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Performance of low GWP R1234yf/R134a mixture as a replacement for R134a in automotive air conditioning systems

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ABSTRACT

In this study, the performance of a new refrigerant, R1234yf/R134a (with a ratio of 89:11, by mass), was measured as alternative to R134a in automotive air conditioning systems using micro-channel heat exchangers in cooling and heating modes. Test results show that the capacities of R1234yf/R134a and R134a are similar in cooling and heating modes. The COP of R1234yf/R134a was lower than that of R134a by 4–9% in cooling mode, while it was lower by 4–16% in heating mode. The average compressor discharge temperature of R1234yf/R134a was up to 10 °C lower than that of R134a in cooling and heating modes. By adding 11% R134a, R1234yf/R134a can be made virtually non-flammable. In addition, R1234yf/R134a has no ozone depletion potential, with a global warming potential of less than 150, thus meeting the requirement of European mobile air-conditioner directives. R1234yf/R134a can be used as an environment-friendly replacement for R134a in automotive air conditioning systems, with minor modifications.

1. Introduction

Since 1930, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) that were responsible for the destruction of the ozone layer have been extensively utilized in air-conditioning and refrigeration equipment. These refrigerants, with their ozone depletion potential (ODP), should be phased out in accordance with the Montreal protocol proposed in 1987 [1]. In order to fill the gap caused by the phase out of CFCs and HCFCs, extensive research has been carried out to find environment-friendly alternative refrigerants whose ODP are zero [2]. As a result, R134a has been successfully used in domestic refrigerators and mobile air conditioners and also in water chillers for the past two decades.

As the consequences of global warming continue to become increasingly serious and evident, it is important to reduce the use of refrigerants that lead to global warming. Consequently, R134a was defined as a controlled greenhouse gas, according to the Kyoto protocol proposed in 1997 [3]. The 100-year global warming potential (GWP) of R134a is 1300, compared with that of carbon dioxide [4]. EU F-Gases Regulation and European mobile air-conditioner directives ban fluorinated gases with a GWP higher than 150 from automotive air conditioning systems (MACs) in new vehicles from January 1, 2011, as well as in all vehicles manufactured since January 1, 2017 [5]. As global warming intensifies, newer refrigerants should be researched to replace R134a in the near future.

In the past, the potential low-GWP refrigerants researched as alternatives to R134a included hydrocarbons (HCs), R152a and CO_2. HCs showing good miscibility with mineral oils, while being chemically unreactive with common materials, are widely utilized in refrigeration equipment. In addition, the performance of HCs has competitive advantages over R134a [6]. However, HCs may lead to unsafe conditions because of their high flammability. R152a, classified as HCFCs, also has a performance similar to R134a [7]. The COP of R152a is higher than that of R134a, while its cooling capacity is slightly lower than that of R134a. However, the use of R152a is not recommended because of its flammability and high compressor discharge temperature. Meanwhile, CO_2, the natural refrigerant, is non-flammable. The performance of the vapor compression system using CO_2 was competitive, when used with R134a [8]. However, the system requires major modifications because CO_2 operates on a trans-critical cycle.

Lately, R1234yf has been recommended as a potential replacement for R134a in MACs and in beverage coolers. The thermophysical properties and heat transfer coefficient of R1234yf are similar to those of R134a [9–10]. R1234yf has zero ODP and excellent life cycle climate performance [11]. The 100-year GWP of R1234yf is

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Nomenclature

Q	capacity, W
P	compressor power consumption, W
COP	coefficient of performance
m_{ref}	measured mass flow rate, kg/h
$m_{ref.t}$	theoretical mass flow rate, kg/h
T_{dis}	compressor discharge temperature, °C
N	compressor speed, rev/min
V_{dis}	compressor displacement, cc/rev
h	specific enthalpy, kJ/kg
Greek symbols	
ρ	density, kg/m^3
η_v	compressor volumetric efficiency
η_g	compressor global efficiency
Subscripts	
c	cooling mode
h	heating mode
com	compressor
ev	evaporator
co	condenser
i	inlet
o	outlet
s	isentropic compression

lower than 1 as compared to that of CO_2 [4]. Hence, R1234yf is in accordance with the current EU regulations.

Many papers have been published on R1234yf as a drop-in replacement of R134a in the open literature. Sethi et al. [12] presented a theoretical comparison of the thermodynamic properties of both the refrigerants. They carried out an experimental analysis in a representative vending machine system at two representative outdoor ambient temperatures, revealing that the performance of R1234yf was similar to that of R134a under identical conditions. Some studies [13–14] present a side-by-side comparison of the energy performance of both refrigerants in a vapor compression system by controlling the values of evaporation and condensation temperatures. The tests showed that the cooling capacity of R1234yf was lower than that of R134a by approximately 9%, while its volumetric efficiency was lower than that of R134a by approximately 5%. The COP of R1234yf was approximately 6–13% lower than that obtained with R134a within the test range. Cho et al. [15] carried out an experimental analysis to investigate the performance of R1234yf and R134a, with and without an internal heat exchanger in an automotive refrigeration system. Tests showed that the cooling capacity and COP of R1234yf reduced by 7% and 4.5% compared with R134a, respectively, while those with the internal heat exchanger reduced by 1.8% and 2.9%, respectively. Zhao et al. [16] investigated the performance of a typical MACs, composed of a micro-channel condenser and a laminated plate evaporator, using R1234yf and R134a as the working refrigerants under different conditions. The data showed that the cooling capacity and COP of R1234yf were 12.4% and 9% lower than those of R134a, respectively. The COP and the cooling capacity of the referenced studies are different. This is because they tested in different facilities and conditions. However, it can be concluded that the COP and the cooling capacity of R1234yf are not much lower than these of R134a.

One of the issues faced by R1234yf is its mild flammability. R1234yf, with an LFL of 6.8% at 23 °C, is classified as A2 L by the ANSI/ASHRAE standard 32 [17,18]. In Europe, a major automobile manufacturer refused to use R1234yf because of its flammability issue in real-life situations. Moreover, another European automobile manufacturer [19] has offered to investigate the safe usage of R1234yf through relevant departments. In a new real-life test scenario, R1234yf showed dynamic distribution at high pressure, close to the hot units of the test MACs. This corresponds to a severe head-on collision, in which the refrigerant line could be damaged, releasing R1234yf into the exhaust system, thus causing a fire. However, R134a did not ignite under similar tests. Therefore, some companies prefer to use the safer R134a in their vehicles, instead of R1234yf.

The blends of R1234yf are presented as potential substitutes of R134a. Mota-Babiloni et al. [20] investigated the ARM-41a and ARM-42a as alternatives to R134a, revealing that best results (cooling capacity and COP) were observed for ARM-41a. Experimental studies reviewed also showed good results for ARM-42a when substituting R134a. According to AHRI research, in a water-cooled chiller, XP-10 cooling capacity was similar to that performed by R134a [21]. In the study of Mota-Babiloni et al. [22], R513A could provide benefits from energetic and environmental point of views. Moreover, the direct replacement of R134a with R513A only required a TXV adjustment. However, in most cases, they do not meet the GWP restrictions approved by the European normative. Furthermore, some of the mixtures proposed would have problems due to their flammability.

At present, R1234yf/R134a mixture with 10–11% R134a is presented as a feasible substitute of R134a. Aprea et al. [23] presented a comparative experimental analysis using R1234yf/R134a (10/90% weight) as alternative to R134a in a domestic refrigerator. The result showed that R134a/R1234yf was the best drop-in refrigerant fluid for R134a in the domestic refrigerator. Lee et al. [24] carried out an experimental analysis to investigate the performance of R134a/R1234yf (10/90% weight) and R134a, in a heat pump bench tester under summer and winter conditions. Test results showed that the COP and capacity using R1234yf/R134a mixture were similar to those using R134a.

Before the worldwide acceptance and implementation of R1234yf/R134a mixture with 10–11% R134a as lower GWP working fluid in the vapor compression systems, more research about the behavior of this fluid is needed. In this paper, an azeotropic mixture of R1234yf/R134a (with a ratio of 89:11, by mass) was used to replace R134a in MACs using variable speed compressor and micro-channel heat exchangers. The mixture can be made non-flammable and its GWP is less than 150, which is within the current EU regulations. In addition, the micro-channel heat exchanger used in this paper according with the latest trend of the MACs. The aims of this study were to investigate the system performance of R1234yf/R134a and R134a in cooling and heating modes in the same MACs, subsequently comparing the data.

2. Thermodynamic analysis

2.1. Fluid properties

The environmental and physical properties of R134a, R1234yf and R1234yf/R134a are shown in Table 1. All the thermodynamic properties were obtained from the NIST database REFPROP 9.1 [25] and the GWP calculation of R1234yf/R134a was cited from ref-