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Research Paper

Evaluation of R448A and R450A as low-GWP alternatives for R404A and R134a using a micro-fin tube evaporator model

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HIGHLIGHTS

- Different correlations for flow boiling in microfin tubes are evaluated.
- Akhavan-Behabadi et al. correlation presents the best predictions.
- Min. and max. deviations occur with R134a and R450A, respectively.
- R450A and R134a evaporator performances are almost the same.
- Due to high R448A glide, its evaporator performance is very different from R404A.

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ABSTRACT

When retrofitting new refrigerants in an existing vapour compression system, their adaptation to the heat exchangers is a major concern. R450A and R448A are commercial non-flammable mixtures with low GWP developed to replace the HFCs R134a and R404A, fluids with high GWP values. In this work the evaporator performance is evaluated through a shell-and-microfin tube evaporator model using R450A, R448A, R134a and R404A. The accuracy of the model is first studied considering different recently developed micro-fin tube correlations for flow boiling phenomena. The model is validated using experimental data from tests carried out in a fully monitored vapour compression plant at different refrigeration operating conditions. The main predicted operational parameters such as evaporating pressure, UA_{TP}, and cooling capacity, when compared with experimental data, fit within ±10% using the Akhavan-Behabadi et al. correlation for flow boiling. Results show that R450A and R404A are the refrigerants in which the model fits better, even though R448A and R134a predictions are also accurate.

1. Introduction

During the past decades, R134a, R404A and R507A have being used in different refrigeration and air conditioning applications as non-ozone depleting R12 [1] and R22 [2] substitutes, respectively. They present good energy performance, are non-toxic and non-flammable. However, due to the Kyoto Protocol approval [3], they have been identified as greenhouse gas (GHG) as the rest of HFCs (hydrofluorocarbon).

In order to enforce that agreed at the Kyoto Protocol, the European Union approved the Directive 2006/40/EC in 2006 [4], also known as F-gas Regulation. This Directive affected refrigerants with a GWP (Global Warming Potential) higher than 150 in new vehicles from 2011 and in all new vehicles produced from 2017. Then, in 2014, the Directive 2006/40/EC has been replaced by the Regulation (EU) No 517/2014, which bans the use of HFC with high GWP values in the rest of the refrigeration and air conditioning systems [5].

Considering the very large refrigeration applications using the vapour compression system, several low GWP refrigerant fluids with different characteristics can be found to replace HFCs in vapour compression systems, both natural and synthetic [6]. Natural refrigerants comprise hydrocarbons, flammable but economical and energy efficient; carbon dioxide, increasingly relevant and used in transcritical or cascade systems; and ammonia, toxic and flammable but very efficient. Synthetic refrigerants are considered good low and mid-term alternatives and can be differentiated as low-GWP HFCs, HFOs (hydrofluoroolefines) or mixtures of both groups.

Two HFOs appeared as R134a replacements [7]: R1234yf [8] and R1234ze(E) [9]. They present low-flammability, they are non-toxic

Abbreviations: GHG, greenhouse gas; GWP, global warming potential; HFC, hydrofluorocarbon; HFO, hydrofluoroolefines; HTC, heat transfer coefficient; ODP, ozone depletion potential.

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Table 1
Refrigerants' main properties [30].

	R134a	R450A	R404A	R448A
ASHRAE safety classification	A1	A1	A1	A1
ODP	0	0	0	0
100-year GWP	1430	547	3922	1273
Critical temperature (K)	374.21	379.02	345.20	356.81
Critical pressure (kPa)	4059.28	3814	3728.85	4674.93
NBP (K)	247.08	521.20	227.41	233.05
Glide[a] (K)	-	0.78	0.75	6.27
Liquid density[a] (kg m^{-3})	1295.27	1253.28	1150.59	1192.39
Vapour density[a] (kg m^{-3})	14.35	13.93	30.32	22.09
Liquid c_p[a] (kJ kg^{-1} K^{-1})	1.34	1.32	1.39	1.42
Vapour c_p[a] (kJ kg^{-1} K^{-1})	0.90	0.89	1.00	0.98
Liquid therm. cond.[a] (W m^{-1} K^{-1})	$92.08 \cdot 10^{-3}$	$83.09 \cdot 10^{-3}$	$73.15 \cdot 10^{-3}$	$92.41 \cdot 10^{-3}$
Vapour therm. cond.[a] (W m^{-1} K^{-1})	$11.50 \cdot 10^{-3}$	$11.57 \cdot 10^{-3}$	$12.82 \cdot 10^{-3}$	$12.01 \cdot 10^{-3}$
Liquid viscosity[a] (Pa s^{-1})	$267.04 \cdot 10^{-6}$	$258.22 \cdot 10^{-6}$	$179.70 \cdot 10^{-6}$	$188.35 \cdot 10^{-6}$
Vapour viscosity[a] (Pa s^{-1})	$10.72 \cdot 10^{-6}$	$11.15 \cdot 10^{-6}$	$11.00 \cdot 10^{-6}$	$11.42 \cdot 10^{-6}$

[a] Temperature = 273 K.

and their GWP values are 4 and 6 (accomplishing GWP limitations), respectively. R1234yf has been proposed as a R134a drop-in substitute in mobile air conditioning applications [10], and R1234ze(E) can be used in chillers [11] and heat pumps [12], among other applications.

Although R1234ze(E) shows relevant advantages in refrigeration systems, its use as a R134a drop-in replacement is not recommended because it presents lower cooling capacity [13] and low-flammability [14]. With the purpose of finding a most satisfactory solution (non-flammable, lower GWP values, with acceptable cooling capacity) and extending the lower GWP refrigerant usage for substitution of another HFC (as R404A and R410A), it has been mixed with some HFCs [15].

In this way, blends like R444A, R445A and R450A appeared as alternatives to substitute the refrigerant R134a. Focusing on blend R450A, it is a mixture of R1234ze(E) and R134a (58/42 in % mass) intended to replace R134a in medium temperature applications (chillers, heat pumps and commercial refrigeration, among others) [16]. It is non-flammable and its GWP is 549 (though it is not low enough for some cooling systems in Europe). It has shown good efficiency compared to R134a, as demonstrated by Mota-Babiloni et al. [17] in a vapour compression test rig and Tewis Smart solutions [18] or Honeywell International Inc [19] in a supermarket cascade systems. Lower performance has been shown in a water-cooled screw chiller installation [20].

In the other way, R448A appears as a blend alternative to substitute the R404A and it is composed of R32/R125/R134a/R1234yf/R1234ze(E) (26/26/20/21/7 in % mass), resulting non-flammable and GWP of 1205. R448A can substitute R404A in large centralized systems at low and medium evaporating conditions [21]. As happens for R450A, this HFO/HFC mixture also presents good performance. Mota-Babiloni et al. [22] studied theoretically six R404A alternatives in four vapour compression configurations, obtaining high efficiency simulating with R448A. Yana Motta et al. [23], using a 2.2 kW semi-hermetic condensing unit with evaporator for walk-in freezer/cooler, show that R448A matches the capacity of R404A with 6% higher efficiency. Rajendran [24] obtained lower energy consumption for R448A (3% to 8%) in a scroll compressor centralized Direct Expansion system with cases and food simulators. Abdelaziz and Fricke [25], in a test facility that uses reciprocating compressors and two separate temperature/humidity controlled rooms, found that refrigerant R448A average energy efficiency was 11.6% higher than that obtained with R404A.

When designing vapour compression systems, the evaporator selection is one of the most important parts [26]. One of the main parameters in an evaporator design is the flow boiling heat transfer coefficient (HTC) and depends on the evaporator geometry and the refrigerant properties [27]. Flow boiling HTC can be determined accurately through steady-state evaporator models, as demonstrated, for example, by Navarro-Esbrí et al. [28] or Zhao et al. [29] for R1234yf and R134a.

R450A and R448A are promising alternatives to two of most currently used refrigerants, R134a and R404A, due to their similar properties (Table 1). The problem is that the there are few data available for both alternative refrigerants and the effect of replacing HFCs cannot be predicted properly. In this paper a shell-and-micro-fin tube evaporator model is validated and used to evaluate these refrigerants considering different relevant heat exchanger parameters. The most accurate model is applied to compare the evaporator performance between these refrigerants. The conclusions of this work can be used in the evaluation of HFC substitution or in the refrigeration system and heat exchanger design using R450A and R448A, two refrigerants that can achieve great GWP reductions and, therefore, lessen the global warming.

The rest of the paper is structured as follows: In section 2, the experimental setup, refrigerants and test performed are presented. In section 3, the evaporator model is mentioned. In section 4, the correlations selected are exposed. In section 5, the results of the study are discussed. Finally, in section 6, the main conclusions are summarized.

2. Experimental setup

2.1. Test bench

The test bench used in this work is a fully monitored vapour compression plant that consists of a main circuit and two secondary circuits (Fig. 1). The vapour compression system is composed of the following components:

- Reciprocating open compressor, driven by variable-speed 7.5 kW electric motor using polyolester (POE) oil as lubricant. The compressor speed can be selected using an inverter.
- Shell-and-smooth tube condenser (1–2), with refrigerant flowing along the shell and the water (used as secondary fluid) inside the tubes.
- Shell-and-micro-fin tube evaporator (1–2), where the refrigerant flows inside the tubes and a water/propylene glycol mixture (65/35 by volume) along the shell.
- Thermostatic expansion valve.
- Corrugated counterflow tube-in-tube internal heat exchanger (also known as suction-line/liquid-line heat exchanger), which is activated or deactivated by a set of solenoid valves.