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EXPERIMENTAL EVALUATION OF THE AZEOTROPIC MIXTURE R516A AS AN R134A DROP-IN ALTERNATIVE FOR MODERATELY HIGH-TEMPERATURE HEAT PUMPS

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Abstract: *The moderately high-temperature heat pump (MHTHP) is a market with a great potential to reduce greenhouse gas emissions from the heating sector. However, future proof MHTHPs cannot be based on hydrofluorocarbons with high global warming potential (GWP). Fourth-generation refrigerants with GWP below 150 are required. This work experimentally investigates the new azeotropic mixture R516A as a drop-in alternative to R134a, with a low GWP (142). Measurements are taken from a test rig at different steady-state operating conditions. The evaporating temperature is 7.5 ºC, 15 ºC and 22.5 ºC, and condensing temperature varies between 55 ºC and 75 ºC, at steps of 5 ºC. R516A presents a lower discharge temperature (average reduction of 7 ºC), which provides a safer operation for the compressor and increases its lifespan. R516A heating capacity reduction is 13.5% on average, with a reduced heating effect and comparable compressor power consumption. R516A shows a 12% COP reduction at higher evaporating temperatures.*

Keywords: heating, vapour compression system, global warming potential, R134a drop-in replacement, R516A.

1. INTRODUCTION

Global warming represents one of the most significant challenges humankinds has faced in the last decades. In 2020, Europe was 1.2 °C warmer than the average year in the 19th Century [1]. In 2021, several countries suffered the highest temperature on record in Mediterranean basin countries and a higher number of fires than ever before [2]. Heat pump technology enables year-round comfort control for building occupants, domestic hot water, and district heating by extracting heat from ambient, water, ground, or industrial processes (waste heat recovery).

According to a recent strategy approved by Heat Roadmap Europe and the vision of the European Council's 20/20/20 target for reducing greenhouse gas emissions [3,4], it is essential to determine the carbon footprint of a heat pump system with low global warming potential (GWP) refrigerants.

One of the most commonly used HFC refrigerants is R134a, widely used in refrigeration, air conditioning, and heat pump applications [5]. It is a greenhouse gas (GHG) approximately 1400 times more potent than carbon dioxide. Phase-down and transition to working fluids with a GWP below 150 would mitigate the climate impact significantly caused by these systems [6].

The first hydrofluorolefin (HFO), developed by DuPont and Honeywell, is R1234yf [7], presenting comparable thermodynamic properties to R134a. Therefore, some authors consider it a straightforward replacement for R134a, with the only concern of its mild flammability. Colombo et al. [8] proved in a water-to-water heat pump that R1234yf shows a heating capacity and COP reduction to 9.8% and 7.4%, respectively. Thu et al. [9] experimentally investigated an R32/R1234yf/R744 (22/72/6 by mass percentage) mixture as an alternative to R134a for three operation modes: cooling, low temperature, and high-temperature heating. The mixture provided the highest COP for the low-temperature heating mode.

Most previous research has focused on studying new synthetic pure and mixture working fluids in R134a refrigeration applications. In addition, these fluids can also be used for heating, particularly at moderate temperature heat pump conditions. Mota-Babiloni et al. [10] considered R1234ze(E) and R515B for moderately high-temperature heat pumps designed for R134a. The experimental results were comparable amongst the tested refrigerants, with a 15 and 28% reduction in CO_2-eq emissions for R1234ze(E) and R515B, respectively, and a broader operation range, but significant reduction in heating capacity. Therefore, the research on the low-GWP mixture refrigerant R516A is necessary and meaningful. Al-Sayyab et al. [11] performed a numerical performance comparison for a compound ejector-heat pump system using twelve low GWP refrigerants, including R516A, R1234yf, and R513A. The study determined that R516A and R1234yf have comparable energy performance.

From an operational and energetic point of view, this work uses experimental data to comprehensively analyse the benefits and limitations of the R516A as a compatible replacement for R134a at moderately high-temperature heat pump conditions. The thermodynamic properties of R516A can make it a close match to R134a, so it is proposed as a future-proof alternative. Apart from the novelty of presenting R516A experimental results in heating conditions for the first time, the number of experimental tests, detailed description of the vapour compression test bench, and broad range of operating conditions make this paper one of the most extensive assessments of R134a low GWP drop-in assessments.

2. EXPERIMENTAL METHODOLOGY

2.1. Experimental setup

The system is composed of a fully monitored single-stage system with an IHX vapour compression circuit and two closed-loop with glycol brine and water. The main components of the vapour compression circuit are shown in Figure 1. Full system components descriptions were mentioned in [12].

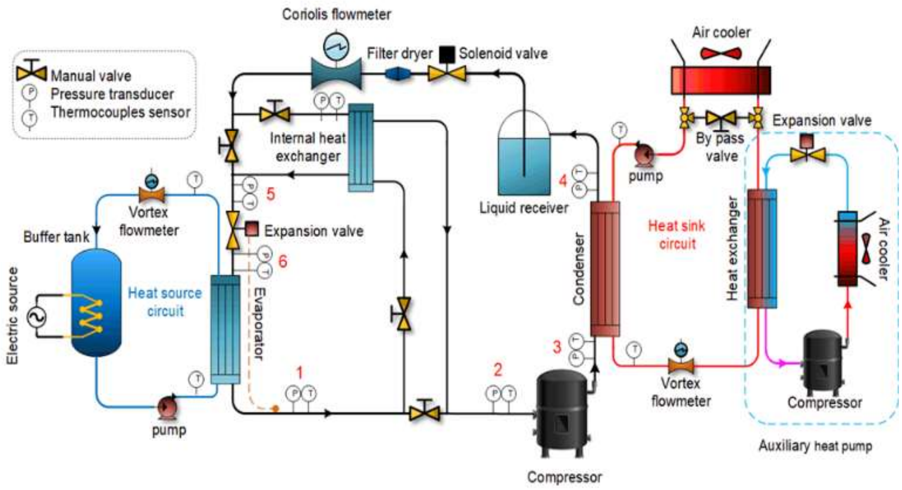


Figure 1. Experimental setup schematic diagram

2.2. Operating conditions

To evaluate the suitability of R516A as an alternative drop-in replacement to R134a in moderately high- temperature applications (Table 1), experiments were carried out at three different evaporating temperatures, 7.5 °C, 15 °C and 22.5 °C, with 12 °C glycol temperature difference across the evaporator. Meanwhile, the condensing temperatures were set at (55 °C to 75 °C by step 5°C), with 20 °C condenser's cooling water temperature difference.

Table 1. Thermophysical properties of the tested refrigerants [13,14]

Refrigerant	Molecular weight (g mol^{-1})	T_{crit}(°C)	P_{crit} (MPa)	ρ_{vapor} [a] kg m^{-3}	ρ_{liquid} [a] kg m^{-3}	h_{fg} [a] kJ kg^{-1}	NBP (°C)	ODP	GWP_{100}	Safetyclass ASHRAE
R134a	102.03	101.0	40.59	5.258	1377	217.0	-26.09	0	1430	A1
R516A	102.58	97.30	36.45	5.929	1321	188.5	-29.40	0	142	A2L

[a] At a pressure of 1.01325 bar

2.3. Equations

The heating effect can be obtained from Eq. (1) using the refrigerant specific enthalpy difference across the condenser.

$$q_k = \left(h_{k,out} - h_{k,in}\right) \tag{1}$$

In the same context, the heating capacity can be evaluated from Eq. (2), multiplying the heating effect by the refrigerant mass flow rate.

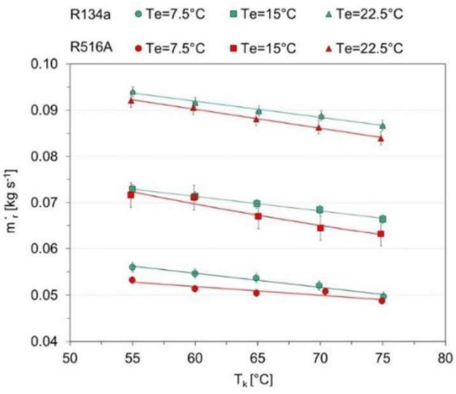
$$\dot{Q}_k = \dot{m}\, q_k \tag{2}$$

The coefficient of performance (COP) results from Eq. (3).

$$COP = \frac{\dot{Q}_k}{\dot{W}_c} \tag{3}$$

3. RESULTS AND DISCUSSION

A higher condensing temperature at constant evaporation temperatures reduces the mass flow rate due to the pressure ratio increase, leading to lower volumetric efficiency values. On the other hand, the evaporator temperature increase positively affects refrigerant mass flow rate at a constant condensing temperature. This effect is caused by increased refrigerant density and volumetric efficiency (Figure 2.a) and a pressure ratio decrease (Figure 2.c). R516A shows a lower average volumetric efficiency and mass flow rate, making larger compressor displacement necessary to match R134a heating capacity. Finally, the R516A pressure ratio is close to R134a at higher evaporating temperatures.



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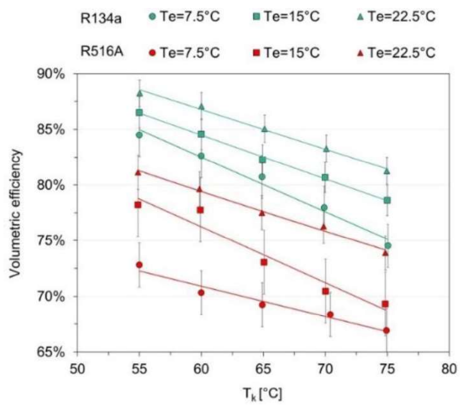

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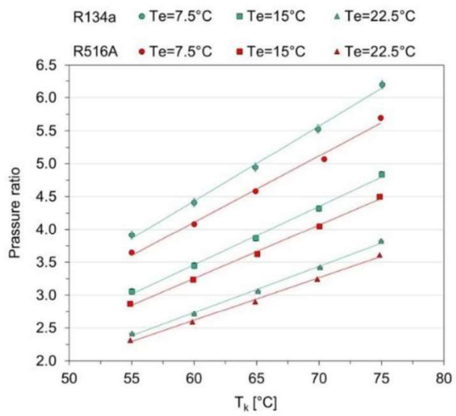
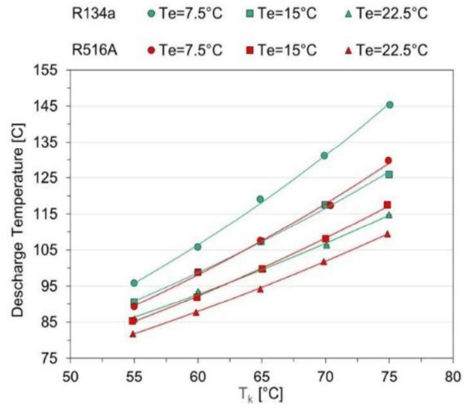


c)



d)

Figure 2. Comparison of a) mass flow rate, b) volumetric efficiency, c) pressure ratio, and d) discharge temperature.

An excessive discharge temperature causes compressor lifetime reduction. This point reflects all heat absorbed by the refrigerant during the evaporation, superheating and compression processes. From Figure 2d, an increase in condensing temperature at constant evaporating temperature led to a higher discharge temperature. R516A ends with a lower discharge temperature.

From Figure 3, the compressor power consumption is directly proportional to the condenser temperature. Meanwhile, the increase in evaporating temperature slightly reduces compressor consumption power due to pressure ratio reduction with refrigerant mass flow rate increasing (one offset the other). Compared with R134a, the R516A present lower values.

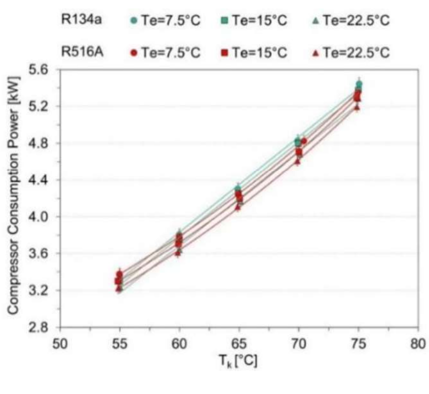


Figure 3. Compressor power consumption versus condensing temperature

The condenser heating capacity is the most critical parameter in heating. The condensing temperature negatively influences the heating capacity at a constant evaporating temperature, Figure 4. The previously analysed mass flow rate reduction is combined with a heating effect reduction. In comparison, R516A shows a lower heating capacity at the highest evaporating temperature. A higher evaporating temperature increases system heating capacity at constant condensing temperature due to the pressure ratio decrement (Figure 2.c) as the refrigerant mass flow rate increases (Figure 2.a). The heating effect is proportional to the condensing temperature at the evaporating temperature of 7.5 °C, as opposed to other evaporating conditions. This is caused by a higher superheating degree, which positively affects the desuperheating process [15].

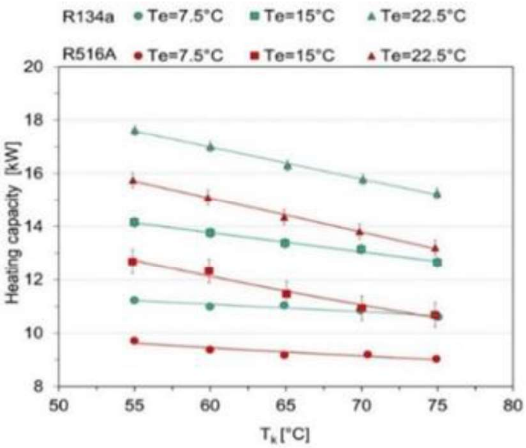


Figure 4. Condensing temperature effect on heating capacity

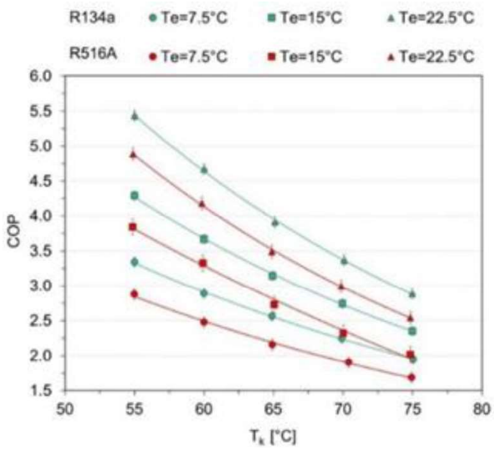


Figure 5. COP versus condensing temperature

Figure 5 exhibits the COP as the indicator of heating energy performance. At constant evaporating temperatures, a higher condensing temperature decreases COP due to compressor consumption power increase, representing the factor that takes a dominant role associated with a heating capacity decrease. On the other hand, the evaporating temperature increases COP at constant condensing temperature, owing to a consumption power decrease (Figure 3) associated with a heating capacity increase (Figure 4). R516A shows a lower COP than R134a for all tested conditions, with an average reduction of 4% to 12%.

4. CONCLUSIONS

Low GWP refrigerant R516A was compared to R134a in a test rig at a wide range of operating conditions. The evaporating temperature was 7.5 ºC, 15 ºC and 22.5 ºC, and five condensing temperatures (55 ºC to 75 ºC, increments of 5 ºC) were considered. The novel mixture R516A exhibits a comparable refrigerant mass flow rate to R134a. R516A results in a lower heating capacity value and a higher consumption power. Therefore, the R516A COP is reduced by 10% to 15% compared to R134a.

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