. As from 2020, refrigerants with GWP below 150 are required as working fluids in air conditioning systems of the new cars manufactured in the USA [20].

In the study carried out by Aized and Hamza [21], some pure and blended HFC chemicals were numerically examined as alternative working fluids in small refrigerating systems. A software called MATLAB R2017a was used to compare the cooling capacity, coefficient of performance (COP), pressure ratio and compressor exit temperature of the studied refrigerants with those of R134a. The investigation singled out R152a from all tested refrigerants as the most efficient refrigerant that matched the performance of R134a. Hence, R152a was recommended as a promising retrofit refrigerant in R134a systems with minimal adjustments.

R152a or 1,1-Difluoroethane, an organo-fluorine chemical with the formula $C_2H_4F_2$ has zero ozone-depleting potential, like R134a, but its GWP of 138 is very low compared with 1300 of R134a. The GWP of 138 met F-Gas Policy for eco-friendly replacement refrigerants in small and medium-sized refrigerators. Table 1 shows excerpt No. 517/2014 from the European Union (EU) Fluorinated-Gas (F-Gas) Policy, which prohibits the use of certain chemicals [22]. As shown in Table 2, the thermal and transport properties of R134a are very close to those of R152a. As a result, this study investigates the performance of R152a as a retrofit substitute refrigerant in a small refrigerator system initially designed to run on R134a. The suitability of R152a was evaluated and compared with that of the conventional working fluid in the system. It also shows the process of retrofitting the existing system with a new non-harmful refrigerant for efficient and better performance after the specified limit date of the existing refrigerant and throughout the entire economic life of the system.

Table 1. Excerpt No. 517/2014 from the EU F-Gas Policy which prohibits the use of chemicals with high GWP in various equipment [22]

Equipment	GWP	Prohibition date (day/month/year)
Small refrigerators and freezers (50 – 250 litres)	≥ 150	01/01/2015
Single unit air-conditioners (cooling capacity 2 - 9 kW)	≥ 150	01/01/2020
Multi-compressor refrigeration plants with a rated capacity of 40 kW or more	≥ 150	01/01/2022
Medium-sized refrigerators and cold-rooms (250 – 490 litres)	≥ 150	01/01/2022
Split systems under 3 kg refrigerant charge	≥ 750	01/01/2025

Table 2. Some thermal, transport and environmental properties of R152a and R134a [23, 24]

Properties	R134a	R152a
GWP	1300	138
ODP	0	0
Molecular weight (kg/kmol)	102.0	66.1
Liquid mass density @ -25 ºC (kg/m^3)	1373.4	1013.2
Vapour mass density @ -25 ºC (kg/m^3)	5.5	3.2
Standard boiling temperature (ºC)	- 26.1	- 24.0
Critical point temperature (CPT) (ºC)	101.1	113.3
Critical point pressure (CPP) (kPa)	4100	4500

MATERIALS AND METHODS

Analysis of the refrigeration system

The vapour compression cycle is the most popular standard of operation for small air-conditioning and refrigeration systems. Figure 1 shows pressure-enthalpy graph of a refrigeration cycle based on the principles of vapour-compression. This diagram is used to determine the input power to the compressor, refrigerating capacity and COP which are the most important performance criteria to consider when evaluating a refrigeration system. The experimental refrigerator is shown schematically in Figure 2. It has a volume capacity of 0.12 m^3 (120 litres) and consists of a hermetic type reciprocating compressor, a wire-tube type condenser, an evaporator (consisting of an in-built coiled tube attached to the inner wall plate) and a coiled capillary tube as the main components.

Compressor: The main power consumption (P_{input}, kW) of the refrigerator is through the compressor and is computed as the product of variation in enthalpy per unit mass in the compressor and the mass of refrigerant flowing through the compressor per unit time ($\dot{m}$, kg/s) (Eq. 1):

$$P_{input} = (h_2 - h_1)\dot{m} \qquad (1)$$

where h_1 and h_2 (in kJ/kg) are the enthalpies of the refrigerant at point 1 (compressor inlet) and point 2 (compressor outlet), respectively, as shown in Figure 2.

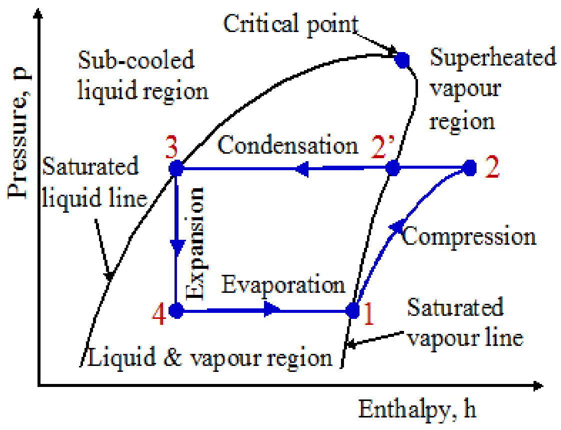

Figure 1. Pressure-enthalpy diagram of a simple refrigeration cycle

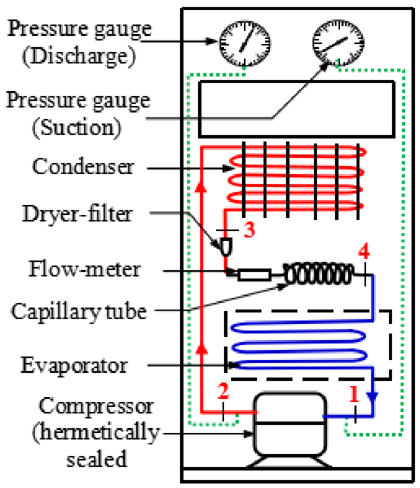

Figure 2. A simplified picture of the experimental refrigerator

The actual power consumption of compressor (P_{actual}, kW) is given by equation 2:

$$P_{actual} = \frac{P_{input}}{\eta_{comp}} \quad (2)$$

where η_{comp} is the compressor efficiency.

Capillary tube: The refrigerant's enthalpy through the capillary tube (expansion device) is constant and the process is known as isenthalpy (Eq. 3):

$$h_3 = h_4 \quad (3)$$

where h_3 and h_4 are the refrigerant enthalpies at point 3 (condenser outlet) and point 4 (evaporator inlet), respectively, as shown in Figure 2.

Evaporator: Heat removal from the refrigerator occurs inside the evaporator and the refrigerant takes the heat to provide the cooling effect. The evaporator cooling capacity (*ECC*, kW) of the refrigerator is computed as the product of variation in enthalpy per unit mass within the evaporator and the mass of refrigerant flowing through the evaporator per unit time (Eq. 4):

$$ECC = (h_1 - h_4)\dot{m} \quad (4)$$

The COP (coefficient of performance) of a refrigerator is the vital significant performance factor in selecting the appropriate working fluid, and it is the ratio of evaporator cooling capacity (*ECC*, kW) and the actual power consumption of compressor (P_{actual}, kW) (Eq. 5).

$$COP = \frac{ECC}{P_{actual}} \quad (5)$$

Experimental procedure

The test device used for the experiment, shown in Figure 2, was made from locally available materials. Pressure gauges with a precision of ± 0.5 kPa were installed for measuring the inlet and outlet pressure of the compressor (Figure 2). Thermocouples with a precision of ± 0.1 °C, copper-constantan type, were used to determine the refrigerant's temperatures at four different points. The inlet and outlet of the compressor are represented by points 1 and 2, respectively, while points 3 and 4 are the outlet of the condenser and the inlet of the evaporator, respectively. The compressor input power was determined using an energy meter with a precision of 0.2 kWh. The refrigerant flow rate was determined using a Coriolis mass flow meter with a precision of ± 0.01 kg/h placed next to the expansion device. Table 3 shows the experimental uncertainty of the measuring instruments.

Table 3. The experimental uncertainty of the measuring instruments

Measurement	Instrument	Uncertainty
Refrigerant temperature	Copper-constantan thermocouples	± 0.1 °C,
Compressor pressures	Pressure gauge	± 0.5 kPa
Compressor input power	Energy meter	0.2 kWh.
Refrigerant flow rate	Coriolis mass flow meter	± 0.01 kg/h

Retrofitting procedure

Retrofitting a refrigeration system will allow the system that uses environmentally harmful conventional refrigerant to work successfully and efficiently with new eco-friendly refrigerants after the stated date of banning the use of harmful refrigerant and throughout the entire economic life of the system. The test device was first filled with 100 g of R134a, and pressures, temperatures, compressor input power and refrigerant flow rate were obtained. After collecting data using the base (traditional) refrigerant (R134a), the system was modified for the proper operation of retrofit refrigerant (R152a).

In the retrofitting process, the harmful refrigerant was removed from the refrigerator and the existing oil in the compressor was removed via the inlet port and new well-matched polyol-ester oil was filled. Refrigeration compressor lubricants minimize friction, protect against wear, and serve as a seal between the high and low pressure side. The refrigeration oil is necessary for the proper operation of the compressor. Because of its high thermal and chemical stability, polyol-ester (POE) is used as compressor oil in R152a and R134a systems. It is the most commonly used synthetic lubricant with HFC refrigerants, such as R134a, R152a, and R410A. POE oil outperforms mineral oils in terms of lubrication, thermal stability, and miscibility with HFC refrigerants. The old filter-drier and capillary tube were replaced with new ones. The system was cleaned of moisture and non-condensable molecules using a MK-180-DL model of ITE Blue-Vac vacuum pump.

The test device was filled with R152a and thoroughly evaluated and confirmed to be in good working order. Tests were carried out in the laboratory at different evaporation temperatures and a controlled room temperature of 27.5 °C. Data collected during the tests were used to calculate the compressor power consumption (P_{input}), coefficient of performance (COP), and evaporator cooling capacity (ECC). REFPROP 9.1 software was used to compute the thermal and transport properties of R134a and R152a refrigerants [24].

RESULTS AND DISCUSSION

Figure 3 shows the effect of saturation temperature on the vapour pressure for R152a and R134a refrigerants. The suitability of a refrigerant as an alternative to another refrigerant depends on its close match to that other refrigerant in terms of vapour pressure and volume per unit mass. As shown in the figure, the vapour pressure profiles of R152a and R134a followed the same pattern with an average increase in R152a vapour pressure of 5.6 % in the temperature range of - 30 to 40 °C. This indicates that R152a and R134a refrigerants have similar qualities and that R152a will be a good replacement for R134a.

Figure 4 shows the effect of saturation temperature on specific volume for the conventional and retrofit refrigerants. As shown in this graph, the volume the refrigerant per unit mass increases as the saturation temperature decreases. In the range of saturation temperatures from - 30 to 40 °C, the two considered working fluids had a relatively comparable vapour volume per unit mass, which indicates the possibility of using the same compressor.

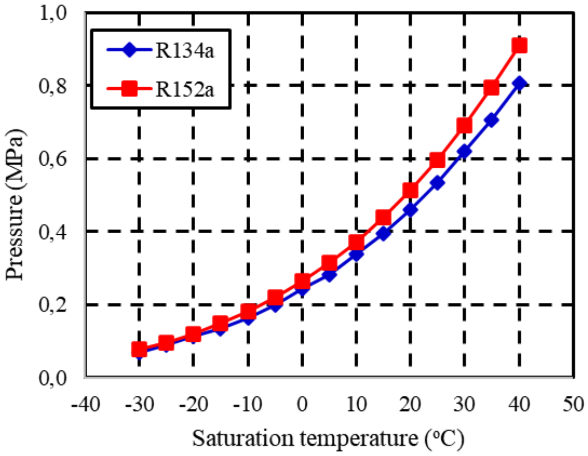

Figure 3. Effect of saturation temperature on vapour pressure

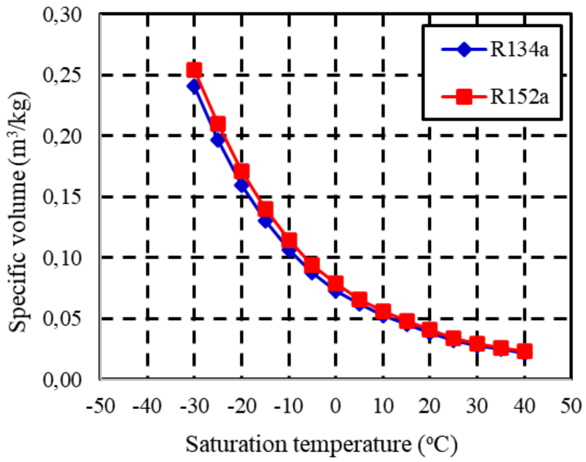

Figure 4. Effect of saturation temperature on the specific volume

The curves of the evaporator chamber air cooling time or pull-down time for the two refrigerants under consideration are shown in Figure 5. Pull-down time is one of the parameters that is typically used to evaluate the functionality of the refrigerator. This is the time it takes for refrigerator´s cooling chamber to reach the lowest temperature below the standard room temperature. The two refrigerants achieved the standard set by the International Standard Organisation (ISO) which specified -3 °C as the reference lowest temperature for small refrigerators [25]. As shown in the graph, for a refrigerant charge of 100 g, the evaporator chamber air cooling time of about 60 and 70 min was achieved for refrigerants R152a and R134a, respectively. A comparison with a previous study [17] which gave a pull-down time of 100 min for R134a refrigerant at a charge of 120 g shows a significant improvement in this study. Figure 5 also shows the achievement of minimum temperatures of -23 and -21 °C at 180 and 210 min for R152a and R134a refrigerants, respectively.

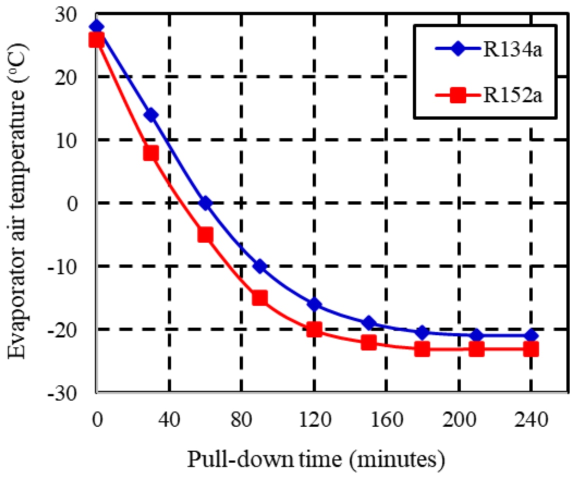

Figure 5. Pull-down time curves for R152a and R134a

Figure 6 shows the effect of evaporation temperature on the compressor power for R152a and R134a refrigerants. The figure reveals that the power consumed by the refrigerator decreases as the temperature of the evaporation increases. This can be related to an increase in the flow rate of refrigerant as a consequence of the rise in the temperature and pressure of the refrigerant during compression. The result reveals a lower power consumption of 4.2 % for the refrigeration system using R152a compared to R134a as a working fluid. Therefore, retrofitting the refrigerator enhances its reduced power consumption.

Figure 7 shows the effect of refrigerant temperature during evaporation on the evaporator cooling capacity for the two considered refrigerants (R152a and R134a). It can be seen in the diagram that the cooling effect increases as the evaporation temperature increases due to the increase in temperature of the refrigerant. One of the good properties of a refrigerant is the high value of latent heat which reduces the flow rate required per unit cooling effect. Regarding the cooling capacity of the evaporator, the results revealed a better performance for R152a (eco-friendly refrigerant) system than the R134a (conventional refrigerant) system. The average cooling capacity of R152a was higher compared to that of R134a by 14.6 %.

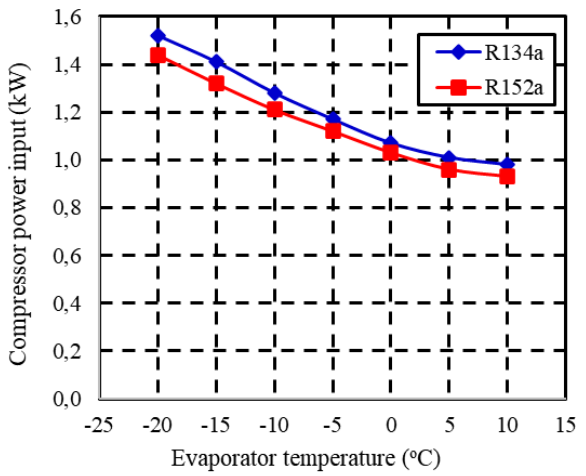

Figure 6. Effect of evaporation temperature on the compressor power

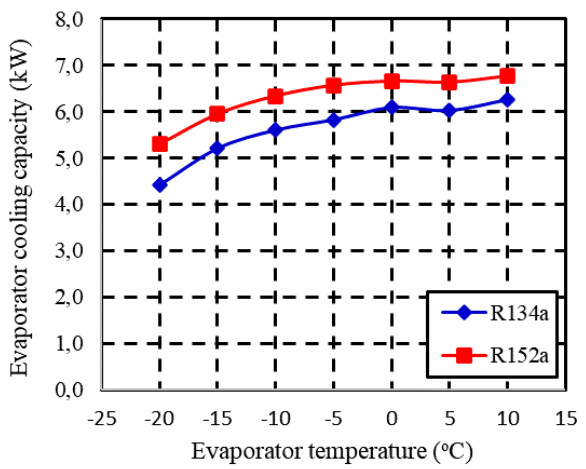

Figure 7. Effect of evaporation temperature on cooling capacity

The coefficient of performance (COP) of refrigeration system is a significant influencing parameter when choosing an alternative refrigerant because it gives an idea about the general performance of the system. The effect of evaporation temperature on the COP of the system for both retrofit and conventional refrigerants is shown in Figure 8. For both refrigerants, the coefficient of performance increases with the increase in the evaporation temperature. Compared to the base refrigerant (R134a), operation with the retrofit refrigerant (R152a) resulted in a 12.2 % higher COP.

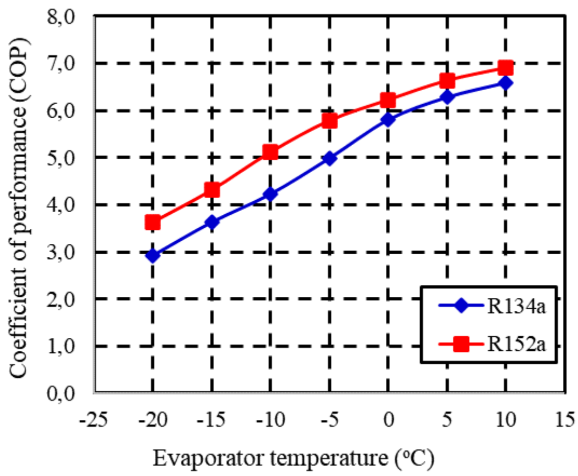

Figure 8. Effect of evaporation temperature on the coefficient of performance (COP) of the refrigeration system

CONCLUSION

An eco-friendly refrigerant (R152a) was tested as a retrofit replacement working fluid in a small refrigerator that was initially developed to work with conventional refrigerant (R134a) which is harmful to the environment. The following conclusions can be drawn in accordance with the findings of the study:

- The vapour phase temperature, volume and pressure profiles of R134a and R152a followed the same pattern indicating that the two refrigerants have similar qualities and that R152a, the retrofit refrigerant, will be a good replacement for the eco-unfriendly refrigerant (R134a). It also indicates the possibility of using the same compressor.
- The two refrigerants met the ISO standard, however R152a achieved a faster pull-down time than R134a.
- In terms of cooling capacity, the retrofit refrigerant (R152a) showed a better performance than the base refrigerant. Compared to R134a, the average cooling capacity of R152a is 14.6 % higher.

- Compared with R134a, the power consumption of the system when using R152a is 4.2 % lower.
- The refrigerating system operating with retrofit refrigerant had a 12.2 % higher coefficient of performance than the system with harmful refrigerant (R134a).
- Finally, the retrofit refrigerant outperformed the base refrigerant in all performance criteria tested. R152a is recommended, due to its eco-friendly properties and better performances, as retrofit refrigerant for the existing small and medium-sized refrigerators.

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