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RE170 (Dimethyl Ether) and ternary mixtures (R744 / RE170 / R600) as alternatives to R290 for refrigeration and heat pump applications

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A R T I C L E I N F O

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A B S T R A C T

This study explores the potential of dimethyl ether (RE170) and ternary mixtures (R744/RE170/R600) as alternatives to R290 in refrigeration and heat pump applications. A thermodynamic analysis using Refprop v.10 was conducted to determine optimal compositions, followed by an experimental evaluation in a single-stage vapor compression cycle with a variable speed compressor. Results indicate that RE170 and its mixtures provide superior energy efficiency compared to R290, with maximum COP improvements of 29.8 % (refrigeration) and 17.99 % (heat pump), albeit with reduced cooling and heating capacities. Experimental tests show that RE170 is the best candidate for substitution, as it avoids temperature glide and maintains higher heat transfer coefficients. These findings suggest that RE170 and its optimized mixtures could enhance system efficiency, provided adequate system modifications are implemented.

1. Introduction

The search for environmentally friendly and energy-efficient solutions has intensified the investigation into alternative refrigerants for refrigeration and heat pump applications. The exploration of new fluids was first driven by the need to find replacements to high GWP refrigerants such as R134a, R404A, R410A or even R32, most of which resulted in mildly flammable or highly flammable refrigerants. Subsequently, this search was intended to combine energy efficiency and flammability reduction.

One of the most extensive searches for alternatives to R404A and R410A was conducted by Domanski et al. (2017), who concluded that the availability of single component low-GWP options to replace them is very limited and the possible alternative mixtures are at least mildly flammable. Moreover, they stated that refrigerant mixtures should be closely analysed and specifically for given applications. Bell et al. (2019) focused the search to find non-flammable alternatives to R134a in air-conditioning applications identifying 16 binary and ternary mixtures that, being non-flammable, presented similar capacity to R134a by offering a reduction in the GWP nearly of 54 %. Additionally, they found 7 mixtures that, despite being ‘marginally flammable,’ offered a 99 % reduction in GWP. Later, Calleja-Anta et al. (Calleja-Anta et al., 2021) amplified the method to find fluids with GWP below 150 and established the frontier between mixtures belonging to A3 or A2 ASHRAE security classifications (ASHRAE 2016). They concluded that only mixtures of hydrocarbons (R290, R600a and R1270) with A2 or A2L components (HFOs and R152a) could meet the criteria, but they would always present mildly flammable characteristics.

Industry, when the security restrictions allowed it, has selected pure hydrocarbons, specially R600a and R290, as final solutions for low- and medium stand-alone capacity applications, since they offer negligible GWP along with good thermodynamic and energy performance. However, the search for solutions that maintain excellent environmental behaviour but with greater energy efficiency has been intensified. In fact, Calleja-Anta et al. (2020) elaborated the first screening of mixtures alternatives to R600a and R290 concluding that, compared to those fluids, the COP could be increased by up to 7.6 % for R600a and up to 11.6 % for R290. Mixtures identified theoretically are based on the use of the base fluids (R600a and R290) with small proportions of other fluids, such as R600, R152a, R1234yf, among others. This theoretical study was subsequently validated. First, with an experimental domestic fridge, where in relation to R600a the mixtures R-600a/R-1234yf (92.5/7.5 %), R1234ze(E)/R600 (10.5/89.5 %) and R600/R290 (89.0/11.0 %) reduced the energy consumption of the appliance by 2.15, 3.84 and 1.31 % respectively (Calleja-Anta et al., 2022). And second, with a large commercial cooler, where the blends R-1234ze (E)/R600 (8/92) and R-152a/R-600 (8/92) achieved energy consumption reductions of 2.69 % and 5.04 %, respectively in relation to R600a (Calleja-Anta et al., 2023).

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Nomenclature

c_p	specific heat at constant pressure, kJ·kg^{-1}·K^{-1}
COP	Coefficient of Performance
COP_{HP}	Coefficient of Performance referred to heat pump
COP_R	Coefficient of Performance referred to refrigeration
DME	Dimethyl ether
EXV	Electronic Expansion Valve
GWP	Global Warming Potential over 100-year, $kg_{co2,eq}·kg^{-1}_{ref}$
h	specific enthalpy, kJ·kg^{-1}
m	mass flow rate, kg·s^{-1}
M	Molar mass, g·mol^{-1}
N	compressor speed, rpm
NBP	Normal Boiling Point, °C
ODP	Ozone Depletion Potential
p	absolute pressure, bar
P_c	compressor power consumption, W
$\dot{Q}_o$	cooling capacity, W
q_o	specific cooling capacity, kJ·kg^{-1}
$\dot{Q}_k$	heating capacity, W
q_k	specific heating capacity, kJ·kg^{-1}
SH	Superheating, K
SUB	Subcooling, K
t	temperature, °C
$\bar{t}_k$	average refrigerant condensing temperature, °C
$\bar{t}_o$	average refrigerant evaporation temperature, °C
V	volume flow rate, L·h^{-1}
VCC	Volumetric Cooling Capacity, kJ·m^{-3}
VHC	Volumetric Heating Capacity, kJ·m^{-3}
v	specific volume, m^{-3}·kg
w_c	specific compression work, kJ·kg^{-1}

Subscripts

crit	at critical conditions
dis	refers to compressor discharge conditions
exp	refers to the expansion device
glyc	refers to propylene glycol-water mixture
in	inlet
k	related to condensation
liq	refers to liquid
o	related to evaporation
out	outlet
rel	relative
sat	refers to saturated state
suc	refers to compressor suction conditions
sec,fluid	related to the secondary fluid
vap	refers to vapour
w	related to the water

Greek symbols

λ	latent heat of phase change, kJ·kg^{-1}
ρ	density, kg·m^{-3}
ε_{comp}	global compressor efficiency
Ø	diameter, mm
Δt_k	refrigerant temperature difference between the condenser inlet and outlet, K
Δt_o	refrigerant temperature difference between the evaporator inlet and outlet, K

However, when it comes to R290 alternative fluids, the investigations are scarce and still ongoing. There are mixtures developed to substitute R22, which also fit in R290 plants (Antunes and Bandarra Filho, 2016; Shaik et al., 2023; Paradeshi et al., 2019), such as R436A, R435A or R510A, based on mixtures of R290/R600a, RE170/R152a and RE170/R600a respectively (Albà et al., 2023), but no experimental results analysing them has been found. One of the components of the above-mentioned blends is the dimethyl ether (DME or RE170), which is considered one of the first refrigerants in history (Engelbrecht et al., 2024). The use of DME has regained again attention during the last years, since it is a fluid with excellent thermophysical and environmental properties (low GWP and zero ODP). Recent theoretical works have highlighted the possible potential of DME and its mixtures in refrigeration applications. Bolaji et al. (2021), Bolaji and Huan (2012) observed that R510A [RE170/R600a, (88/12 %)] and RE170 presented higher COP and refrigerating capacity in relation to R134a in evaporation temperatures from −30 to 10 °C, predicting COP increments of 6.2 % for the RE170 and of 10.0 % for R510A. Maalem et al. (2020) considered an azeotropic mixture, R134a/RE170/R600a (3.3/83.7/13.0 %), as replacement of R134a in some refrigeration and heat pump architectures and concluded that the mixture consistently improves the performance in relation to R134a and also presents higher specific cooling effect. Liu et al. (2022) considered different large glide mixtures of RE170 with some other components in air source heat pumps for hot water production, remarking the best performance achieved by the mixture R744/RE170 (30/70 %). Vaccaro et al. (2024) explored CO_2-DME mixtures for application in transcritical refrigeration cycles. They concluded that the mixture CO_2/RE170 (92/8 %) could allow a non-flammable mixture with a COP increase of 25 % in relation to pure CO_2. And finally, Caramaschi et al. (2024) focused on a residential heat pump with low refrigerant charge with the mixtures RE170/CO_2 (96/4 %) and RE170/R1270 (75/25 %) concluding that the best potential was that of the mixture with CO_2.

Experimentation with RE170 and its mixtures has gained interest in the past year, allowing to verify the previous theoretical hypothesis. First experimental work was performed by Cop et al. (2024), who tested two mixtures of R290/RE170 in a commercial laundry dryer with a heat pump system. Although the system fluid was R134a, they observed that the mixtures with RE170 were able to increase the heating COP >7 %, with larger heating capacity, and, in addition, to operate with 40 % lower refrigerant charge. Second, Vaccaro et al. (2024) used RE170 to create CO_2-doped mixtures to be used in a water chiller. After system optimization, they measured experimental COP increments in relation to CO_2 operation of 15 % for a mixture containing 10 % of RE170. They indicated that the experimental improvements are below to those predicted theoretically, but confirmed the trends observed in the theoretical evaluations (Vaccaro et al., 2024). Finally, the last work up to date, is that of Calleja-Anta et al. (2024) who evaluated in a laboratory test rig the mixtures RE170/R600 as potential substitutes of R600a. After composition optimization, they verified that the best one was RE170/R600 (15/85 %), which can be considered a drop-in fluid for R600a, with COP increments from 10.1 to 17.6 % in the tested conditions and with similar cooling capacities.

As mentioned, the search for alternative fluids to pure hydrocarbons for small refrigeration systems with best energy efficiency is a new line of research which has been already verified experimentally for R600a systems, confirming initial theoretical studies. Some of the alternative fluids are based on zeotropic mixtures with dimethyl-ether (RE170) being one of the components that has shown the best results when mixed with other substances. However, although this search has been considered from a theoretical perspective as a replacement for R290, it has not yet been experimentally validated. This work, aiming to contribute to this research line, considers RE170 and its mixtures with CO_2 and R600 as potential alternatives to R290 in refrigeration and heat pump applications. The work covers a detailed thermodynamic analysis of DME and the optimum composition of the mixture, and an accurate experimental evaluation in a laboratory test rig using a single-stage compression cycle with a variable speed hermetic compressor.

2. Theoretical evaluation of alternative mixtures

This section provides a thermodynamic approach that determines the compositions of the mixture containing R744, RE170 and R600 that provides the best energy performance in relation to R290 that can be used as R290 substitute in refrigeration and heat pump application. These three refrigerants were chosen after a preliminary analysis done in which different mixtures were considered. Calculations in this section are based on Refprop v.10 (Lemmon et al., 2018), the most accurate database up to the moment, but it needs to be considered that this approach has limitations, as Refprop does not contain the binary mixing coefficients for this mixture for the moment.

2.1. Considered fluids

In relation to the base fluids, Table 1 contrasts important properties and Fig. 1 represents their pressure-enthalpy diagram. Two of them are pure hydrocarbons while RE170 is an ether and R744 an inorganic compound. All feature negligible GWP values; and regarding ASHRAE safety classifications, all are categorized as A3, except for R744, which is classified as A1.

First, RE170 has higher NBP, t_{crit} and p_{crit} than R290. This implies that for the same working temperatures a system will operate with lower pressures than R290. However, it also exhibits higher latent heat of phase change, which increases by 16.0 % at 0 °C and 26.1 % at 50 °C in relation to R290. Specific volume of RE170 is significantly higher than that of R290 (+77 % at 0 °C). Although the latent heat of phase change increases, its higher volume will imply important reductions in capacity if used directly as substitute fluid. Second, R600 has also higher NBP and t_{crit} than R290, but its p_{crit} is lower. This fluid has also larger latent heat of phase change than R290 (+2.7 % at 0 °C and +17.0 % at 50 °C) and higher specific volume (+274 % at 0 °C) and, again it cannot be considered as drop-in fluid of R290 since the capacity of the plants will greatly drop. Finally, R744 has opposite properties. Its latent heat of phase change is 38.4 % lower at 0 °C and its high p_{crit} and working pressures in comparison to R290 (34.8 vs. 4.7 bar) generate lower specific volumes (−89.7 % at 0 °C). The combination of these last properties will provide systems with larger capacities, however, due to its low t_{crit}, their use in R290 systems is not feasible since will require operation in transcritical conditions.

Generation of a mixture able to operate in R290 systems with these fluids can be done strategically by taking the advantage of RE170 and R600 (higher latent heat of phase change) and combining them with R744 to increment the operating pressures and reduce their high specific volumes. This analysis is presented in the next subsection.

Table 1
Physical and environmental characteristics of the refrigerants involved in this work (obtained with Refprop 10 (Lemmon et al., 2018)).

	R290	R600	RE170	R744
M ($g \cdot mol^{-1}$)	44.1	58.1	46.1	44
NBP (°C)	−42.1	−0.5	−24.8	−56.6*
t_{crit} (°C)	96.7	152.0	127.2	31.0
p_{crit} (bar)	42.5	37.9	53.4	73.8
λ at $t = 50$ °C ($kJ \cdot kg^{-1}$)	284.9	333.8	359.4	-
λ at $t = 0$ °C ($kJ \cdot kg^{-1}$)	374.9	385.3	435.0	230.9
v_{suc} at $t = 0$ °C & $x_v = 1$ ($m^3 \cdot kg^{-1}$)	0.097	0.363	0.172	0.010
$GWP_{100\text{-}years}$ (IPCC 2023)	3	3	1	1
ASHRAE 34 safety group	A3	A3	A3	A1

* triple point.

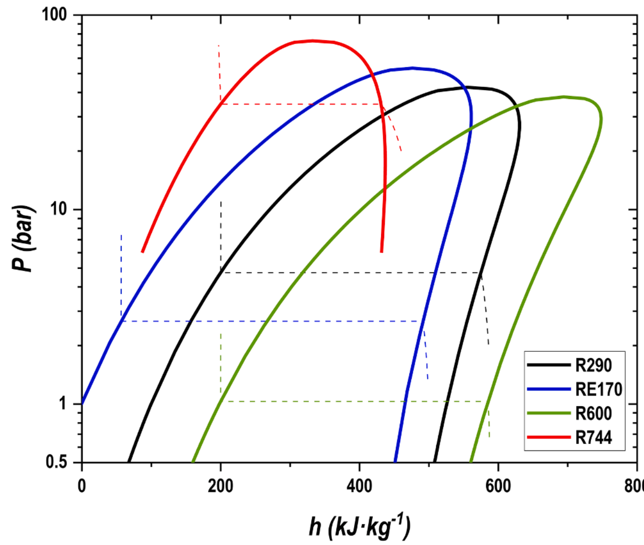

Fig. 1. Pressure enthalpy diagram of pure components and 0 °C isotherm.

2.2. Theoretical performance mixtures

As an initial approximation, this section provides a thermodynamic analysis of the mixtures containing R744, RE170 and R600, as possible alternatives to R290 to be used in heat pump and refrigeration applications. The theoretical analysis, considering some important performance parameters, aims to determine the range of most promising compositions for the experimental testing. It needs to be highlighted that Refprop v.10 does not have fitted interaction coefficients to calculate with accuracy the thermodynamic properties of these mixtures, thus, this analysis is only approximate. Determination of specific interaction coefficients requires accurate measurement of thermodynamic properties, as detailed by Menegazzo et al. (2025), but it has not been realized for the considered mixture yet.

Mixtures are evaluated when working in a simple vapour compression cycle operating at fixed evaporation (t_o) and condensing (t_k) temperatures of 0 °C and 50 °C respectively. Superheating (SH) and subcooling (SUB) values are set to 4 K and 1 K, respectively, while the isentropic efficiency (ε_{ise}) and global efficiency (ε_{glo}) of the compressor are fixed at 0.8 and 0.65, respectively (Calleja-Anta et al., 2024). A pressure drop (Δp) of 0.15 bar is assumed between the evaporator inlet and outlet, as well as between the compressor discharge and condenser outlet. (see (Calleja-Anta et al., 2020) as reference) These values are derived from the initial experimental tests conducted with propane using the test rig described in this work (Calleja-Anta et al., 2024).

The evaporation pressure of the mixtures (p_o), corresponding to the evaporation temperature, is determined using an iterative method based on the mean enthalpy (h_m) in the evaporator, as defined by Eqs. (1) and (2), as suggested by Radermacher and Hwang (2005). Similarly, the condensing pressure (p_k) is calculated based for a vapor quality (x_v) of 50 %, which corresponds to the mean enthalpy, as shown by Eq. (3):

$$h_m = \left(\frac{h_{o,in} + h_{o,out}}{2}\right) \tag{1}$$

$$p_o = f(t_o,\ h_m) \tag{2}$$

$$p_k = f(t_k,\ x_v = 0.5) \tag{3}$$

The enthalpy at the evaporator outlet ($h_{o,out}$) and the condenser outlet ($h_{k,out}$) are defined based on their respective pressures, reduced by half of the pressure drop (Δp), and accounting for the corresponding saturation temperatures (t_{sat}), SH, and SUB, as expressed in Eqs. (4) and (5):

$$h_{o,out} = f\left(p_o - \frac{\Delta p}{2},\ t_{sat,vap} + SH\right) \tag{4}$$

$$h_{k,out} = f\left(p_k - \frac{\Delta p}{2},\ t_{sat,liq} - SUB\right) \tag{5}$$

The expansion process is considered isenthalpic.

The discharge enthalpy (h_{dis}) is calculated using the isentropic discharge enthalpy ($h_{dis,S}$), the evaporator outlet enthalpy, and the isentropic efficiency of the compressor, as shown in Eq. (6). The specific energy absorbed by the compressor (w_c) is calculated as quotient of the isentropic compression work and its overall efficiency (ε_{comp}), as expressed in Eq. (7):

$$h_{dis} = \frac{h_{dis,S} - h_{o,out}}{\varepsilon_{ise}} + h_{o,out} \tag{6}$$

$$w_c = \frac{h_{dis,S} - h_{o,out}}{\varepsilon_{comp}} \tag{7}$$

The Coefficient of Performance is computed for both, refrigeration application (COP_R) and heat pump (COP_{HP}) applications, as well as the Volumetric Cooling Capacity (VCC) and Volumetric Heating Capacity (VHC), as detailed by Eq. (8) to Eq. (11).

$$COP_R = \frac{q_o}{w_c} = \frac{h_{o,out} - h_{o,in}}{w_c} \tag{8}$$

$$COP_{HP} = \frac{q_k}{w_c} = \frac{h_{dis} - h_{k,out}}{w_c} \tag{9}$$

$$VCC = \frac{q_o}{v_{suc}} \tag{10}$$

$$VHC = \frac{q_k}{v_{suc}} \tag{11}$$

At the specified conditions, propane obtains the following values: COP_R =2.58, COP_{HP} = 3.39, VCC = 2477 kJ·m^{-3}, VHC = 3259 kJ·m^{-3} and t_{dis} = 65.9 °C.

Since the aim of the theoretical study is to provide an initial estimation of the most promising compositions for subsequent experimental testing, specific criteria are established to exclude mixtures with unfavourable characteristics. The maximum allowable effective glide in both heat exchangers is limited to 20 K, and the maximum increment in t_{dis} is restricted to 25 K above the value observed with R290. Additionally, to ensure that the mixture's capacities are comparable to those of propane, only compositions yielding VCC and VHC within ±30 % of propane's values are considered.

The selection of the mixtures, considering the restrictions, is based on the relative COPs and capacities in relation to R290, as detailed by Eq. (12) to Eq. (15).

$$COP_{R,rel} = \frac{COP_{R,mixture}}{COP_{R,R290}} \tag{12}$$

$$COP_{HP,rel} = \frac{COP_{HP,mixture}}{COP_{HP,R290}} \tag{13}$$

$$VCC_{rel} = \frac{VCC_{mixture}}{VCC_{R290}} \tag{14}$$

$$VHC_{rel} = \frac{VHC_{mixture}}{VHC_{R290}} \tag{15}$$

The theoretical performance of the mixtures is evaluated considering 0.5 % mass proportion variation in each constituent using the described model. Figs. 2 and 3 present the relative COP and capacity results for the different compositions. Only the compositions in colour satisfy the predefined restrictions. In grey colour, compositions containing >30 % CO_2 exceeded the t_{dis} limit, while those with over 75 % R600 showed significantly reduced capacity. Additionally, when the refrigerant mass proportions are similar, the effective glide in the evaporator exceeded the 20 K threshold. Minor differences in boundary compositions are observed between cooling and heating perspectives.

From a COP perspective, for both cooling and heating applications, a notable increase in COP is observed across all the presented compositions. The results suggest that as CO_2 and R600 concentrations increase, the COP tends to improve. COP_R increments range from 8.3 to 13.5 % for the mixtures RE170/R600 (6/94) and R744/RE170/R600 (8/56/36) respectively. COP_{HP} increments vary from 6.5 to 10.3 % for pure RE170 and the mixture R744/RE170/R600 (8/56/36). These trends highlight that the addition of CO_2 to the mixture is needed to guarantee high energy performance.

From a capacity perspective (Fig. 3), all mixtures suffer reduction in the VCC and VHC, especially with high proportions of RE170, and blends with low CO_2 concentrations are close to the −30 % capacity boundary. As expected, capacity increases sharply with higher CO_2 content and decreases with the addition of R600. VCC is reduced between 1.5 to 30 % for the mixtures R744/RE170/R600 (2/82/16) and RE170/R600 (98/2); and VHC is shortened by 4 to 30 % by the blends R744/RE170 (16/84) and RE170/R600 (98/2).

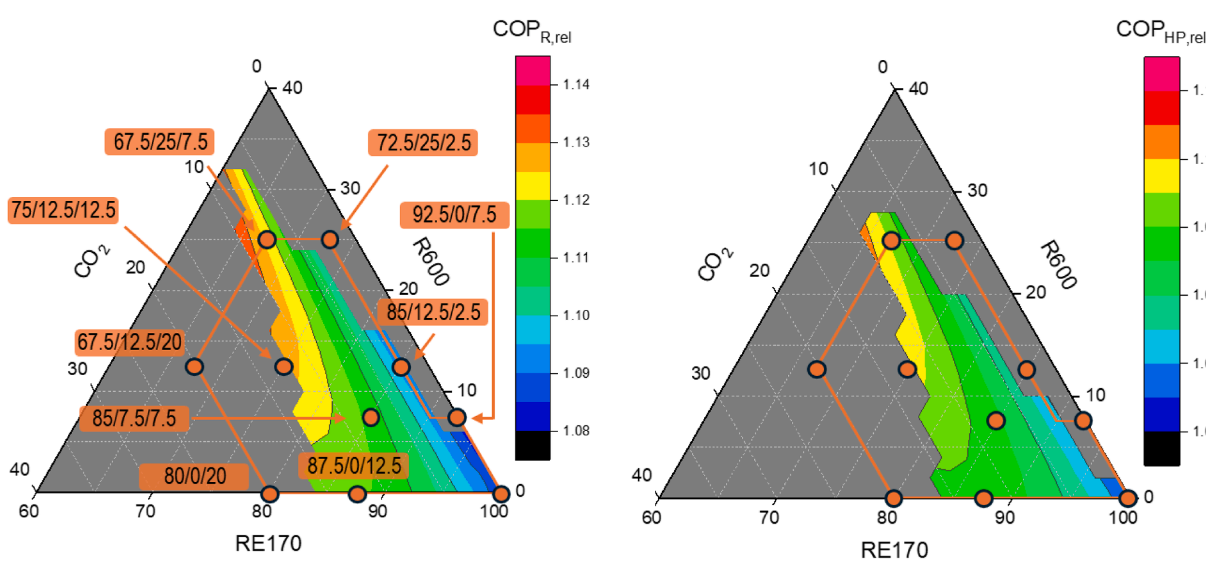

Fig. 2. $COP_{R,rel}$ (left) and $COP_{HP,rel}$ of mixtures respect to R290. Points to be tested experimentally.

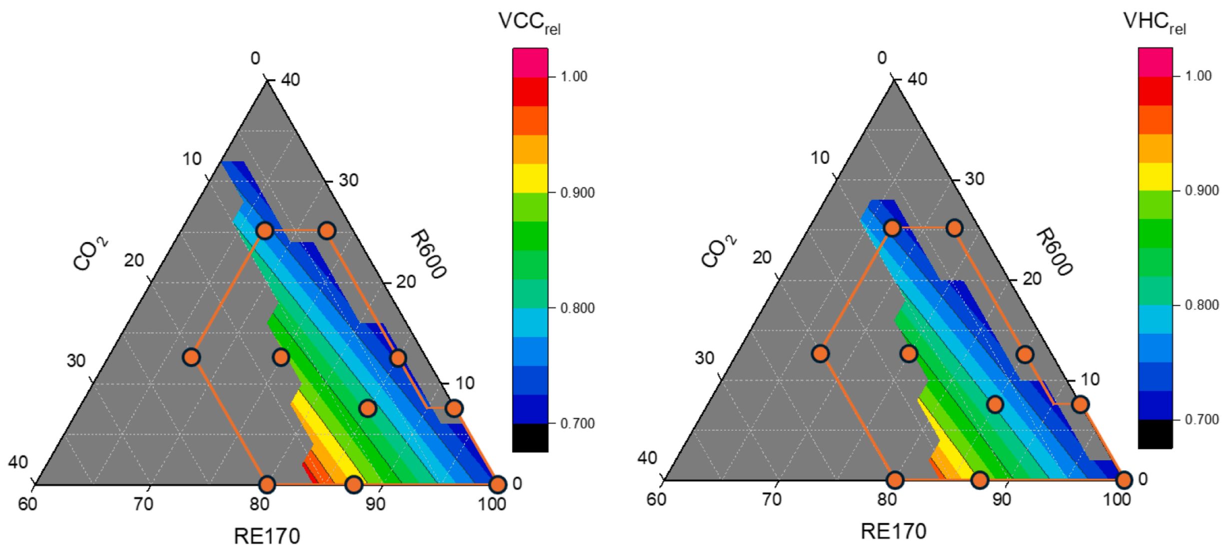

Fig. 3. VCC_{rel} (left) and VHC_{rel} (right) of mixtures respect R290.

From this initial analysis, we have selected 10 mixtures near the range of compositions satisfying the restriction criteria to be tested experimentally. These mixtures, whose composition is detailed in Fig. 2 (left), will allow to obtain information about their actual operation in a real system, and will be used later to determine the compositions maximizing the energy performance.

3. Methods and materials

This section describes the test rig used for the experimental evaluation, the experimental procedure and methodology as well as the energy parameters considered for the comparison.

3.1. Description of the experimental plant and measurement system

The experimental plant used for the evaluation of R290 alternatives (Fig. 4) was previously employed to test R600a substitutes (Calleja-Anta et al., 2024; Calleja-Anta et al., 2024). This plant, designed according to ATEX regulation (European Commission 2014), was adapted to operate with R290 by replacing the compressor and the lubricant, using an Embraco hermetic variable-speed compressor, by replacing the expansion valve and the pressure gauges. The system is a to a water-to-water single-stage vapour compression cycle with electronic expansion valve (EXV). Condenser and evaporator, built in our lab, are concentric tube-in-tube heat exchangers with the refrigerant flowing through the inner tube and the secondary fluid through the annular space. These heat exchangers are divided steps to measure the temperature evolution of the refrigerant along the heat exchanger and to guarantee an accurate thermal measurement in the secondary fluid. The plant uses an EXV, working as thermostatic, that can be customized by introducing the bubble and dew point curves, in this case estimated with Refprop v.10 for the mixtures. Whole details of the components are given in Table 2. The plant also incorporates an accurate measurement system, with all the sensors detailed in Table 3. It is thermally insulated and placed in a climatic chamber with temperature control.

3.2. Experimental procedure and methodology

To evaluate the pure fluids R290, RE170 and the above-mentioned mixtures the following experimental procedure was followed:

- Preparation of the refrigerant: Pure components (R290, R600, RE170 and CO_2) with at least 99.5 % purity were used. For the mixtures, the

Table 2
Characteristics of the main elements of the refrigeration circuit.

Element	Characteristics
Compressor	R290 Variable speed hermetic reciprocating compressor Displacement: 11.14 cm^3, 3/4 HP, MBP. Speed adjustable from 1800 rpm to 4500 rpm. Model: EMBRACO FMFT411U. Lubricant type/viscosity: ESTER/ISO 22
Condenser	Tube-in-tube heat exchanger. Counter current flow. 17 steps per 23.5 cm pipe. Outer tube intended for water flow. $Ø_i$ = 16 mm. Inner tube intended for refrigerant flow. $Ø$ = ¼''. Thickness= 0.8 mm. Total heat exchange area = 750 cm^2
Electronic valve	Used as thermostatic expansion valve. Driver configurable to each refrigerant mixture with bubble and dew point curves.
Evaporator	Tube-in-tube heat exchanger. Counter current flow. 15 steps per 23.5 cm pipe. Outer tube intended for water flow. $Ø_i$= 16 mm. Inner tube intended for refrigerant flow. $Ø$ = 3/8″. Thickness= 0.8 mm. Total heat exchange area = 984.5 cm^2

Table 3
Measurement devices and uncertainties.

Measurement	Device	Range	Uncertainty
High pressure	4 - Pressure gauge	1 to 31 bar	±1 % of value
Low pressure	2 - Pressure gauge	0 to 9 bar	±1 % of value
Refrigerant temperature	32 - T-type immersion thermocouple 4 - T-type surface thermocouple	−150 to 200 °C	± 0.5 K
Secondary fluid temperature	8 - T-type immersion thermocouple 18 - T-type surface thermocouple	−150 to 200 °C	± 0.5 K
Refrigerant mass flow rate	Coriolis mass flow meter	0 to 20 $kg{\cdot}h^{-1}$	±0.15 % of value
Evaporator secondary fluid mass flow rate	Coriolis mass flow meter	0 to 150 $kg{\cdot}h^{-1}$	±0.55 % of value
Condenser secondary fluid volumetric flow rate	Magnetic volumetric flow meter	0 to 200 $m^3{\cdot}h^{-1}$	±0.3 % of value
Compressor power consumption	Digital wattmeter	0 to 500 W	±0.5 % of value

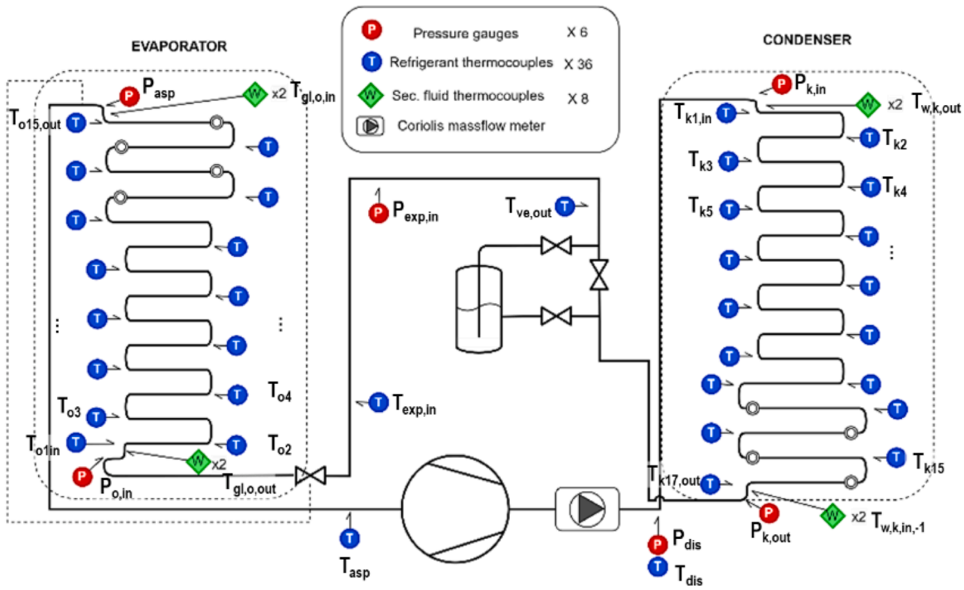

Fig. 4. Scheme of the test bench and allocation of measurement devices.

plant was always charged with 160 g, the accumulator vessel was used in the cycle to avoid variations in the overall performance of the plant, and we ensured visually that at the inlet of the expansion valve the refrigerant was in liquid state. For each composition, after a vacuum process of one hour minimum, it was filled with the right quantity of the fluid with lowest NBP (R600), then the RE170 and finally with CO_2. For the process a weight scale with $\pm$ 0.5 g of uncertainty was used. To avoid uncertainties related with the unexpected degradation of the lubricant or due to the absorption of a component inside the oil, the following order of tests was used: first, R290; second RE170; and then the mixtures in the order reflected in Table 4. Then, the process was repeated until having a minimum of two different tests for each composition. Only a composition was tested three times.

- For each composition, the electronic expansion valve of the evaporator was adapted to work with each mixture, configuring the controller according to the bubble and dew temperatures of each mixture (evaluated with REFPROP), as thermostatic valve.

Experimental evaluation covered three approaches:

- Drop-in test: the vapour compression system was tested with the compressor running at a fixed speed of 2100 rpm, for the pure fluids and for the mixtures. The water inlet temperature at condenser was fixed at 30.0 $^{\circ}C \pm$ 0.2 K and its mass flow rate kept at 105 $\pm$ 0.75 kg·h^{-1}; secondary fluid of the evaporator (50/50 % volume mixture of propylene glycol and water) entered always at 15.0 $^{\circ}C \pm$ 0.18 K with a mass flow rate of 90.0 $\pm$ 0.8 kg·h^{-1}. This type of comparison, usually considered in literature, corresponds to a direct substitution process (Aprea et al., 2018; Llopis et al., 2017; Maiorino et al., 2020; Oruç et al., 2018), but in the case of alternative fluids with lower/higher cooling or heating capacities the fixed exchange area of the heat exchangers can mask the real performance of the alternative fluids.
- Fixed cooling capacity test: the system was evaluated with matching cooling capacity as that measured for the operation of R290 at the conditions stablished in the drop-in test. In these tests, the inlet conditions of secondary fluid to the heat exchangers were those defined in the drop-in test (inlet temperature and flow rate), but the compressor speed was increased to match the VCC of R290, since the tested mixtures presented lower VCC.
- Fixed heating capacity test: the cycle was evaluated varying the compressor speed to match the heating capacity measured for R290 in the conditions defined in the drop-in test (inlet temperature and flow rate. The other variables were kept at the drop-in test conditions.

Experimental measurements and the energy parameters that are discussed in the next section are detailed in Table 4 for the drop-in tests, in Table 5 for the fixed cooling capacity test and in Table 6 for the heating capacity test.

3.3. Energy parameters

Refprop is the general database to evaluate the thermodynamic properties of the refrigerants, however, as analysed by Calleja-Anta et al. (2024) for fluids without experimental measurements the binary interaction coefficients used by Refprop are estimated, thus, unexpected uncertainty is associated to this calculation. To avoid Refprop-related uncertainty in the experimental evaluation, authors have considered the heat transfer rates measured in the secondary fluids in the plant. Cooling capacity ($\dot{Q}_o$) is evaluated with Eq. (16) using the Coriolis measurement, specific heat at constant pressure for propylene-glycol mixtures (Engineering, 2011) and temperature difference across the evaporator. Heating capacity ($\dot{Q}_k$) is calculated considering the water volumetric flow, its density and specific heat at constant pressure evaluated with Refprop (Lemmon et al., 2018) and the temperature difference in the condenser, as detailed by Eq. (17). From these values the coefficient of performance in refrigeration application (COP_R) and in heating applications (COP_{HP}) are calculated using the power consumption of the compressor with Eq. (18) and Eq. (19), respectively. As each test is repeated a minimum of two times, the result is considered the average of the two tests.

$$\dot{Q}_o = \dot{Q}_{glyc} = \dot{m}_{glyc} \cdot c_p \cdot \Delta t \quad (16)$$

$$\dot{Q}_k = \dot{Q}_w = \dot{V}_w \cdot \rho \cdot c_p \cdot \Delta t \quad (17)$$

$$COP_R = \frac{\dot{Q}_o}{P_c} \quad (18)$$

Table 4
Summary of the reference test conditions, various thermodynamic aspects and energy parameters during the optimization during drop-in process.

	Reference parameters					High pressure cycle section				Low pressure cycle section				Compression process					Energy parameters								
Refrigerant and mass composition	$t_{w,k,in}$ (°C)	$t_{gl,o,in}$ (°C)	$\dot{V}_{w,k}$ (L/h)	$\dot{m}_{gl,o}$ (kg/h)	N° reps	$\bar{p}_k$ (bar)	Δp_k (mbar)	$\bar{t}_k$ (°C)	Δt_k (K)	$\bar{p}_o$ (bar)	Δp_o (mbar)	$\bar{t}_o$ (°C)	Δt_o (K)	p_{dis} (bar)	t_{dis} (°C)	C_r (-)	m_{ref} (kg/s)	P_c (W)	COP_R (-)	ΔCOP_R (%)	$\dot{Q}_o$ (W)	$\Delta\dot{Q}_o$ (%)	COP_{HP} (-)	ΔCOP_{HP} (%)	$\dot{Q}_k$ (W)	$\Delta\dot{Q}_k$ (%)	ε (%)
R290	34.95	14.96	104.63	89.85	2	17.2	123	50.4	1.3	4.6	97	−0.6	−0.7	17.4	67.3	3.8	11.0	299.9	2.50	0.0	748.7	0.0	3.34	0.0	1000.6	0.0	4.2
RE170	34.99	14.97	104.59	89.70	2	10.6	107	46.4	0.5	2.8	67	1.8	−0.2	10.7	66.6	3.8	7.2	191.5	3.24	29.8	620.5	−17.1	3.94	18.0	753.7	−24.7	5.4
RE170/R600/R744 (optimization process)																											
92.5/7.5/0	35.02	14.97	104.70	90.01	2	10.3	96	46.5	0.7	2.7	58	1.6	0.3	10.5	66.8	3.9	7.0	185.8	3.34	33.8	620.6	−17.1	4.04	21.1	750.7	−25.0	5.4
87.5/0/12.5	35.02	15.01	104.67	89.94	2	14.3	98	47.0	9.9	3.3	90	0.3	5.4	14.4	77.8	4.4	8.0	245.8	2.72	8.8	667.8	−10.8	3.38	1.2	830.1	−17.0	4.9
85/12.5/2.5	35.01	14.99	104.70	89.99	2	10.9	87	46.9	4.1	2.8	62	1.0	1.9	11.0	68.0	4.0	7.1	192.2	3.28	31.6	631.1	−15.7	4.00	20.0	769.0	−23.1	5.3
85/7.5/7.5	35.03	14.99	104.76	89.44	3	12.6	82	47.1	8.5	3.0	63	0.3	4.1	12.6	73.3	4.3	7.3	213.3	3.09	23.8	659.2	−11.9	3.78	13.3	806.5	−19.4	4.1
80/0/20	35.01	15.02	104.66	89.80	2	17.6	69	47.4	15.1	3.5	77	−1.2	8.5	17.6	87.5	5.1	8.1	284.7	2.50	1.74	713.1	−4.4	3.1	−5.3	891.6	−11.0	4.6
75/12.5/12.5	35.04	15.04	104.65	89.61	2	14.4	69	46.9	12.9	3.1	75	−0.3	6.7	14.4	77.7	4.7	7.6	235.4	2.83	13.2	664.9	−11.2	3.48	4.2	818.1	−18.2	5.0
72.5/25/2.5	35.07	15.03	104.65	90.04	2	10.2	100	46.1	4.4	2.6	54	1.3	2.9	10.3	65.2	3.9	7.0	179.3	3.31	34.60	594.2	−20.3	4.0	20.2	713.1	−28.8	5.6
67.5/25/7.5	35.04	15.04	104.61	90.17	2	12.3	78	46.3	11.4	2.8	69	0.2	6.3	12.4	72.5	4.5	7.1	203.8	3.09	23.6	628.7	−16.0	3.72	11.4	757.2	−24.3	5.3
67.5/12.5/20	35.03	15.05	104.72	90.04	2	17.9	45	47.1	16.8	3.4	93	−1.0	9.9	17.9	86.8	5.3	8.0	279.8	2.50	1.73	700.6	−6.1	3.1	−5.7	872.9	−12.9	4.7

Table 5
Summary of the reference test conditions, various thermodynamic aspects and energy parameters during the optimization for refrigeration purposes.

	Reference parameters					High pressure cycle section				Low pressure cycle section				Compression process				Energy parameters					
Refrigerant and mass composition	$t_{w,k,in}$ (°C)	$t_{gl,o,in}$ (°C)	$\dot{V}_{w,k}$ (L/h)	$\dot{m}_{gl,o}$ (kg/h)	N° reps	$\bar{p}_k$ (bar)	Δp_k (mbar)	$\bar{t}_k$ (°C)	Δt_k (K)	$\bar{p}_o$ (bar)	Δp_o (mbar)	$\bar{t}_o$ (°C)	Δt_o (K)	p_{dis} (bar)	t_{dis} (°C)	C_r (-)	m_{ref} (kg/s)	P_c (W)	COP (-)	ΔCOP (%)	RPM (-)	ΔRPM (%)	ε (%)
R290	34.95	14.96	104.63	89.85	2	17.2	122	50.4	1.3	4.6	97	−0.6	−0.7	17.4	67.3	3.8	11.0	300.0	2.50	–	2100	–	4.2
RE170	34.98	15.05	104.78	89.10	2	11.2	119	48.7	0.8	2.6	72	−0.3	−0.3	11.3	74.1	4.4	8.3	256.6	2.92	17.2	2760	31.4	4.24
RE170/R600/R744 (optimization process)																							
92.5/7.5/0	35.00	15.01	104.68	90.39	2	11.0	128	48.9	1.1	2.6	77	−0.5	0.0	11.2	73.4	4.5	8.5	259.9	2.87	14.9	2850	35.7	4.23
87.5/0/12.5	34.97	15.06	104.76	90.15	2	14.6	95	48.5	10.4	3.1	87	−1.1	5.0	14.7	81.9	4.8	8.6	282.8	2.63	5.5	2400	14.3	4.22
85/12.5/2.5	34.96	14.98	104.86	89.52	2	11.5	113	48.9	4.1	2.6	80	−0.8	1.5	11.6	74.0	4.5	8.4	256.5	2.90	16.3	2760	31.4	4.22
85/7.5/7.5	34.99	15.03	104.88	89.84	3	13.0	91	48.7	8.5	2.8	77	−1.0	3.5	13.0	77.1	4.7	8.3	260.9	2.86	14.7	2510	19.5	3.47
80/0/20	35.02	15.04	104.86	89.11	2	17.7	70	48.0	15.2	3.5	84	−1.6	8.3	17.7	88.6	5.2	8.4	298.1	2.50	0.3	2190	4.3	6.04
75/12.5/12.5	35.04	15.02	104.77	89.18	2	14.7	77	48.4	13.2	3.0	81	−1.5	6.2	14.8	81.1	5.1	8.4	277.3	2.70	8.0	2430	15.7	4.22
72.5/25/2.5	35.02	15.00	104.80	90.21	2	10.9	130	49.2	4.8	2.5	90	−1.2	1.8	11.1	73.6	4.7	8.8	273.0	2.76	10.4	3030	44.3	6.08
67.5/25/7.5	35.00	14.98	104.83	89.91	2	11.9	113	48.9	8.3	2.5	91	−1.4	3.6	12.0	75.5	4.9	8.6	270.4	2.78	11.2	2895	37.9	4.22
67.5/12.5/20	35.02	15.06	104.78	90.37	2	18.0	42.5	49.1	17.3	3.3	89	−1.6	9.6	18.0	88.6	5.5	8.5	304.0	2.44	−2.41	2250	7.1	6.19
RE170/R600/R744 (selected compositions)																							
85/10/5	35.00	15.05	104.85	90.02	2	12.6	89	48.9	7.4	2.75	71	−1.0	2.92	12.7	77	4.7	8.3	262.3	2.84	13.9	2595	23.6	4.22
83/9/8	35.03	15.03	104.98	89.88	2	13.2	89	48.8	9.5	2.84	78	−1.1	4.00	13.3	77.8	4.8	8.3	263.7	2.83	13.3	2505	19.3	4.27

Table 6
Summary of the reference test conditions, various thermodynamic aspects and energy parameters during the optimization for heat pump purposes.

Refrigerant and mass composition	Reference parameters $t_{w,k,in}$ (°C)	$t_{gl,o,in}$ (°C)	$\dot{V}_{w,k}$ (L/h)	$\dot{m}_{gl,o}$ (kg/h)	N° reps	High pressure cycle section $\bar{p}_k$ (bar)	Δp_k (mbar)	$\bar{t}_k$ (°C)	Δt_k (K)	Low pressure cycle section $\bar{p}_o$ (bar)	Δp_o (mbar)	$\bar{t}_o$ (°C)	Δt_o (K)	Compression process p_{dis} (bar)	t_{dis} (°C)	C_r (-)	m_{ref} (kg/s)	Energy parameters P_c (W)	COP (-)	ΔCOP (%)	RPM (-)	ΔRPM (%)	ε (%)
R290	34.95	14.96	104.63	89.85	2	17.2	122	50.4	1.3	4.6	97	−0.6	−0.7	17.4	67.3	3.8	11.0	299.9	3.34	-	2100	–	4.30
RE170	34.98	15.04	104.85	89.93	2	11.4	133	49.4	0.9	2.6	81	−0.9	−0.5	11.6	76.0	4.6	8.8	282.6	3.51	5.0	2970	41.4	4.06
RE170/R600/R744 (optimization process)																							
92.5/7.5/0	34.96	14.95	104.71	89.88	2	11.2	137	49.5	1.2	2.5	87	−1.1	−0.4	11.3	75.3	4.6	8.9	283.5	3.51	5.2	3030	44.3	4.07
87.5/0/12.5	34.96	15.05	104.81	90.18	2	14.8	106	49.1	10.3	3.1	86	−1.7	4.6	14.9	83.9	4.9	9.0	306.3	3.25	−2.5	2640	25.7	4.11
85/12.5/2.5	35.00	15.00	104.93	90.73	2	11.7	127	49.7	4.2	2.5	87	−1.3	1.1	11.9	76.0	4.7	8.9	282.4	3.53	5.9	2955	40.7	4.15
85/7.5/7.5	35.00	15.03	104.95	89.78	3	13.1	96	49.5	8.5	2.8	82	−1.6	3.2	13.3	79.3	4.9	8.7	285.3	3.48	4.2	2790	32.9	3.32
80/0/20	35.05	15.01	104.70	89.92	2	17.9	66	48.9	15.4	3.4	95	−2.3	8.0	18.0	90.0	5.2	8.85	324.3	3.07	−7.3	2370	12.9	5.70
75/12.5/12.5	35.02	15.02	104.83	89.95	2	14.9	82	49.3	13.3	2.9	87	−2.1	5.8	15.0	83.0	5.3	8.9	303.7	3.28	−1.6	2730	30.0	4.05
72.5/25/2.5	35.02	15.05	104.92	90.49	2	11.1	133	49.7	4.9	2.4	94	−1.5	1.5	11.3	75.2	4.8	9.1	289.9	3.44	4.0	3180	51.4	5.90
67.5/25/7.5	34.99	15.02	104.87	89.98	2	12.0	110	49.6	8.4	2.5	97	−1.9	3.2	12.2	77.4	5.0	9.0	292.6	2.7	9.1	3075	46.4	4.06
67.5/12.5/20	35.07	15.07	104.84	91.11	2	18.2	42	48.8	17.5	3.3	89	−2.1	9.2	18.2	90.0	5.6	8.9	326.5	3.41	2.3	2430	15.7	5.95
RE170/R600/R744 (selected compositions)																							
85/10/5	34.97	15.04	104.89	90.47	2	12.8	103	49.6	7.4	2.7	76	−1.5	2.6	12.9	78.5	4.9	8.8	285.5	3.49	4.7	2835	35.0	4.11
83/9/8	34.97	14.97	105.03	89.86	2	13.4	97	49.4	9.5	2.8	79	−1.7	3.7	13.5	79.8	4.9	8.7	284.9	3.47	3.9	2760	31.4	4.09

$$COP_{HP} = \frac{\dot{Q}_k}{P_c} \quad (19)$$

Uncertainty analysis of the above-mentioned energy parameters is detailed in the Annex of the work of Calleja-Anta et al. (2024) and the resulting uncertainties detailed in Tables 4–6.

4. Energy analysis

This section details the analysis of the experimental results of the evaluation of R290, RE170 and the mentioned blends of R744/RE170/R600 under the three considered approaches.

4.1. Drop-in test

Drop-in performance of RE170 and the analysed mixtures is presented in Figs. 5 and 6. All data corresponding to these tests is collected in Table 4 for reference.

Fig. 5 represents the COPs obtained by the pure fluids and mixtures in the drop-in test conditions. As it can be observed, nearly all the mixtures and RE170 obtain higher COPs, except two mixtures which have lower COP_{HP} and nearly coincident COP_R. Among them, RE170 offered a COP_R of 3.24 and COP_{HP} of 3.94, they are 29.8 % and 18.0 % higher than that of R290 in the same conditions. Additionally, there were three mixtures RE170/R600/R744 with (85/12.5/2.5), (72.5/25/2.5), (92.5/7.5/0) which offered even better results than RE170. Maximum improvement was given by RE170/R600 (92.5/7.5) that obtained a 33.8 % and 21.1 % increase in COP_R and COP_{HP} respectively in relation to R290. However, as mentioned, the capacities provided with the alternative fluids to R290 are substantially lower (see Fig. 6). RE170 presents a reduction in refrigerating capacity of 17.3 % and in heating capacity of 24.7 %, the reductions are similar for the blend RE170/R600 (92.5/7.5). That indicates that these fluids cannot be considered as direct drop-in of R290 due to loss in capacity.

These significant increases in COP can be partly explained by smaller temperature differences in the heat source and sink due to lower cooling/heating capacities. As shown in Table 4, the mixtures present lower average condensing and evaporating temperatures ($\bar{t}_k$ *and* $\bar{t}_o$, respectively), which leads to a lower specific compression work.

4.2. Fixed cooling capacity test

Performance of the considered mixtures providing the same cooling capacity as that of R290 is presented in Figs. 7 and 8, and all the whole set of data corresponding to the fixed cooling capacity test in Table 5.

Fig. 7 details the COP values achieved by the pure fluids and tested mixtures where it is observed that the best performing fluid is the pure RE170, with COP_R and COP_{HP} higher by 12.7 % and 8.4 % than R290 respectively. Blend RE170/R600/R744 (85/12.5/2.5) obtains close values to DME. However, all mixtures require a high increase on the compressor speed (Fig. 8) to match the cooling capacity of R290. For RE170 the increase in compressor speed is of 31 % and for the mentioned mixture of 36 %. In relation to the drop-in test the increment of COP in relation to R290 decreases as the heat transfer rates in condenser and evaporator are higher.

4.3. Fixed heating capacity test

Performance of the considered mixtures providing the same heating capacity as that of R290 is presented in Figs. 9 and 10.

Again, when the plant requires providing the same capacity in the condenser, the frequency of the compressor needs to be increased (Fig. 10). For most mixtures the COP values are significantly higher than that of R290, specially RE170, which obtains increments of 12.8 % in COP_R and 5.1 % in COP_{HP}. Some mixtures obtain close results to RE170, which complete data is included in Table 6. To match the capacity of

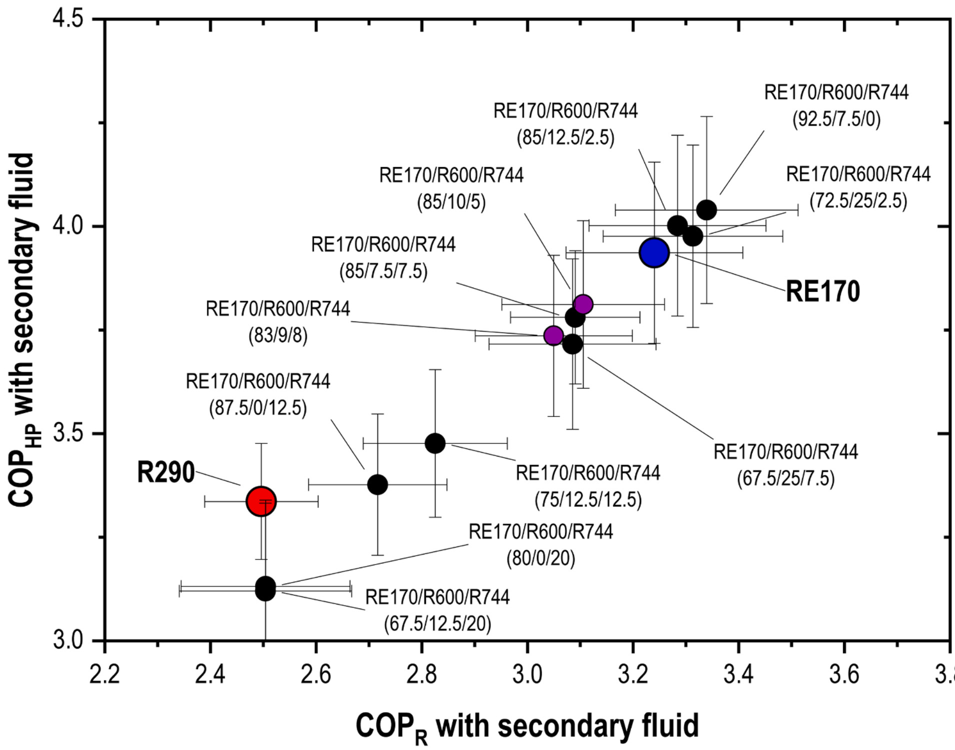

Fig. 5. COP_{HP} vs. COP_R at drop-in test conditions.

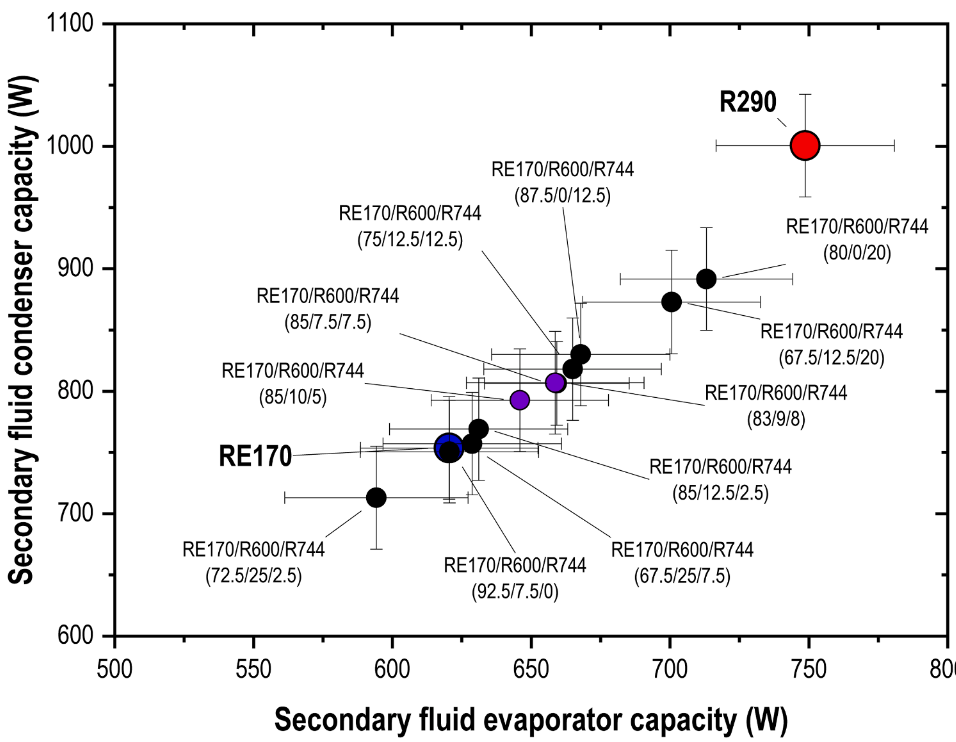

Fig. 6. Q_k vs. Q_o at drop-in test conditions.

R290 the compressor with RE170 needs to increase the compressor speed by 41.4 % and for the other mixtures between 14 % to 50 %. Again, as in the fixed cooling capacity test, the increments in COP of RE170 and the mixtures in relation to R290 decrease because of limited surface area in the heat exchangers.

4.4. Discussion of performance of RE170 and the mixtures

As it can be observed in the previous comparisons of the performance of the mixtures in relation to R290, depending on the test, some mixtures improve in one approach and do not improve too much in another. Since the selected compositions for testing are discrete and their compositions

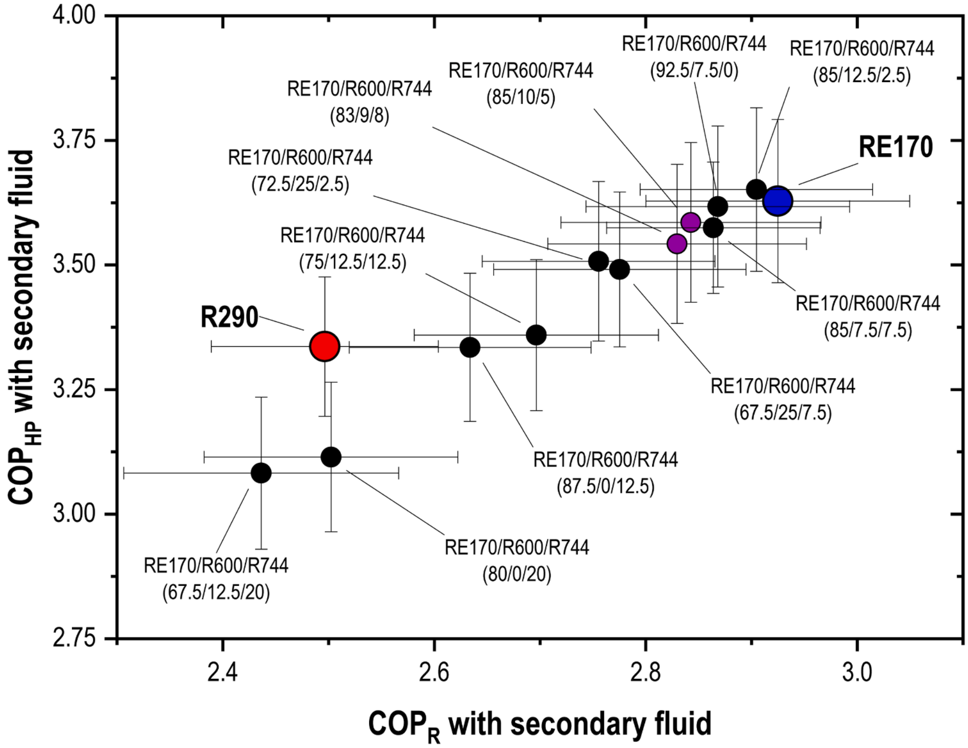

Fig. 7. COP_{HP} vs. COP_R at fixed cooling capacity test conditions.

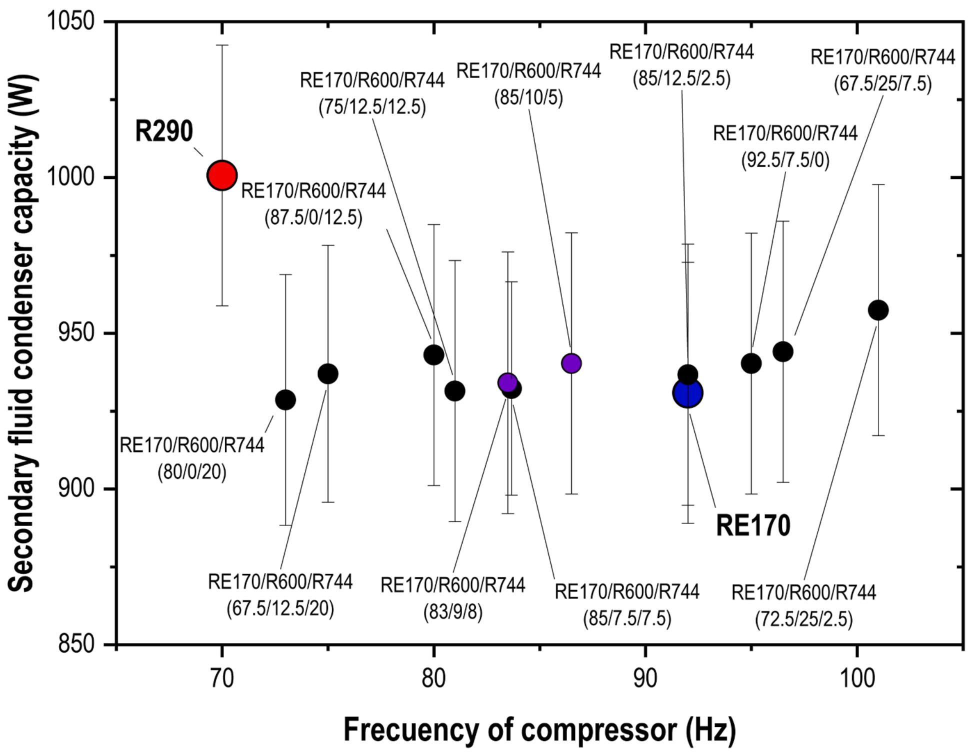

Fig. 8. Q_k vs. compressor frequency at fixed cooling capacity test conditions.

have not been optimized (see Fig. 2 left), authors analysed the tendencies of relative COPs as function of the mass percentage of each compontent.

Fig. 11 represents the trends of relative COP_R [Eq. (12)], and Fig. 12 shows the trend of COP_{HP} [Eq. (13)] as a function of the constituents. On these figures, isocapacity trend lines have been plotted, intersecting the compositions that provide the same cooling or heating capacity with an identical speed compressor. This allows for a clearer visualization of how different mixtures behave in terms of efficiency and required compressor adjustments. According to the trends, pure RE170 and the mixtures RE170/R600/R744 (85/10/5) and RE170/R600/R744 (83/9/8) exhibit the highest COP values in the refrigeration scenario at a given

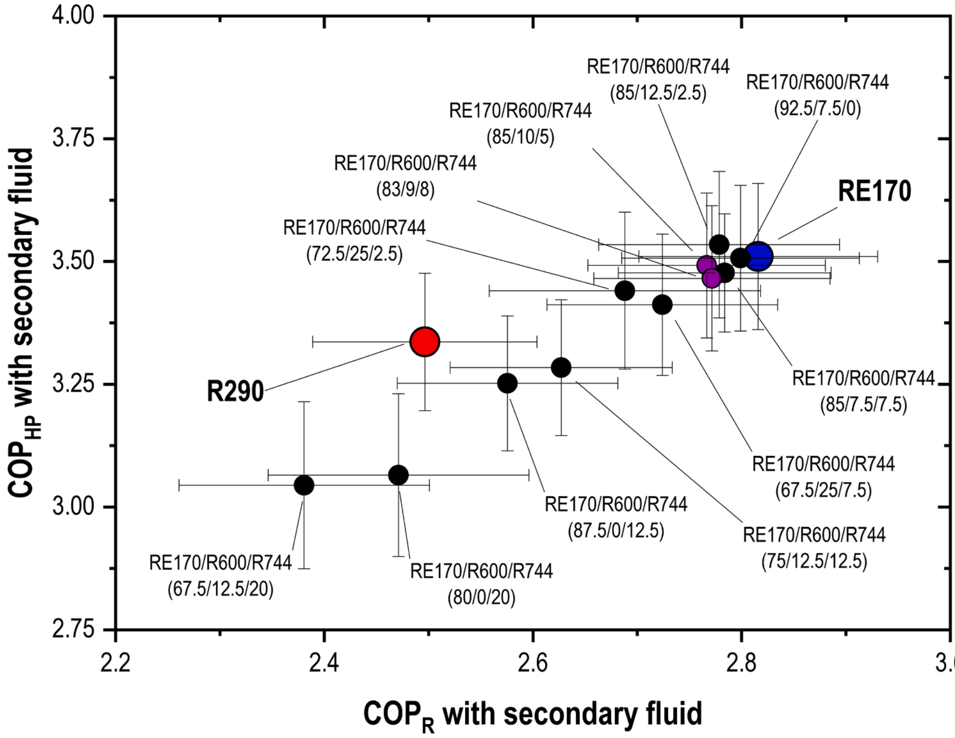

Fig. 9. COP_{HP} vs. COP_R at fixed heating capacity test conditions.

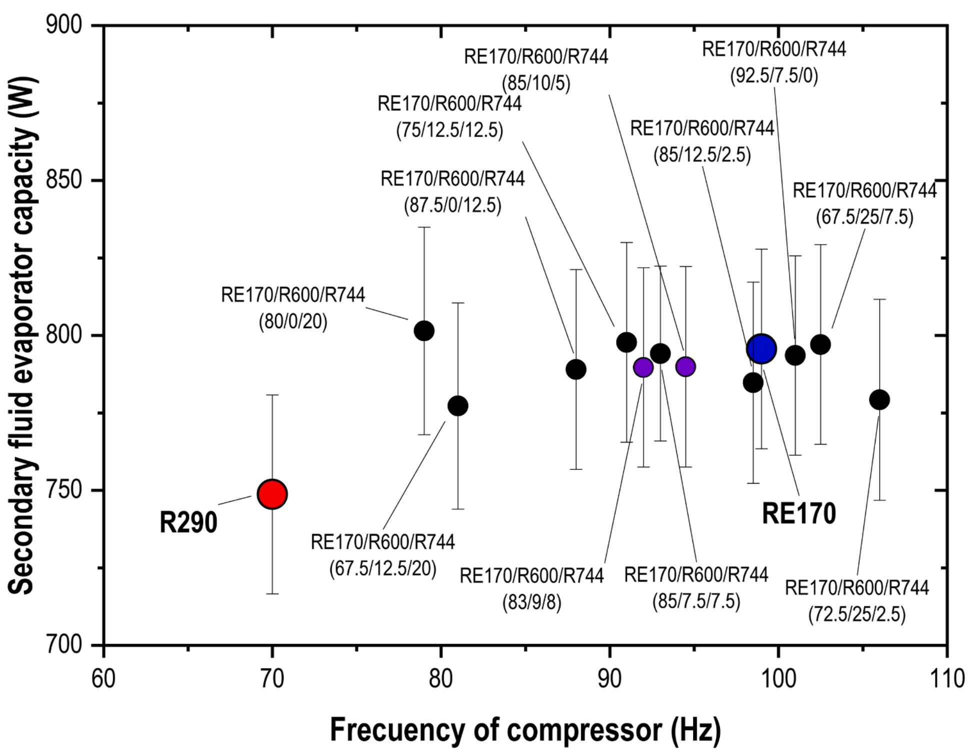

Fig. 10. Q_o vs. compressor frequency at fixed heating capacity test conditions.

compressor speed, leading to the selection of these two compositions for additional testing. For the heating scenario, the mixtures with the highest COP values are the previously mentioned RE170/R600/R744 (85/10/5) and the already tested RE170/R600/R744 (85/12.5/2.5). Although these two new compositions were selected at this stage, they have also been represented in the previous graphs using purple dots.

Figs. 13–15 present the analysis of the main relative energy parameters of RE170 and the last two selected mixtures in comparison to R290 operation under the three test scenarios considered in this work. If a drop-in substitution is performed (Fig. 13), considering the same compressor operating frequency and same sizes of the heat exchangers, the COP_R increases between 22.1 to 29.8 % and the COP_{HP} between 11.2

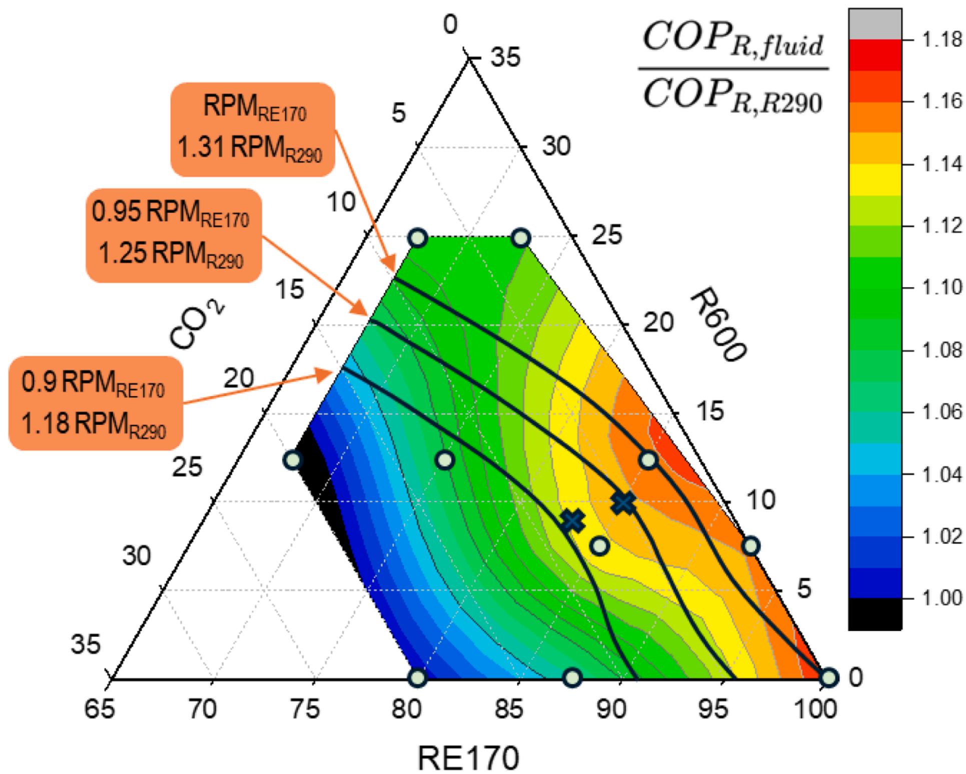

Fig. 11. Relative COP_R as function of mass percentage of components.

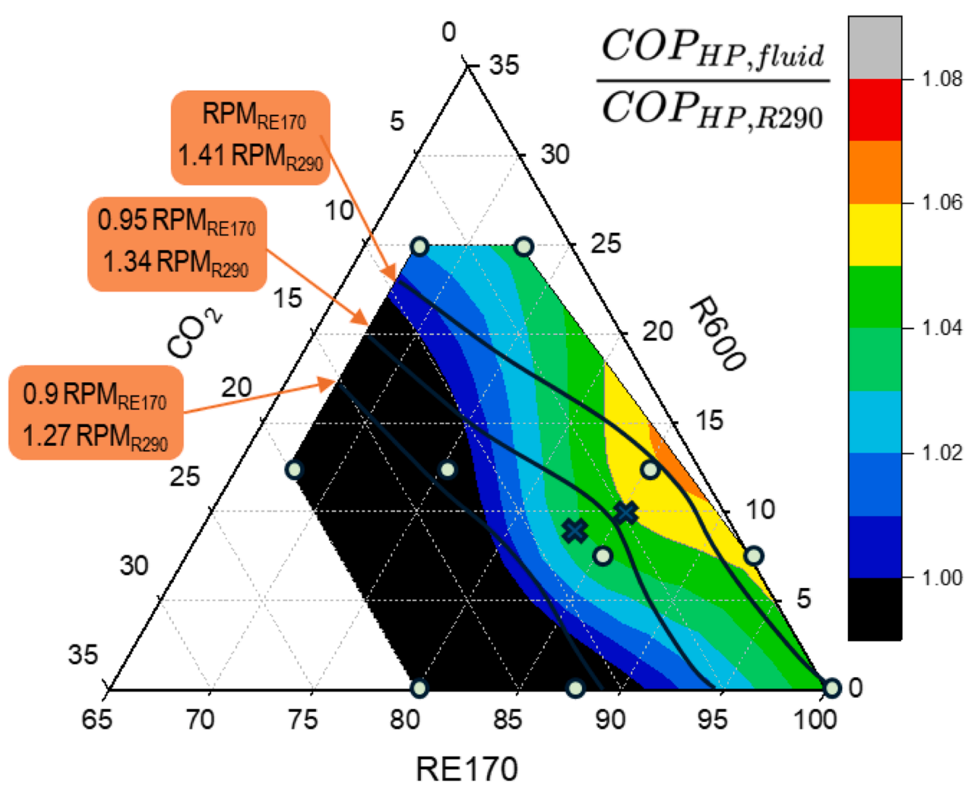

Fig. 12. Relative COP_{HP} as function of mass percentage of components.

to 11.8 %; but the capacities are reduced between 12.0 to 17.1 % in refrigeration and between 19.4 to 24.7 %. That indicates that the drop-in substitution could be effective from an energy point of view only if the system is oversized. Considering a substitution process maintaining the cooling capacity of the system in relation to R290 (Fig. 14), the substitution process is also effective, since the COP_R increases between 13.3 to 17.2 %, but in this case the compressor should be also oversized, since the compressor speed should increase between 19.2 to 31.4 %. Finally,

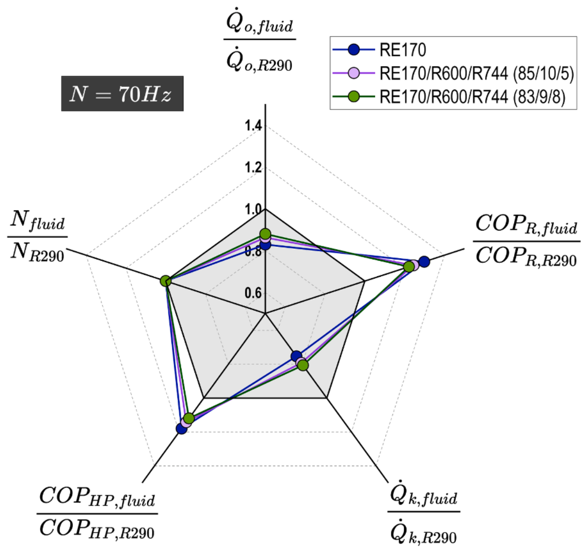

Fig. 13. Relative main parameters in relation to R290 in drop-in test.

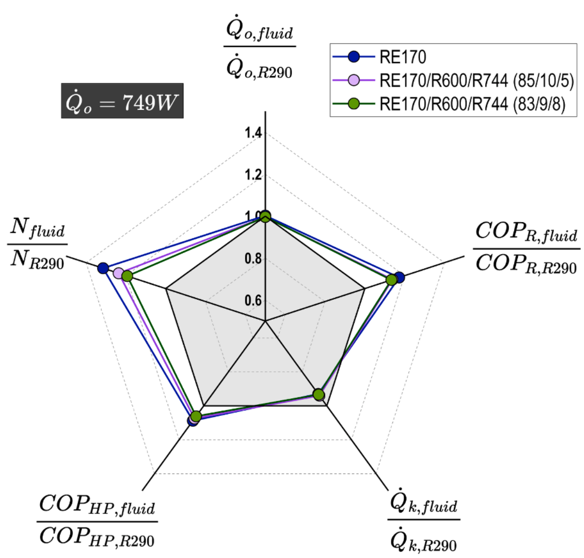

Fig. 14. Relative main parameters in relation to R290 in fixed cooling capacity test.

for heating purposes (Fig. 15) the substitution results less effective, since COP_{HP} increments by 3.9 to 5.2 % with compressor speed increments from 31.4 to 35.0 %.

Another important observation is that the best-performing fluid for R290 global substitution is the RE170, since it provides in general the maximum combined COP increments for heating and refrigeration purposes. The use of a pure fluid is recommended to avoid temperature glide in the heat exchangers and to avoid the reduction of the heat transfer rates in heat exchangers due to the use of mixtures. However, the use of the proposed mixture RE170/R600/R744 (85/10/5) allows reducing the compressor size by 5 % respect the one needed by RE170 with similar COP_R and COP_{HP} than RE170. Additionally, the mixture RE170/R600/R744 (83/9/8) enables a reduction of 10 % for refrigeration with only a slight COP_R reduction. Therefore, the use of mixtures should be only recommended when system size constraints are a key consideration or if the system is not oversized, since they require less increment of compressor speed.

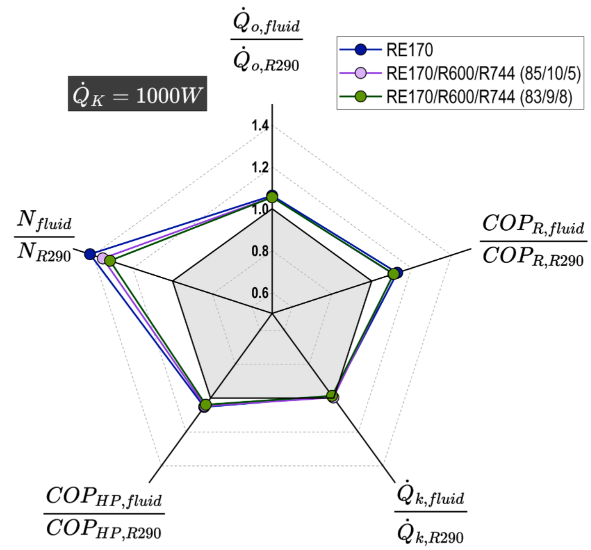

Fig. 15. Relative main parameters in relation to R290 in fixed heating capacity test.

5. Conclusions

This work has addressed the possibility of determining alternative fluids to R290 with the aim to increase the energy performance for refrigerating and heating purposes. An initial thermodynamic approach, based on the thermodynamic properties calculated with Refprop v.10 using a close model to reality indicates that pure RE170 and mixtures of RE170/R600/R744 could provide high increments in refrigerating and heating COPs. Concretely, the model indicates that for evaporation at 0 °C and condensation at 50 °C the alternative fluids could offer theoretical COP_R increments between 8.3 to 13.5 % and COP_{HP} between 6.5 to 10.3 %. As the thermodynamic properties are estimated with Refprop due to the absence of adjusted binary mixing coefficients, this work has addressed the analysis using an experimental approach.

A custom designed single-stage vapour compression system using a variable speed compressor, a customable electronic expansion valve and double-tube counter-flow condenser and evaporator has been used to analyse the fluids. Heat sink and hot source were regulated using secondary fluids varying inlet temperature and flow. This plant incorporates a high accuracy measurement system to be able to evaluate its energy parameters with an average uncertainty around 5 % for COP and capacity measurements. To avoid uncertainties related to the thermodynamic properties' evaluation, all the energy parameters are calculated through the measurements in the secondary fluids.

Experimentation has been made at secondary fluid inlet temperatures of 15 °C in the evaporator and 35 °C in the condenser. It has considered R290 and RE170 as pure fluids and 11 blends composed of different proportions of RE170/R600/R744. Evaluation has covered three scenarios: a drop-in process with all the parameters maintained constant; a fixed cooling capacity test, where the compressor speed has been increased to provide the same cooling capacity than with R290; and a fixed heat rejection capacity test; in this case to match the heat rejection of R290 in the condenser.

Experimental evaluation has demonstrated that nearly all the mixtures and RE170 offer higher COP values for heating and refrigeration than R290, but all of them suffer large reductions in the capacity. In the drop in tests, RE170 offered COP increments in relation to R290 of 29.8 % (COP_R) and 17.99 % (COP_{HP}) with capacity reductions of 17.3 % and 24.7 % respectively. In this test, mixture RE170/R600 (92.5/7.5) obtained 22.8 % increase in COP_R and 21.1 % in COP_{HP}, also with a loss of capacity. When the fluids were tested under the fixed cooling capacity scenario, the increments in COPs were reduced. RE170 offered 12.7 %

COP_R and 8.4 % COP_{HP} increments with similar values for the mixture RE170/R600 (92.5/7.5). In this case the compressor speed needed to increase >30 %. At the fixed heating capacity scenario, again the best fluid was RE170 with COP increments in relation to R290 of 12.8 % (COP_R) and 5.1 % (COP_{HP}) with compressor speeds higher up to 41 %. Some mixtures offered similar results.

Finally, to select the best mixtures for R290 replacement, two additional compositions have been tested RE170/R600/R744 (85/10/5) and (83/9/8). These mixtures are not able to improve the energy benefit of obtained with RE170 but are able to maintain similar energy performance with 5 % and 10 % lower compressor speed than RE170, respectively. Authors, conclude that for substitution processes it will be recommended to use pure RE170, since it offers the highest combined COP and will avoid introducing temperature glides in the heat exchangers and operate with higher heat transfer coefficients than with the mixtures. However, the proposed mixtures remain a viable alternative when system size constraints are a key consideration.

Based on these results, the use of pure RE170 is recommended as the best overall alternative to R290, since it offers the highest COP values for both cooling and heating, and avoids issues related to temperature glide. However, in systems where compressor size or speed is a limiting factor, mixtures such as RE170/R600/R744 (85/10/5) or (83/9/8) could be a suitable option, as they provide similar performance with slightly lower compressor speed. Therefore, the choice between pure RE170 and a mixture should consider the specific design constraints and priorities of each application.

CRediT authorship contribution statement

Daniel Calleja-Anta: Methodology, Investigation, Conceptualization. **Manel Martínez-Ángeles:** Writing – review & editing, Investigation. **Rodrigo Llopis:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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