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Experimental Assessment of the Internal Heat Exchanger in Vapour Compression Systems With Low GWP Refrigerant R516A#

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ABSTRACT

Internal heat exchangers (IHX) are commonly used to improve the energy performance of vapour compression refrigeration cycles. However, the magnitude of the improvement depends on the refrigerant and operational conditions. This paper experimentally investigates the influence of a high IHX on vapour compression systems. The new low global warming potential refrigerant R516A is assessed as a drop-in replacement to R134a at different medium temperature refrigeration conditions. In the case of a 40% effectiveness IHX, R516A shows the highest cooling capacity (4.8% to 9.1%), and COP (4.9% to 11.6%) increases compared to the situation without this element. It can be concluded that the IHX always benefits the energy performance of the refrigeration system at acceptable compressor discharge temperatures.

Keywords: IHX, cooling, vapour compression system, low global warming potential (GWP), R516A

NONMENCLATURE

Abbreviations	
NBP	Normal Boiling Point (°C)
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IHX	Internal heat exchanger
ON	With IHX
OFF	Without IHX
Symbols	
COP	Coefficient of performance (-)
h	Specific enthalpy (kJ kg^{-1})
$\dot{m}$	Refrigerant mass flow rate (kg s^{-1})
P	Pressure (kPa)
$\dot{Q}$	Cooling capacity (kW)
RPM	Revolutions per minute
T	Temperature (°C)
TEWI	Total Equivalent Warming Impact ($CO_{2\text{-}eq}$)
$\dot{W}$	Compressor power consumption (kW)
ε	Heat exchanger effectiveness (-)
Subscripts	
c	Compressor
e	Evaporator
in	Inlet
k	Condenser
N	Normalised (for TEWI calculation)
out	Outlet

1. INTRODUCTION

Hydrofluorocarbons (HFCs) are greenhouse gases with remarkable global warming potential (GWP), which replaced ozone-depleting substances in the past decades. They are primarily used as refrigerants in refrigeration and heat pump applications. According to the Kigali Amendment to the Montreal Protocol, the meeting parties agreed on 15 October 2016 to add HFCs to the list of controlled substances and decrease their use by 80% to 85% by 2040 [1].

Phase-down (place on the gradual market reduction) and transition to refrigerants with a GWP below 150 would mitigate the environmental impact caused by heating, ventilation, air conditioning and refrigeration (HVACR) systems [2].

Hydrofluoroolefins (HFOs) are included in the fourth generation of fluorine-based (synthetic, organic) refrigerants, potentially offering many of the benefits of HFCs but with a lower GWP. The first HFO, developed by DuPont and Honeywell, is R1234yf [3]. It presents an ultralow GWP (below 10, according to different revisions of the Intergovernmental Panel on Climate Change

(IPCC)), and it is mildly flammable (A2L ASHRAE Standard 34 classification).

Some authors have evaluated the energy performance of refrigeration systems with R1234yf as a drop-in substitute for R134a. Janković et al. [4] experimentally studied R1234yf and R1234ze(E) as alternative refrigerants to R134a in small refrigeration units. R1234yf provided comparable energy performance to R134a., whereas R1234ze(E) was required to increase the compressor size to match cooling capacity. De Paula et al. [5] simulated and optimised a 1200 L cooling unit using R744 (CO2), R290 (propane), and R1234yf as R134a alternative refrigerants. The optimised system with R290 showed the highest energy and environmental performance.

Many studies have already investigated HFC/HFO mixtures as R134a drop-in replacements offering a trade-off between flammability and GWP. Thu et al. [6] 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 mode. The mixture provided the highest system COP at low-temperature heating mode. Mota-Babiloni et al. [7] determined the influence of IHX effectiveness variation on system performance at different evaporating temperatures. R513A presented a noticeable reduction in discharge temperature compared to R134a and a cooling capacity and COP benefit when the IHX was used.

Due to the GWP value of 631, it can be limited to specific applications by phase 3 or the F-gas Regulation EU 517/2014 phase-out for refrigerants with GWP above 150 in 2025 [8]. Therefore, the research on refrigerant R516A, a mixture with a GWP of less than 150, is necessary and meaningful. Al-Sayyab et al. [9] simulated a compound ejector-heat pump system and compared the energy performance of twelve low GWP refrigerants, including R516A. The study concluded that R516A and R1234yf have comparable system energy performance.

This work experimentally studies the IHX influence on vapour compression systems' energy performance using R516A as a replacement for R134a under different operational conditions.

2. MATERIALS AND METHODS

2.1 Low Global Warming Potential Refrigerants

In the current study, the suitability of the low GWP refrigerant R516A is evaluated as a replacement for R134a. Figure 1 shows that R516A presents a GWP reduction of 90% with nearly comparable properties. Moreover, molecular weight, critical temperature and vapour density are comparable. The major differences between refrigerants are observed in the critical pressure, liquid density, and Normal Boiling Point (NBP). However, these differences benefit the operational characteristics of the new mixture, so its experimental evaluation as an R134a replacement is justified and convenient.

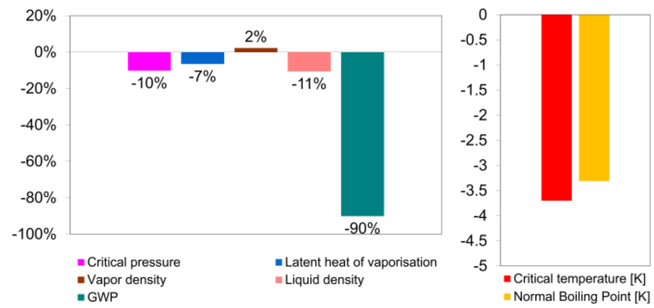

Fig. 1 R516A Properties Comparison with R134a

2.2 Experimental Setup

Figure 2 shows the schematic diagram of the test rig, including its main components and sensors. It comprises a fully monitored single-stage IHX vapour compression cycle connected to two closed loops with glycol brine and water. Full component descriptions were mentioned in previous work [10].

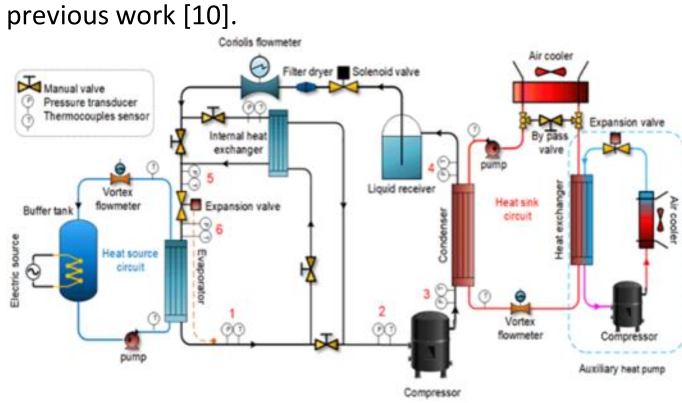

Fig. 2 Refrigeration Test Rig Schematic Diagram

2.3 Operating Conditions

Experimental tests are carried out to evaluate the IHX influence according to the conditions mentioned in Table 1. The metering devices' accuracy is mentioned in Table 2.

Table 1. Experimental Operational Conditions

Parameters	**Conditions**
Condensing Temperature	32.5 °C
Evaporating Temperature	−15 °C to −5 °C
Glycol Temperature Difference	5 °C
Water Temperature Difference	6 °C
Compressor Rotational Speed	2030 RPM
Compressor Displacement Volume	114.5 cm^3

Table 2. Metering Devices Accuracy

Components	**Accuracy**
Refrigerant Coriolis Mass Flow Meter	±0.15%
Glycol and Water Volumetric Flow Meter	±0.33% (Glycol) and ±0.114 m^3h^{-1} (Water)
Pressure Transducer	±0.15%
Thermocouple K Type	±0.3 K
Compressor Power Consumption	±1.55%

2.4 Theory/calculation

The equations required to determine the energy performance are listed in Table 3.

Table 3. Main Equations

Parameter	Equation
IHX Effectiveness	$\varepsilon_{IHX} = \dfrac{h_{c,in} - h_{e,out}}{h_{k,out} - h_{e,out}}$
Cooling Capacity	$\dot{Q} = \dot{m}(h_{e,out} - h_{e,in})$
COP	$COP = \dfrac{\dot{Q}}{\dot{W}}$

3. RESULTS AND DISCUSSION

For all situations, Figure 3 presents that the refrigerant mass flow rate is directly proportional to evaporating temperature. Moreover, the compressor suction density decreases because of a higher superheating degree, so the IHX reduces the refrigerant mass flow rate. Comparing the 40% IHX effectiveness case without it, R516A shows the most significant mass flow rate reduction (2.3% to 3.7%). R516A has a higher mass flow rate than R134a (5 to 53%).

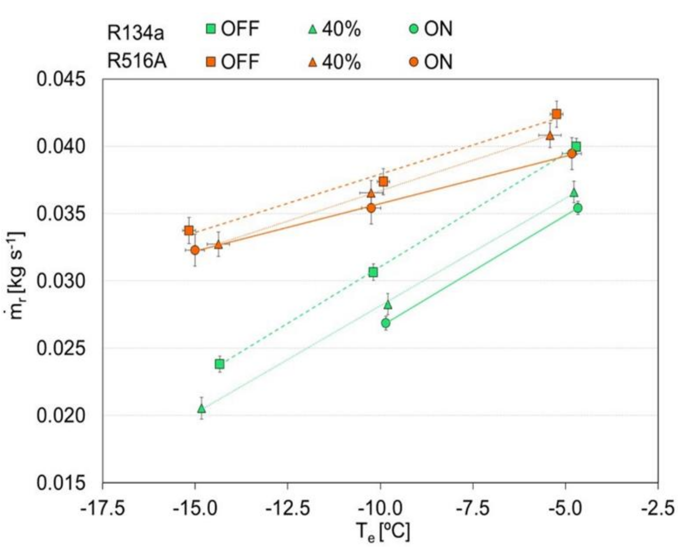

Fig. 3 Refrigerant Mass Flow Rate

Figure 4 shows that the IHX significantly increases the cooling capacity at a given evaporating temperature due to a dominant refrigerating effect increment. Regarding 40% IHX effectiveness compared with the OFF case, R516A exhibits the most significant cooling capacity increment (4.8% to 9.1%). Then, R516A shows the highest cooling capacity at low evaporating temperatures, 15% to 40%. This indicates that R516A is suitable for low-temperature refrigeration applications.

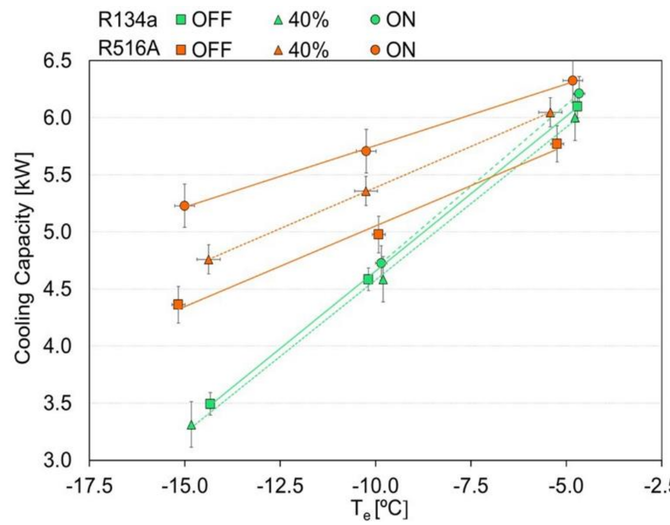

Fig. 4 Cooling Capacity Measurements

From Figure 5, in all IHX cases, the increasing evaporating temperature slightly reduces consumption power, so R516A shows the highest values. On the other hand, the IHX reduces compressor power consumption (Figure 5) because the refrigerant mass flow rate diminution (Figure 3). The IHX impact on compressor pressure ratio can be considered unremarkable, and the higher specific compressor work is negligible compared to the mass flow rate increase.

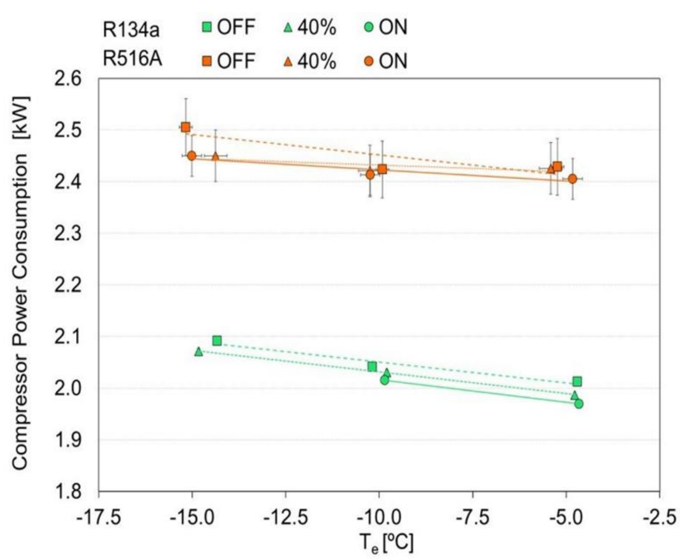

Fig. 5 Compressor Power Consumption Measurements

For all IHX cases, the evaporating temperature increases COP (Figure 6). On the other hand, the IHX also leads to a higher COP owing to consumption power consumption reduction and cooling capacity increase. When 40% IHX effectiveness is actuated at a defined evaporating temperature, R516A has the highest COP increase compared without IHX (4.9% to 11.6%).

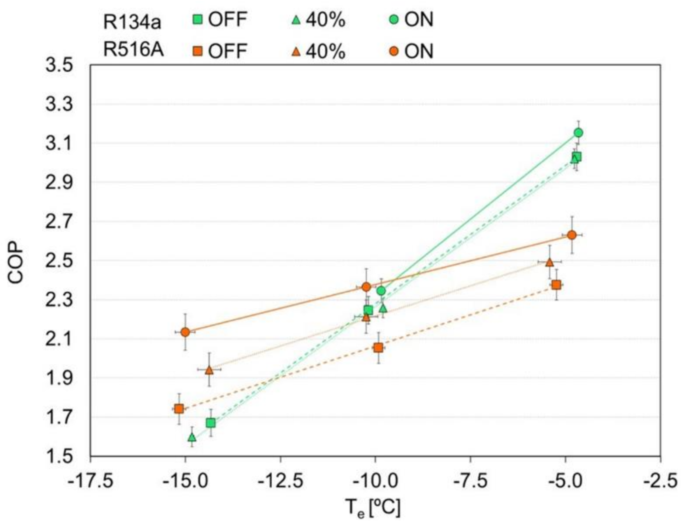

Fig. 6 COP Measurements

The Total Equivalent Warming Impact (TEWI) parameter analyses different carbon emission factors and refrigerant leakage ratios. TEWI results are normalised to the cooling capacity of the respective refrigerant ($TEWI_N$) to prevent cooling capacity inequivalence. The heat pump with R516A shows $TEWI_N$ reduction, ranging from 41% to 86% (Figure 7).

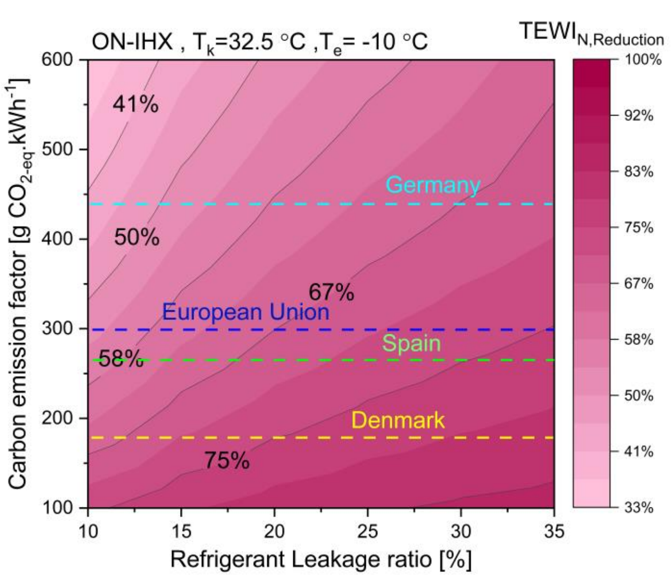

Fig. 7 $TEWI_N$ Reduction Using R516A

4. CONCLUSIONS

In this experimental assessment considering R516A and R134a refrigerants, it was proved that the IHX always increases energy performance under all considered conditions. In the case of 40% IHX effectiveness and compared with the off case, R516A shows the highest cooling capacity and COP increase of 4.9% to 11.6% and 4.8% to 9.1), respectively. R516A presents the highest consumption power, with the lowest cooling capacity at high evaporating temperatures.

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