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Research Paper

Transient and cyclic characteristics of a household refrigerator using ternary hydrocarbon mixture – An experimental investigation

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HIGHLIGHTS

- Transient and cyclic characteristics of a household refrigerator are presented.
- The refrigerator used hydrocarbon mixture of R290:R600:R600a of 60:26.6:13.4%.
- Cyclic losses are recognized by comparing cyclic and continuous refrigerator power.
- The best charge and capillary tube combination is identified to be 70 g and 5.5 m.
- 306.6 kWh per refrigerator and 36.8 TWh on the globe scale are saved annually.

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ABSTRACT

A household refrigerator designed to work with R134a was used as an investigation unit to assess its transient startup and cyclic characteristics using ternary hydrocarbon mixture. Twenty-five combinations of refrigerant mass (30, 40, 50, 60 and 70 g) and capillary tube length (4, 4.5, 5, 5.5 and 6 m) are tested under severe tropical environment using a mixture of propane: isobutene: n-butane of 60:26.6:13.4% by mass. Also, typical variations of compressor, condenser and evaporator temperatures during transient and cyclic operations are considered. The energy losses during off-time are addressed by comparing refrigerator power during cyclic and continuous operation. The results demonstrate that while 15 out of 25 tested combinations satisfy the required air freezer and cabinet temperatures and achieve reasonable startup transient characteristics, only 5 combinations work satisfactorily under cyclic operation. The most appropriate combination of charge and capillary tube length is identified to be 70g and 5.5m. This combination consumes the lowest energy during permanent cyclic operation and achieves reasonable cooling rate, pull-down time and startup energy. In comparison with R134a, the energy applied to this combination may save about 306.6 kWh annually for each refrigerator that would result in 36.8 TWh on the world scale.

1. Introduction

The concept of environmentally-friendly refrigerant has been acknowledged since the Montreal Protocol in 1987 that aimed at protecting the environment from high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) substances. Thus, the search for appropriate alternatives to chlorofluorocarbon (CFC) and hydrochloroflurocarbon (HCFC) refrigerants for domestic, commercial and industrial applications, has been started before 1992 [1] and the topic is reviewed by many authors [2–6]. These reviews concluded that natural refrigerants are the ideal, environmentally-friendly refrigerants and the ultimate solution to the problems of ozone layer depletion and global warming [4]. Natural refrigerants include water, ammonia, hydrocarbons (HCs) and carbon dioxide where hydrocarbons are considered as a long-term alternative for halogenated (CFC and HCFC) refrigerants [5].

Hydrocarbons are naturally existing substances that include propane (R290), n-butane (R600), isobutane (R600a) and pentane (R601). HCs are excellent refrigerants in many ways - energy efficiency, critical point, solubility, transport and heat transfer properties [5]. HCs have zero ODP and low (less than 20) or no GWP and are safe (i.e. nontoxic and nonflammable when used in small capacity domestic refrigerators). HCs and their mixtures

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Nomenclature

A	area (m^2)
COP	coefficient of performance
E	energy consumption (kWh)
h	free convection heat transfer coefficient (W/m^2 K)
h_{ei}	specific enthalpy of the refrigerant at evaporator inlet (kJ/kg)
h_{eo}	specific enthalpy of the refrigerant at evaporator outlet (kJ/kg)
k	thermal conductivity (W/mK)
L	layer thickness (m)
$\dot{m}_r$	mass flow rate of refrigerant (kg/s)
p	pressure (Pa)
P	compressor power (W)
Q_L	heat loss from the refrigerator (W)
Q_e	cooling capacity of the evaporator (W)
t	time (s)
T	temperature (C)
T_1: T_5	temperatures in the refrigerant circuit, see Fig.1a (C)
T_{c3}: T_{c5}	cabinet temperatures, see Fig.1b (C)
T_{f1}: T_{f2}	freezer temperatures, see Fig.1b (C)
U	overall heat transfer coefficient (W/m^2 K)

Subscripts

a	Ambient
c	cabinet
cy	cycle
f	freezer
h	refer to heat loss from walls and door only
i	inner
L	loss
o	outer
on	on-time
r	refrigerator

Abbreviation

CFC	chlorofluorocarbon
GWP	global Warming Potential
HC	hydrocarbon
HCFC	hydrochloroflurocarbon
HCM	hydrocarbon Mixtures
HPS	high pressure side
LPG	liquified Petroleum Gas
LPS	low pressure side
ODP	Ozone Deplition Potential
R290	propane
R600	n-butane
R600a	isobutane
R601	pentane

(HCMs) are miscible with both mineral oil used in R12 and polyolester oils used in R134a systems [5]. Also, they are fully compatible with all materials traditionally used in refrigeration systems. Thus, they are considered as an appropriate replacement for R12 and R134a [2].

Hydrocarbon blends are zeotropic mixtures that do not behave like a single substance when changing the state. Instead, HCMs evaporate and condense between two temperatures (temperature glide). But, HCMs have greater potential for improvements in energy efficiency and capacity modulation [3]. However, important issues of HCs flammability and risk are addressed by a number of authors including Bolaji and Huan [5]. The authors indicated that the most significant concern about the adoption of HCs as refrigerant is their flammability and stated the measures that must be taken to prevent potential fire or explosion. Thus, the development of new refrigeration systems with low refrigerant inventory is essential [3].

During the last two decades, many experimental and theoretical investigations have been reported on HCs and HCMs. Recently, studies that evaluate the use of HC as a possible refrigerant for domestic refrigerators have been considered by a number of authors [4–7]. Table 1 summarizes the main work reported for domestic refrigerators working with HCs or HCMs. It is recognized that the early experimental studies concentrated on the use of HCMs as replacements for R12 refrigerant [2,8–13] and the relatively recent experimental and theoretical studies focused on substituting R134a by HC and HCM refrigerants [14–23]. HCMs composed of different concentrations of two and three HCs are tested (Table 1). Effects of refrigerant type, refrigerant charge, capillary tube and compressor type are investigated. It is indicated in Table 1 that the validity of the HCMs as a possible alternative to R12 in an unmodified household refrigerators was examined first [8–9]. Then, various charges of many HCMs and capillary tubes were tested to improve the performance of the household refrigerators [13,14,16,18–19,21–22].

The benefits of using HCMs as a refrigerant over R12 or R134a are given in Table 1. These include larger COP [9–13,16,18,20,23], better energy efficiency [10,22] and large cooling rate [2,10,13,17,19], with lower energy consumption [14,16,18–23], pull-down time [16,18], on-time ratio [10,14,18,22], compressor power [17], compressor dome temperature [10], compressor discharge temperature [10,18] and lower global warming impact [21]. On the other hand, few papers show relatively lower COP [8] or higher energy consumption [2] when using HCMs. In both of these papers, neither the refrigerant charge nor the capillary tube was optimized. However, lower compressor discharge temperature can improve the life of the refrigerator compressor [13]. Also, the environmental impacts of HCM were reported to be lower than that of R134a due to its lower energy consumption [18]. It should be stated that the pull-down time is defined as the time required to bring the freezer from ambient temperature to the recommended temperature of the considered refrigerator class.

The performance of a household refrigerator may be assessed using standard experiments, steady-state models and transient models. The steady-state models are used for component matching whilst the transient models are used to optimize the control strategy and the system performance. Hermes and Melo [24] reviewed the dynamic models for general refrigeration systems and for household refrigerators. The use of these dynamic models in order to obtain "optimal performance" from a household refrigerator is extended. Therefore, a number of authors presented different types of models to investigate the issues related to circuit components and control [25–28]. Innovative modeling approaches were introduced for each of the refrigerator components: heat exchangers (condenser and evaporator), non-adiabatic capillary tube, reciprocating compressor, and refrigerated compartments. However, Hermes and Melo [24] stated that very few approaches are able to simulate the refrigerator cycling behavior, and none of them were validated against experimental data on energy consumption.

The operation of domestic refrigerators composed of transient response (pull-down) which is a continuous operation to bring the refrigerator to the setting temperature followed by a cyclic on/off operation to maintain the refrigerator at the setting temperature. Among the reviewed work in Table 1, few studies