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Energy efficiency enhancement of a domestic refrigerator using R436A and R600a as alternative refrigerants to R134a

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ABSTRACT

This paper is devoted to feasibility study of substitution of two hydrocarbon refrigerants instead of R134a in a domestic refrigerator. Experiments are designed on a refrigerator manufactured for 105 g R134a charge. The effect of parameters including refrigerant type, refrigerant charge and compressor type are investigated. This research is conducted using R436A (mixture of 46% iso-butane and 54% propane) and R600a (pure iso-butane) as hydrocarbon refrigerants, HFC type compressor (designed for R134a) and HC type compressor (designed for R600a). The results show that for HFC type compressor, the optimum refrigerant charges are 60 g and 55 g for R436A and R600a, respectively. Moreover, for this type of compressor, the energy consumption of R436A and R600a at the optimum charges is reduced about 14% and 7%, respectively in comparison to R134a. On the other hand, when using HC type compressor, the optimum refrigerant charges for R436A and R600a are both 50 g, and the energy consumption of R436A and R600a at the optimum charges are reduced about 14.6% and 18.7%, respectively. Furthermore, when the refrigerator is equipped with HC type compressor, working under optimum charges of R436A and R600a have a total equivalent warming impact about 16% and 21% lower than base refrigerator, respectively.

Total exergy destruction of the domestic refrigerator with HFC type compressor for R134a, R600a and R436A are 0.0389, 0.0301, 0.0471, respectively and for R600a and R436A with HC type compressor are 0.0292, 0.0472, respectively.

1. Introduction

Domestic refrigerators are identified as major energy consuming domestic appliances in every household [1]. The American Household Appliances Manufacturers (AHAM) has recognized that R134a can be used in domestic refrigerants as refrigerant [2]. R134a is considered as an environmentally safe refrigerant and is essentially non-toxic [3] but its GWP (global warming potential) effect is very high. The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) asked for reduction in emission of six categories of greenhouse gases, including R134a, used as refrigerant in domestic refrigerators [4]. Therefore, according to Kyoto protocol [5] the consumption of R134a must be seriously reduced. From the environmental, ecological and health points of view, it is urgent to find some better substitutes for HFC (hydrofluorocarbon) refrigerants [6].

The process of investigating the use of hydrocarbons in domestic refrigerators and freezers by many researchers goes back to the 1990s [7–9]. During the last two decades, the use of natural refrigerants in domestic refrigeration systems was under the focus of some publications [10]. Many researchers have reported that hydrocarbon mixtures were found to be environment friendly alternative refrigerants [7,11]. The properties of some refrigerants used in domestic refrigerators and freezers are shown in Table 1.

Since the latent heat of hydrocarbons is much higher than that of R134a, the amount of refrigerant charge can be reduced. An experimental investigation was conducted by Mohanraj et al. [12] using a hydrocarbon mixture consisting of propane and isobutane with a ratio of 45.2:54.8 by weight as a replacement for R134a in a domestic refrigerator. The results showed that this hydrocarbon mixture leads to a reduction in the compressor energy consumption, pull down time,[1] and ON time ratio[2] by 11.1%, 11.6% and 13.2%, respectively. Moreover, the mixture of hydrocarbons was

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[1] The time required to reduce the air temperature inside the refrigerator from ambient condition to the desired freezer and cabin air temperatures.

[2] It is the operating time of the compressor in one cycle divided into the total cycle time.

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Nomenclature

Ex	exergy rate (kW)
h	specific enthalpy (kJ kg^{-1})
$\dot{Q}$	heat transfer rate (kW)
RI	relative irreversibility
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
$\dot{W}$	work rate (kW)
V	potential difference (V)
I	electrical currency (A)
t	time (h)
m	refrigerant charge (kg)
l	leakage rate (%)
S_l	service life (yrs)
r	CO_2 generation emission (kg CO_2/kWh)
E	energy consumption (kWh)
V_{room}	minimum room volume (m^3)
m_r	actual charge weight (kg)

Greek symbols

η	exergetic efficiency

Subscript

Cap	capillary tube
Comp	compressor
Cond	condenser
Evap	evaporator
i	particular component
in	inlet
out	outlet
Cap-Hx	capillary tube-suction line heat exchanger
T	total
0	dead state

offered as the best substitute for R134a. The results showed that for a domestic refrigerator with 110 g R134a, the optimum weight of the hydrocarbon mixtures was 60 g. Another investigation was carried out with a mixture of propane and iso-butane with a ratio of 50:50 by weight in a domestic refrigerator [13] which worked with 150 g of R134a. The results showed that this hydrocarbon mixture reduced the energy consumption by 4.4% and the weight of the refrigerant used was reduced by 40% compared to that of R134a. By using a hydrocarbon mixture [14], the temperature changes in refrigerator cabin occurs faster and the ON time ratio is less than that of R134a.

The results of using R290, R600 and R600a hydrocarbons in a domestic refrigerator [15] showed that R290 could not be used as an alternative refrigerant due to its high operating pressure in comparison with R134a. Although R600 and R600a represent many desirable characteristics such as operating pressure, mass flow rate and discharge temperature, although the compressor should be changed. Experiments conducted on pure butane [16] in a domestic refrigerator designed for R134a at 25 °C and 28 °C ambient temperatures showed that their energy consumption are the same and the inlet temperature of the evaporator for hydrocarbons are lower than that of R134a. Therefore, it is better to use hydrocarbon for low temperature applications. The weight of R134a used was 140 g, while the weight of the required hydrocarbon was 70 g. Also, the results showed that using pure butane as refrigerant is possible without any change in the refrigerator components. In spite of the flammability of hydrocarbons, many companies especially in Europe and Asia use hydrocarbons as refrigerants without any hazard for consumers [17]. Using propane and butane mixture (LPG) achieves lower freezer and refrigerator temperatures than using R134a [18]. When hydrocarbon and R134a are compared form the energy consumption viewpoint, mass flow rate and refrigerant mass are lower for hydrocarbons [18,19]. Somchai and Nares [20] and Bilal and Salem [21] recommended that a mixture of 60% R290 and 40% R600 (or R600a) was the best substitute for R134a in all environmental conditions.

Table 1
Properties of some refrigerants.

Refrigerant	Molecular weight	Normal boiling point, °C	Liquid density (kg/m^3)	Critical temperature, °C	Critical pressure, Mpa	ΔH_{vap} (kJ/kg)
R134a	102.0	−26	1225.3	101.1	4.06	216.87
R290	44.0	−42	500.1	96.7	4.25	423.33
R600a	58.1	−12	556.9	134.7	3.64	364.25

Recently, Mohanraj et al. [22] have reviewed the developments of new refrigerant mixtures for vapor compression based refrigeration systems. They stated that hydrocarbon refrigerants are identified as long-term alternatives to phase out the existing halogenated refrigerants in the vapor compression based systems. Regarding the performance, hydrocarbon mixtures are found to be better substitutes for R12 and R134a in domestic refrigerators [23]. A survey conducted by Jose et al. [24] proved that certain hydrocarbons have excellent characteristics as refrigerants from a thermodynamic point of view. Furthermore, hydrocarbon as a refrigerant may be used in small systems like refrigerators and small freezers (with hydrocarbon charge lower than 150 g) provided that they incorporate a few special safety measures.

In addition to energy analysis, exergy analysis is required for a better understanding of the refrigeration cycle performance [25]. Ahamed et al. indicated that in a domestic refrigerator with R600a and R134a as refrigerants, compressor had the highest exergy destruction and R600a showed 50% more exergy efficiency than R134a [26]. Joybari et al. reported an experimental analysis conducted on R600a to evaluate it as an alternative refrigerant for R134a in a domestic refrigerator. The results showed that compressor had the highest amount of exergy destruction followed by the condenser, capillary tube, evaporator and superheating coil had the highest exergy destruction. Also, for R600a as a refrigerant compressor had the highest amount of exergy destruction followed by the capillary tube, condenser, evaporator and superheating coil. In addition, total exergy destruction in optimum condition with R600a was 45.05% of the base refrigerator [27].

In this research, an experimental investigation to calculate the optimum refrigerant charge amount, the energy consumption, and a Total Equivalent Warming Impact (TEWI[3]) analysis for a domestic refrigerator that works with hydrocarbon refrigerants (R436A, and R600a) is carried out.

2. Materials and methods

The test object was a 238 L domestic refrigerator which was originally designed for R134a refrigerant with 105 g charge. The most important specifications of the refrigerator are summarized in Table 2. R436A and R600a were purchased from Parsian

[3] - TEWI is defined as the sum of refrigerant emissions expressed in terms of CO_2 equivalents (direct effect), and CO_2 emissions from the system's energy use over its service life (indirect effect) [28].