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Retrofit assessment of refrigerator using hydrocarbon refrigerants

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HIGHLIGHTS

- We employed HC refrigerants as alternatives for R134a refrigerator.
- The content range of R290 in HC refrigerants was 0–65%.
- The HCs charged ratios were 30–60% based on the charged mass of R134a.
- The refrigerator was conducted the pull-down and 24-hour cycling test.
- R600a in HC refrigerants can enhance the EFs of refrigerators.

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ABSTRACT

This study used hydrocarbon (HC) refrigerants in a small R134a refrigerator to evaluate the refrigeration performance and feasibility of using these alternative refrigerants by conducting the no-load pull-down test and 24-hour on-load cycling test. The mixed mass ratios of the HC refrigerants, R290 and R600a, were 65% and 35% (HC_1), 50% and 50% (HC_2), and 0% and 100% (HC_3), respectively. The charged ratios were 30%, 40%, 50%, and 60% based on the charged mass of R134a for HC refrigerants. The results of the no-load pull-down test revealed that the optimal charged mass for all the HC refrigerants was 40% of that of R134a. Most of the experimental results of the HC refrigerators obtained using the optimal charged masses showed that freezer temperature and power consumption were higher than those of the R134a refrigerator. Therefore, the capillary tube lengths of R134a, HC_1, HC_2, and HC_3 were recalculated to be 2.77, 5.05, 5.34, and 5.60 m, respectively, and the recalculated capillary tube was used in the 24-hour on-load cycling test. The results of the 24-hour on-load cycling test showed that the freezer temperatures considerably decreased when the HC refrigerants were used, and that all of the HC refrigerants could be used in the R134a refrigerator after changing the capillary tube lengths. All of the HCs refrigerants yielded lower electricity consumption, lower on-time ratios, and higher energy factors (EFs) than R134a did. The EFs of HC_1, HC_2, and HC_3 were 9.1%, 12.2%, and 42.3% higher than that of R134a, respectively. Using a higher proportion of R600a in HC refrigerants can enhance the EFs of refrigerators.

1. Introduction

Because of global warming-related concerns, the use of materials with strong greenhouse effects must be controlled. Such a material is R134a, a hydrofluorocarbon (HFC) that is used as a refrigerant in small- and medium-sized refrigerators and automotive air conditioners. R134a is a controlled substance under the Kyoto Protocol, and must be phased out in future [1,2]. Many countries have not explicitly legislated to control the usage of R-134a but only to reduce the actual and potential emission of this refrigerant. Therefore, R134a should be replaced with the other refrigerants because this is the most efficient way to reduce the potential level of the emission of this refrigerant. Ideally, R134a must be replaced with a refrigerant that has no ozone depletion potential (ODP), low global warming potential (GWP), low toxicity, a low price, high chemical stability, and excellent thermodynamic properties. Some long-neglected natural refrigerants, such as ammonia, hydrocarbons (HCs), CO_2, water, and air, may be alternatives to hydrofluorocarbons (HFC) and hydrochlorofluorocarbon (HCFC) refrigerants. Many researchers have studied HC refrigerants as alternatives to traditional refrigerants in a variety of equipment [3–14]; however, these studies were focused on medium and

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Nomenclature

ρ	density (kg/m^3)
$\dot{m}_r$	mass flow rate (kg/s)
c_p	specific heat (kJ/kg °C)
ΔL	tube length increment (m)
$\dot{V}$	velocity (m/s)
μ	viscosity (Pa s)
$\dot{Q}_{comp}$	motive power of compressor (kW)
$\dot{Q}_{evap}$	refrigeration capacity (kW)
COP	coefficient of performance
CR	compression ratio
D	experimental data
D_i	inner diameter of tube (m)
EF	energy factor (L/kW-h/month)
f	fraction factor
h	enthalpy (kJ/kg)
P_c	power consumption (W)
R	ratio
R_{on}	on-time ratio
T	temperature (°C)
t	time (hour)
V	volume (liter)
v	specific volume (m^3/kg)
W_c	energy consumption (kWh)
x	quality of two-phase flow

Subscripts

amb	ambient
cap	capillary
comp	compressor
cond	condenser
evap	evaporator
fr	freezer
g	gas
in	inlet
liq	liquid
out	outlet
sat	saturation
vap	vapor

small-scale refrigerators or air-conditioners due to consideration of flammable property and safety.

Previous studies on using HC drop-in refrigerants have consisted of theoretical analyses and experimental research. To conduct theoretical analyses, theoretical calculations and simulation analyses were used to assess the use of HCs as alternative refrigerants in refrigerators [15–18]. The related experimental research concerning refrigerators retrofitted with HC refrigerants involve studies in which adjusting the components in the refrigeration system was necessary, and those in which it was not.

In the following studies, the refrigeration system components were not adjusted:

In 1998, Alsaad and Hammad [19] used liquefied petroleum gas (LPG) with 24.4% propane (R290), 56.4% butane (R600), and 17.2% isobutane (R600a) in 320 L of the domestic refrigerant R12. Experimental results showed that the evaporation temperature reached −15 °C with a coefficient of performance (COP) value of 3.4 at a condensation temperature of 27 °C and an ambient temperature of 20 °C. LPG was successfully used as an alternative for R12 in a domestic refrigerator; the refrigerator functioned normally, and adjusting the refrigeration system was not required.

In 2005, Wongwises and Chimres [20] used the HC refrigerants R290, R600, and R600a to replace R134a in a domestic refrigerator with a gross capacity of 239 L. The refrigerant mixtures used were divided into three groups: a mixture of the three HCs, a mixture of two HCs, and a mixture of two HCs and R134a. The experiments were conducted with the refrigerants under the same no-load condition at a surrounding temperature of 25 °C. The results showed that the mixture of R290 and R600 (60% and 40% according to mass, respectively) was the most appropriate alternative. Compared with using R134a, using this HC mixture reduced the refrigerator's energy consumption by 86%. The refrigerant charge of the HC mixture system was approximately 50% of that of the R134a system (120 g).

In 2008, Mani and Selladurai [21] conducted an experimental study on a vapor compression refrigeration system (VCRS) using an HC mixture of R290 and R600a (68% and 32% according to mass, respectively) as a drop-in replacement for R12 and R134a. The experimental results showed that the HC mixture had a 19.9%–50.1% higher refrigeration capacity than R12 did and a 28.6%–87.2% higher refrigeration capacity than R134a did. The refrigerant R134a exhibited a slightly lower refrigeration capacity than R12 did. The HC mixture consumed 6.8%–17.4% more energy than R12 did. The refrigerant R12 consumed slightly more energy than R134a did at high evaporation temperatures. The COP of the HC mixture increased from 3.9% to 25.1% higher than that of the R12 at lower evaporation temperatures and from 11.8% to 17.6% at high evaporation temperatures. The R12 exhibited a slightly higher COP than the R134a did. The discharge temperature and discharge pressure of the HC mixture was close to those of the R12. Therefore, the HC mixture can be considered a drop-in replacement refrigerant for R12 and R134a.

In 2009, Mohanraj et al. [11] conducted an experimental investigation using an HC mixture of R290 and R600a (45.2% and 54.8% according to mass, respectively) as an alternative to R134a in a 200-L single-evaporator domestic refrigerator. Continuous running tests were performed in various ambient temperatures (24, 28, 32, 38, and 43 °C), whereas cycling running (on and off) tests were implemented only at an ambient temperature of 32 °C. The results showed that the HC mixture exhibited approximately 11.1% lower energy consumption, an 11.6% lower pull-down time, a 13.2% lower on-time ratio, and a 3.25%–3.6% higher COP than R134a did. The discharge temperature of the HC mixture was determined to be 8.5–13.4 K lower than that of R134a. Jwo et al. [22] used an HC mixture of R290 and R600a (50% and 50% according to mass) as an alternative to R134a in a domestic refrigerator with 150 g of charged R134a. The results showed that the HC mixture exhibited 4.4% lower energy consumption, a 17.4% lower running time, and a 40% lower charging mass of the refrigerant than R134a did.

In 2012, Rasti et al. [23] used R436A, a mixture of R290 and R600a (56% and 44% according to mass, respectively) as an alternative to R134a in a 238-L single-evaporator domestic refrigerator without any modifications in the refrigeration cycle. The refrigerator was charged with various masses of R436A, and in addition to the refrigerator's power consumption during operation, the temperatures in different sections of the refrigerator were measured according to the Iranian National Standard No. 4853-2. The results showed that, compared with the basic refrigerator functioning with R134a, using R436A reduced the on-time ratio and the daily energy consumption by 13% and 5.3%, respectively. The refrigerant charge of the R436A system was approximately 52% of that of the R134a system (105 g).