



Thermodynamic assessment of R1234yf + R1243zf + R600a ternary mixture for domestic heat pumps

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ABSTRACT

Mixtures of hydrofluoroolefins (HFOs) and hydrocarbons (HCs) are increasingly recognized as promising substitutes for hydrofluorocarbon (HFC) refrigerants in residential heating systems due to their favorable environmental profiles and thermodynamic properties. This study investigates the ternary refrigerant mixture comprising 2,3,3,3-tetrafluoropropene (R1234yf), 3,3,3-trifluoropropene (R1243zf), and isobutane (R600a) as a potential drop-in replacement for R410A, widely used in domestic heat pump applications. Firstly, to verify the accuracy of the available thermodynamic property models, experimental measurements of *pvTz* properties for the ternary mixture were conducted across two-phase and superheated vapor regions using an isochoric apparatus at three isochores between temperatures of 260.15 K and 373.15 K. An excellent agreement between experimental results and calculations derived from multi-fluid Helmholtz-energy explicit models with model parameters recently determined for the binary subsystems was found, achieving average absolute relative deviations (AARD) below 1 %. Additionally, heat pump cycle simulations employing these thermodynamic property models revealed key performance indicators including coefficient of performance (COP), volumetric heating effect (VHE), temperature glide, and flammability index. Simulations indicated that no single pure fluid simultaneously optimizes COP and VHE, thereby emphasizing the importance of optimized mixture compositions. An optimal ternary composition was identified, delivering COP deviations up to +2 % compared to R410A, while highlighting environmental advantages and outlining necessary design adjustments for practical residential heat pump integration.

Introduction

The buildings sector is one of the main energy consumers that significantly impacts on greenhouse gas (GHG) emissions. In 2022, it accounted for 30 % of the global end-use energy consumption and represented about 27 % of total CO₂ emissions due to direct and indirect emissions from operations in the buildings (United Nations Environment Programme, 2024). These emissions were mainly due to the direct use of fossil fuels for space and water heating and the production of electricity and heat for use in buildings. In this context, the massive spread and use of efficient and low-carbon electrically-powered heat generation systems, such as heat pumps (HPs), can play a crucial role in decarbonizing the building sector and exploiting the most widespread renewable energy sources (Gaur et al., 2021; Toleikyte et al., 2023).

Currently, the refrigerants mainly used in HPs are hydrofluorocarbons (HFCs) characterized by high global warming potential

(GWP), such as R134a with GWP = 1530, R410A with GWP = 2256, and R32 with GWP = 771 (Intergovernmental Panel on Climate Change, 2021). Since they can significantly contribute to the global warming issue, the production and use of refrigerants with high GWP are being phased down as established by international agreements and regulations, such as the Kigali Amendment to the Montreal Protocol (Heath, 2017; Polonara et al., 2017) and the EU F-gas Regulation No 2024/573 (European Parliament and Council of the European Union, 2024). In this context, different natural and synthetic fluids, such as hydrocarbons (HCs), hydrofluoroolefins (HFOs), and hydrochlorofluoroolefins (HCFOs), have been identified as potential low GWP alternatives for refrigeration, air conditioning, and heat pump (RACHP) applications (McLinden and Huber, 2020). However, none of these fluids meet all the requirements regarding safety, environmental impact, and thermal performance, such as having suitable thermodynamic properties, stability in the system, and low flammability and toxicity. The HCs are considered low-cost and eco-friendly refrigerants that ensure high energy performance, but their

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Nomenclature			
c	Speed of sound [m s^{-1}]	EoS	Equation of state
c_p	Isobaric specific heat [$\text{J kg}^{-1} \text{K}^{-1}$]	GHG	Greenhouse gas
DSC	Subcooling at the condenser outlet [K]	GWP	Global warming potential
DSH	Superheating at the evaporator outlet [K]	HC	Hydrocarbon
e	Specific exergy [J kg^{-1}]	HFC	Hydrofluorocarbon
F_{12}	Scaling factor for departure functions	HFO	Hydrofluoroolefin
h	Specific enthalpy [J kg^{-1}]	HP	Heat pump
k_{ij}	Binary interaction parameter	NFI	Normalized flammability index
$\dot{m}$	Mass flow rate [kg s^{-1}]	ODP	Ozone depletion potential
M	Molar mass [kg kmol^{-1}]	PFAS	Per- and polyfluoroalkyl substances
p	Pressure [Pa]	RACHP	Refrigeration, air conditioning, and heat pump
q	Common abscissa for T - q diagram of heat exchanger	TFA	Trifluoroacetic acid
Q	Thermal power [W]	VHE	Volumetric heating effect [J m^{-3}]
s	Specific entropy [$\text{J kg}^{-1} \text{K}^{-1}$]	VLE	Vapor liquid equilibrium
T	Temperature [K]	<i>Subscripts/superscripts</i>	
U	Expanded uncertainty	c	Critical
v	Specific volume [$\text{m}^3 \text{kg}^{-1}$]	calc	Calculated
W	Power [W]	compr	Compressor
x	Liquid mole fraction	cond	Condenser
y	Vapor mole fraction	des	Destroyed
z	Overall mole fraction	evap	Evaporator
β, γ	Binary interaction parameters	exp	Experimental
ΔH_{vap}	Enthalpy of vaporization [J kg^{-1}]	in/out	Inlet/Outlet
η	Efficiency	is	Isentropic
λ	Thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$]	NBP	Normal boiling point
μ	Viscosity [Pa·s]	pp	Pinch point
ρ	Density [kg m^{-3}]	ref	Refrigerant loop
χ	Vapour fraction	RP	Refprop 10.0 software
<i>Acronyms</i>		sat	Saturated
AARD	Average absolute relative deviation	sh	Superheating
MARD	Maximum absolute relative deviation	sub	Subcooling
BIP	Binary interaction parameter	T	Temperature
COP	Coefficient of performance	tv	Throttling valve
		v	Specific volume
		w	Water loop

use is constrained due to potential safety hazards due to their high flammability (Abas et al., 2018; Palm, 2008). Instead, the HFOs have emerged as promising alternatives to HFCs due to their favorable thermophysical properties and low GWP, attributed to their rapid atmospheric degradation. However, their olefinic bond, while reducing atmospheric lifetime, presents challenges related to material compatibility, environmental safety, and toxicity, which remain active research topics (Bobbo et al., 2014; Domanski and McLinden, 2025; Fedele et al., 2023a; Nair, 2021). The atmospheric breakdown of some HFOs, such as R1234yf, produces compounds such as trifluoroacetic acid (TFA), raising concerns about environmental persistence and accumulation (Henne et al., 2012; Luecken et al., 2010). Fedele et al. (2023a) reviewed the available literature about the matter highlighting that the ecological and health risks are not clear, with some research groups raising attention on a potential threat (Arp et al., 2024; McGillen et al., 2023) and others minimizing the issue (Singh and Papanastasiou, 2021). Moreover, ongoing European Commission discussions on classifying HFOs as per- and polyfluoroalkyl substances (PFAS) may impact their future use (ECHA - European Chemical Agency, 2025). Given these challenges, suitable alternatives can be found in mixtures of natural refrigerants and HFOs since they can ensure improved environmental, safety and thermal performance by balancing their drawbacks.

Among the available hydrofluoroolefins, R1234yf and R1243zf were selected for this study because they are among the most extensively characterized HFOs in both scientific literature and commercial applications. R1234yf operates at pressures comparable to R134a and has

been widely adopted in automotive and small heat pump systems, whereas R1234zf, with lower vapor pressures, is particularly suitable for medium- and low-temperature applications. Their combination therefore enables the investigation of blends with balanced thermodynamic behaviour and practical relevance. Nonetheless, their environmental profile, including the potential classification of HFOs as per- and polyfluoroalkyl substances (PFAS), remains an open issue that could affect their long-term viability.

Different mixtures containing HFOs and natural refrigerants, such as HCs and carbon dioxide (Dai et al., 2015; Luo et al., 2023; Yang et al., 2024; Zendejboudi, 2025), have been analyzed as alternative working fluids for RACHP applications, offering an optimized compromise between performance and sustainability.

To accurately simulate the performance of RACHP systems and design their components, it is essential to determine the thermophysical properties of their working fluids employing reliable equations of state (EoSs), transport property models, and mixture models. At present, the most accurate thermodynamic property calculations for mixtures are provided by multi-fluid Helmholtz-energy explicit models with parameters properly tuned on experimental thermodynamic data (Bell et al., 2021; Mickoleit et al., 2021). These models are used in the most widespread software for estimating the thermodynamic properties of fluids and mixtures, such as Refprop 10.0 (Lemmon et al., 2018). However, the parameters for various mixtures containing HFOs are not available or were developed only on limited datasets since the limited experimentally determined thermophysical properties available in the literature

Table 1

Details of R1234yf, R1243zf and R600a samples.

Chemical Name	ASHRAE Designation	CAS Number	Source	Initial Mole Fraction Purity	Final Mole Fraction Purity
2,3,3,3-tetrafluoroprop-1-ene	R1234yf	754–12–1	Arkema	0.9995	0.9997
3,3,3-trifluoropropene	R1243zf	677–21–4	Mexichem Fluor S.A. de C.V.	0.995	0.9975
Isobutane	R600a	75–28–5	Sigma-Aldrich	-	0.9999

(Bell et al., 2021; Bobbo et al., 2018; Fedele et al., 2023b). Consequently, it is necessary to measure additional thermophysical properties to determine or retrofit the parameters of their mixture models (Bell et al., 2021).

It is important to note that the parameters of the multi-fluid Helmholtz-energy explicit models are generally fitted on the measurements of binary mixtures (Bell, 2022; Bell and Lemmon, 2016). However, to ensure that the models provide accurate thermodynamic properties for ternary and multi-component mixtures, it could be worth verifying their predictive capabilities by comparing the model calculations with their measured thermodynamic properties. To the best of our knowledge, only few studies available in the literature reported this check (e.g., Arami-Niya et al., 2020).

In this study, the performance of heat pump systems using the ternary mixture R1234yf + R1243zf + R600a is compared to that of R410A. The inclusion of two HFOs provides greater compositional flexibility, increasing the likelihood of identifying an optimal HFC substitute. R600a was selected for its high efficiency, low GWP, reduced energy consumption, and widespread use in RACHP applications, while its lower operating pressures contribute to cost savings and noise reduction. R1234yf and R1243zf are promising HFOs with zero ozone depletion potential (ODP) and ultra-low GWP. R1234yf is extensively studied, whereas R1243zf has gained attention for its thermophysical properties, closely resembling R134a. Both are flammable (A2L and A2, respectively), but their lower refrigerating capacities compared to HFCs necessitate their use in multi-component mixtures to enhance performance. Although the operating pressures of R600a + R1234yf + R1243zf mixture resemble those of medium-pressure refrigerants, such as R134a, in this work, R410A has been chosen as the baseline, as it represents the state-of-the-art refrigerant for residential applications (Domanski et al., 2017). Despite their lower volumetric heating/cooling capacity, the use of lower-pressure refrigerants as low-GWP alternatives to R410A could be investigated due to environmental benefits and safety considerations. These alternatives often present trade-offs among pressure levels, thermodynamic performance, and reduction in GWP (Domanski et al., 2017; Fedele et al., 2023c; Menegazzo et al., 2024a).

Several studies have explored mixtures incorporating R600a, R1234yf, and R1243zf for RACHP applications (Kim et al., 1994; Aprea et al., 2004; Calleja-Anta et al., 2022, 2023; Lombardo et al., 2025; Zhang et al., 2021). As regards the thermophysical properties of mixtures including these components, various studies reported measurements for R1234yf + R600a, R1243zf + R600a, and R1234yf + R1243zf binary systems (Bell et al., 2021; Bobbo et al., 2018; Fedele et al., 2023d; Lombardo et al., 2024; Yang et al., 2022).

This study has two primary objectives. First, it assesses the predictive capability of existing binary interaction parameters (BIPs) of the multi-fluid Helmholtz-energy explicit model for the binary systems R1234yf + R1243zf, R1243zf + R600a, and R1234yf + R600a when applied to the ternary mixture R1234yf + R1243zf + R600a. Calculated pressure-specific volume-temperature-composition ($pvTz$) properties are compared against experimental data measured in the two-phase and superheated vapor regions using an isochoric apparatus across three isochores from 260.15 K to 373.15 K — the only available dataset for this ternary mixture. In addition, the prediction capability of the Peng-Robinson EoS (Peng and Robinson, 1976) was also tested on the $pvTz$ properties of the studied ternary system. Second, the most recent BIPs in the multi-fluid Helmholtz-energy explicit model are used to simulate a

simple reverse cycle under typical air-to-water heat pump operating conditions for residential heating. The ternary mixture's performance is evaluated as a drop-in alternative to R410A, the dominant HFC in residential heat pumps, based on key performance indicators such as COP, volumetric heating effect (VHE), temperature glide, and flammability. Based on these performance metrics, an optimal ternary mixture composition is identified, providing insights into its practical viability, potential environmental advantages, and considerations necessary for its effective implementation in residential heat pump applications.

Materials and methods

Measured samples

The measured samples of R1234yf, R1243zf, and R600a are described in Table 1. As already explained elsewhere (Brown et al., 2013; Menegazzo et al., 2025), the purity of the samples was obtained from a gas chromatograph with a thermal conductivity detector. Each refrigerant sample underwent freezing, evacuation, thawing, and ultrasonic stirring cycles to remove the non-condensable gases.

Isochoric apparatus

An isochoric apparatus already used to measure two-phase and vapour phase pvT and $pvTz$ properties of refrigerants and their mixtures, respectively, was employed in this study. Detailed descriptions of the experimental setup, measurement procedure, and uncertainties can be found in studies available in the literature, together with details for the calibration of its main components (Brown et al., 2017; Di Nicola et al., 2005; Giuliani et al., 1995). Here, only its main features are presented. The isochoric apparatus included an AISI 304 stainless steel sphere with a volume of about 273.5 cm³ at 298 K and two thermostatic baths to measure the properties between 210 K and 380 K. A PID controller with a 25 Ω platinum resistance thermometer (Hart Scientific 5680) was used to keep the temperature set-point. The measuring cell was connected to a magnetic pump for mixing the sample and a differential Ruska 7000 pressure transducer with an electronic null indicator to measure the differential pressure. Instead, the atmospheric pressure was measured through a vibrating cylinder pressure gauge (Ruska 6220).

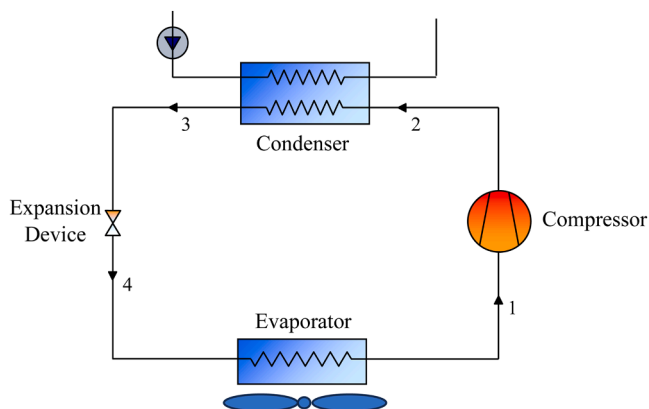
The sample of each mixture component was loaded in the measuring cell by means of the gravimetric method. Firstly, a bottle with the sample of the lower-pressure refrigerant and a vacuumed bottle were weighed with a Gibertini E42S-B analytical balance having an uncertainty of 0.3 mg. After connecting the bottles to the apparatus, the measuring cell, connections, and tubing were vacuumed. Then, the measuring cell was loaded with a specific amount of refrigerant. The mass remaining in the tubing and connections was recovered through the vacuumed bottle. At this point, the two bottles were weighed again to calculate the discharged and recovered sample amounts as the difference between the initial and final masses of the bottles. Therefore, the mass loaded into the measuring cell was calculated as the difference between the discharged and recovered masses. The procedure was repeated to load the samples of the refrigerants with higher pressures. Then, the composition of the measured mixture was determined on the basis of the loaded masses of the three refrigerants.

The expanded uncertainties at the 95 % confidence level ($k = 2$) for temperatures, pressures, volumes, and masses were determined from the

Table 2

Expanded uncertainties at the 95 % confidence level (coverage factor of 2) for the measured properties of R1234yf + R1243zf + R600a ternary system.

Property	Uncertainty
Temperature [K]	0.03
Pressure [kPa]	1
Volumes [cm ³]	0.3
Mass [mg]	1.2
Specific volumes [m ³ kg ⁻¹]	From 0.000065 to 0.000125
Mole fractions	From 0.0018 to 0.0033

**Fig. 1.** Schematic of the thermodynamic cycle simulated.

propagation of uncertainty as described elsewhere (Brown et al., 2017; Di Nicola et al., 2005; Giuliani et al., 1995; Tomassetti et al., 2020b). The uncertainties for specific volumes and mole fractions were also calculated by following the procedure based on the propagation of uncertainty described in the previous studies, but it was adapted for the ternary system. The values of the uncertainties for the measurements presented in this study are summarized in Table 2 and reported in Tables 5 and 6.

The following steps were followed to perform the measurements at each temperature set-point:

- After the system's temperature was stable at the selected set-point, the magnetic pump was turned on for a few minutes.
- The pressures were recorded after about an hour for allowing the charged sample to stabilise.
- The thermostatic bath temperature was changed to a different value and the procedure was repeated to measure the properties at the new temperature set-point.

Thermodynamic calculations

Thermodynamic calculations were carried out to evaluate the performance of heat pump systems working with the ternary mixture R1234yf + R1243zf + R600a with respect to R410A. A thermodynamic model was developed based on the work by Fedele et al. (2023c) to simulate a basic refrigerating cycle, such as the one displayed in Fig. 1.

The details of the thermodynamic model have been described in the Supporting Information (SI) and recall those presented by Fedele et al. (2023c). The model assumptions are the following:

- The heat exchangers are assumed to work in counter-current flow. Because the thermokinetic properties of the new mixtures studied were not available in the literature, the condenser and the evaporator have been considered as ideal. Both heat exchangers were implemented through the pinch point analysis, and the pressure losses have been neglected.

- The compressor isentropic efficiency is fixed and set equal to 0.7.
- The expansion occurring between the condenser and the evaporator is isenthalpic.
- The subcooling at the condenser outlet (*DSC*) is equal to 5 K.
- The superheating at the evaporator outlet (*DSH*) is equal to 10 K.

Such values are relatively high as superheating and subcooling in the case of air-source heat pumps. However, the decision was taken considering the same parameters set in our previous experimental work on a mixture of R1234yf+R600a (0.85/0.15) (Lombardo et al. 2025).

The boundary conditions required to run the simulations are:

- Condenser inlet and outlet temperatures set on the secondary fluid side (user circuit).
- Evaporator inlet and outlet temperatures set on the secondary fluid side (ambient air).
- Pinch point temperature difference, ΔT_{pp} , for both condenser and evaporator.

Given such boundary conditions, the model iteratively calculates the thermodynamic properties of the working fluid at each point in the refrigerant loop, corresponding to the numbers in Fig. 1. The thermodynamic properties of the refrigerants have been calculated with Refprop 10.0 software (Lemmon et al., 2018), which allowed to calculate temperature, pressure, density, enthalpy, entropy and other properties given the mixture composition and two properties among the aforementioned ones as input. Once converged, the performance indicators, i.e., coefficient of performance (COP) and the volumetric heating effect (VHE), have been calculated as Eqs. (1) and (2), respectively.

$$COP = \frac{h_2 - h_3}{h_2 - h_1} \quad (1)$$

$$VHE = \rho_1 \cdot (h_2 - h_3) \quad (2)$$

where h_i and ρ_i represent the specific enthalpy and the density of the fluid at the i th thermodynamic state, respectively, which can be visualized in Fig. 1.

In several studies available in the literature (Heredia-Aricapa et al., 2020; Mota-Babiloni et al., 2015), precise values of saturation temperature are set at the evaporator and the condenser to carry out the simulation. However, when dealing with zeotropic mixtures, this may result confusing. One of the most important features of this thermodynamic model was modelling the heat exchanger with the pinch point analysis, which allows to have a more realistic comparison among refrigerants by setting the requirements imposed by the target application as boundary conditions. Indeed, the inlet and outlet temperatures of the secondary fluids are the boundary conditions, and the operating pressures at the heat exchangers have been optimized to match the temperature profiles of the refrigerant and the secondary fluid with a fixed pinch point equal to 5 K for both the evaporator and the condenser. In particular, the heat exchangers have been modelled as a function requiring the secondary fluid inlet and outlet temperatures, the pinch point temperature difference and the superheating/subcooling temperature difference as fixed parameters and the refrigerant inlet enthalpy and pressure as input. Such functions give a new pressure value as output, which is the result of the optimization of the temperature profiles of the two fluids.

The thermodynamic model used in this study was intentionally simplified to enable a consistent comparative screening of refrigerant mixtures under single-stage cycle conditions, which are representative of typical residential heat pump configurations. This approach allows for the relative evaluation of performance metrics—such as COP and VHE—across different fluids, while minimizing variability introduced by hardware-specific or control-dependent parameters. To partially

Table 4

Simulation cycle conditions. ΔT user is the water temperature variation at the user terminal, DSH is superheating at the evaporator outlet, and DSC is sub-cooling at the condenser outlet.

Parameter	Value
External air [K]	258.15/266.15/275.15/280.15/ 285.15/290.15
Outlet water temperature at the condenser [K]	308.15
ΔT user [K]	5
DSH [K]	10
DSC [K]	5

assess the model's accuracy, we simulated the working conditions reported by Lombardo et al. (2025) for the binary mixture R1234yf + R600a (0.85/0.15)—the only experimental dataset available for a comparable system. The inlet and outlet temperatures measured within this previous study on the water loop for the condenser and the evaporator were set as boundary conditions for the simulations. Then, the performance indicators, i.e. COP and VHE, were calculated and compared with those derived by the measured thermophysical properties recorded within the refrigerant loop. The simulation showed an AARD of 9 % for COP and 24 % for VHE, and a maximum absolute average deviation (MARD) of 15 % for COP and 35 % for VHE, which we attribute to the model's inherent simplifications.

Several mixture compositions have been simulated and compared to the baseline fluid R410A. The target application was assumed to be a residential air-to-water heat pump. The boundary conditions for the simulations were defined according to the Italian standard UNI-TS 11,300–4 (UNI Ente italiano di normazione, 2016), which references the European standard EN 14,511 (EN European Standard, 2022). These standards establish the testing conditions for evaluating the performance of heat pump units. In accordance with these standards, the air-to-water heat pump simulated in this study was assessed under four external air temperatures: 266.15 K, 275.15 K, 280.15 K, 285.15 K. These temperatures effectively represent a broad range of climatic winter conditions, particularly those typical of the Mediterranean region. Additionally, two further air temperatures, 258.15 K and 290.15 K, were included to extend the analysis to more extreme conditions. It was assumed that the heat pump operated with a radiant floor system, maintaining a water inlet temperature of 303.15 K and an outlet temperature of 308.15 K. Operating conditions applied for simulations are summed up in Table 4.

As previously mentioned, the thermodynamic simulations were conducted to optimize the mixture composition. Such process was performed using a heuristic optimization algorithm, Adaptive Search Development Particle Swarm Optimization (Ardizzone et al., 2015), by maximizing the COP.

Furthermore, once calculated the optimal composition, other important indicators have been analysed, such as VHE, compressor discharge temperature, temperature glide and flammability. In particular, the flammability of the mixture was checked to account for safety constraints during both the installation and operation of the heat pump. To provide a preliminary qualitative indication of the flammability, the machine learning algorithm developed by Albà et al. (2024) was utilized.

Finally, the resulting optimal ternary mixture was compared with R410A from the exergy point of view. The fundamental equations employed for the exergetic analysis are given in Supporting Information. Only for such analysis, a mass flow rate value was required, which was calculated as in Eq. (3), considering a target heating capacity equal to 10 kW for each boundary condition. Also, the reference temperature T_0 for the exergetic analysis was set equal to the boundary external temperature.

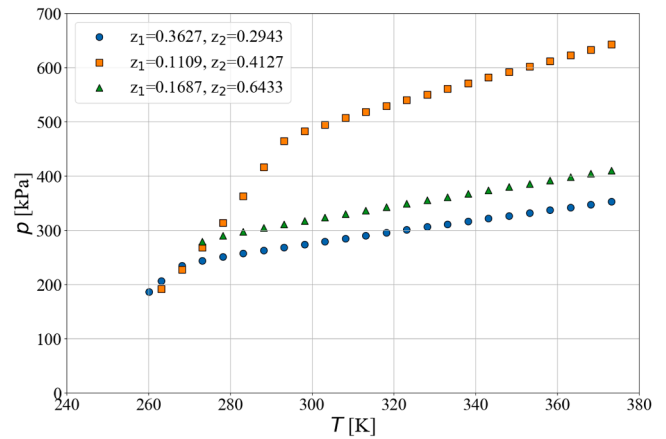


Fig. 2. p - v - T properties for R1234yf (1) + R1243zf (2) + R600a (3) ternary system measured in the two-phase and superheated vapor regions. The symbols p , v , T and z are the experimental pressure, specific volume, temperature, and overall mole fraction, respectively. Orange squares, $z_1 = 0.1109$, $z_2 = 0.4127$ and $v = 0.055457 \text{ m}^3 \text{ kg}^{-1}$; green triangles, $z_1 = 0.1687$, $z_2 = 0.6433$ and $v = 0.078049 \text{ m}^3 \text{ kg}^{-1}$; blue points, $z_1 = 0.3627$, $z_2 = 0.2943$ and $v = 0.095094 \text{ m}^3 \text{ kg}^{-1}$. Error crosses are not shown since the measurement uncertainties are smaller than the symbols.

Table 5

Pressure (p), temperature (T), specific volume (v), and overall mole fractions (z_1 and z_2) for R1234yf (1) + R1243zf (2) + R600a (3) ternary system measured in the two-phase region.

T [K]	p [kPa]	v [$\text{m}^3 \text{ kg}^{-1}$]	$U(v)$ [$\text{m}^3 \text{ kg}^{-1}$]
$z_1 = 0.1109$ and $z_2 = 0.4127^b$			
263.15	191.7	0.055323	0.000,065
268.15	227.8	0.055335	0.000,065
273.15	268.3	0.055347	0.000,065
278.15	313.3	0.055359	0.000,065
283.15	362.9	0.055372	0.000,065
288.15	416.9	0.055384	0.000,065
$z_1 = 0.1687$ and $z_2 = 0.6433^c$			
262.84	200.6	0.077867	0.000,097
263.15	202.7	0.077868	0.000,097
268.15	242.3	0.077885	0.000,097
$z_1 = 0.3627$ and $z_2 = 0.2943^d$			
260.15	186.3	0.094862	0.000,125
263.15	206.8	0.094875	0.000,125

aExpanded uncertainties at the 95 % confidence level are $U(T) = 0.03 \text{ K}$ and $U(p) = 1 \text{ kPa}$.

b $U(z_i) = 0.0018$.

c $U(z_i) = 0.0033$.

d $U(z_i) = 0.0025$.

$$\dot{m} = \frac{\dot{Q}_{\text{cond}}}{h_2 - h_3} \quad (3)$$

Results and discussions

Two-phase and vapour phase p - v - T measurements

Fig. 2 shows the p - v - T measurements of R1234yf + R1243zf + R600a ternary system carried out in the two-phase and superheated vapor regions. The two-phase and vapour-phase data can be distinguished by their different p - T behaviours. The experimental data were measured along three isochores $0.055457 \text{ m}^3 \text{ kg}^{-1}$, $0.078049 \text{ m}^3 \text{ kg}^{-1}$, $0.095094 \text{ m}^3 \text{ kg}^{-1}$ for temperatures between 260.15 K to 373.15 K. Tables 5 and 6 present the two-phase and the vapour-phase p - v - T properties, respectively.

Table 6

Pressure (p), temperature (T), specific volume (v), and overall mole fractions (z1 and z2) for R1234yf (1) + R1243zf (2) + R600a (3) ternary system measured in the superheated vapor regiona.

T [K]	p [kPa]	v [m ³ kg ⁻¹]	U(v) [m ³ kg ⁻¹]	T [K]	p [kPa]	v [m ³ kg ⁻¹]	U(v) [m ³ kg ⁻¹]
z ₁ = 0.1109 and z ₂ = 0.4127 ^c				z ₁ = 0.3627 and z ₂ = 0.2943 ^e			
293.15 ^b	464.4 ^b	0.055396 ^b	0.000065 ^b	268.15 ^b	234.8 ^b	0.094896 ^b	0.000125 ^b
298.15 ^b	482.7 ^b	0.055408 ^b	0.000065 ^b	273.15 ^b	243.9 ^b	0.094917 ^b	0.000125 ^b
303.15 ^b	495.0 ^b	0.055420 ^b	0.000065 ^b	278.15	251.2	0.094938	0.000,125
308.15	507.7	0.055432	0.000,065	283.15	257.1	0.094958	0.000,125
313.15	518.7	0.055445	0.000,065	288.15	262.9	0.094979	0.000,125
318.15	529.4	0.055457	0.000,065	293.15	268.5	0.095000	0.000,125
323.15	540.0	0.055469	0.000,065	298.15	274.0	0.095021	0.000,125
328.15	550.5	0.055481	0.000,065	303.15	279.5	0.095042	0.000,125
333.15	561.0	0.055493	0.000,065	308.15	285.0	0.095063	0.000,125
338.15	571.4	0.055505	0.000,065	313.15	290.4	0.095083	0.000,125
343.15	581.7	0.055517	0.000,065	318.15	295.6	0.095104	0.000,125
348.15	591.9	0.055530	0.000,065	323.15	300.9	0.095125	0.000,125
353.15	602.2	0.055542	0.000,065	328.15	306.2	0.095146	0.000,125
358.15	612.4	0.055554	0.000,065	333.15	311.3	0.095167	0.000,125
363.15	622.5	0.055566	0.000,065	338.15	316.5	0.095188	0.000,125
368.15	632.7	0.055578	0.000,065	343.15	321.7	0.095209	0.000,125
373.15	642.9	0.055590	0.000,065	348.15	326.9	0.095229	0.000,125
z ₁ = 0.1687 and z ₂ = 0.6433 ^d				353.15	332.2	0.095250	0.000,125
273.15 ^b	279.6 ^b	0.077903 ^b	0.000097 ^b	358.15	337.3	0.095271	0.000,125
278.15 ^b	290.0 ^b	0.077920 ^b	0.000097 ^b	363.15	342.4	0.095292	0.000,125
283.15	297.5	0.077937	0.000,097	368.15	347.6	0.095313	0.000,125
288.15	304.3	0.077954	0.000,097	373.15	352.7	0.095334	0.000,125
293.15	310.9	0.077971	0.000,097				
298.15	317.4	0.077988	0.000,097				
303.15	323.8	0.078005	0.000,097				
308.15	330.2	0.078022	0.000,097				
313.15	336.5	0.078039	0.000,097				
318.15	342.7	0.078057	0.000,097				
323.15	349.0	0.078074	0.000,097				
328.15	355.2	0.078091	0.000,097				
333.15	361.4	0.078108	0.000,097				
338.15	367.6	0.078125	0.000,097				
343.15	373.8	0.078142	0.000,097				
348.15	379.8	0.078159	0.000,097				
353.15	385.9	0.078176	0.000,097				
358.15	392.0	0.078193	0.000,097				
363.15	398.1	0.078211	0.000,097				
368.15	404.3	0.078228	0.000,097				
373.15	410.3	0.078245	0.000,097				

aExpanded uncertainties at the 95 % confidence level are U(T) = 0.03 K and U(p) = 1 kPa.

bNot considered in the calculations since their pressure behaviour is different from that of the other vapor-phase measurements due to sorption effects.

cU(z_i) = 0.0018.

dU(z_i) = 0.0033.

eU(z_i) = 0.0025.

Table 7

Mixing rules and binary interaction parameters for the binary subsystems of R1234yf + R1243zf + R600a ternary system used in the calculations. The symbols are defined in the Nomenclature.

Binary subsystem	Mixing rules	β _{T,12}	γ _{T,12}	β _{v,12}	γ _{v,12}	F ₁₂	Ref.
R1243zf (1) + R1234yf (2)	XR0	1.0081	0.9985	0.9417	0.9986	0	Lombardo et al. (2024)
R1234yf (1) + R600a (2)	KW0	0.9754825488	0.9185192036	1.1099828721	1.1295537308	0.0183894768	Zhang et al. (2018)
R1243zf (1) + R600a (2)	XR0	0.99315	0.94481	1.0046	0.99445	0	Menegazzo et al. (2025)

Two-phase pvTz calculations

The pvTz measurements carried out in the two-phase region were used to assess the vapor-liquid equilibrium properties of R1234yf + R1243zf + R600a ternary system through the “flash method” coupled with the multi-fluid Helmholtz-energy explicit model and the Peng-Robinson EoS extended to the mixture through the van der Waals one-fluid mixing rules (Poling et al., 2001). The calculations were based on the procedure presented in previous studies for binary systems (Di

Nicola et al., 1998; Tomassetti et al., 2020a) but adjusted for the ternary system. The fundamental EoSs expressed as a function of the Helmholtz energy for R1234yf and R600a available in Refprop 10.0 (Lemmon et al., 2018) were employed. Instead, the recent EoS proposed by Akasaka and Lemmon (2025) was used for R1243zf. To extend these models to the studied ternary system, the mixing rules and binary interaction parameters (BIPs) recently presented in the literature for its binary subsystems were considered. The values of the BIPs are reported in Table 7, together with the literature references.

Table 8

Comparison between the accuracy of the multi-fluid Helmholtz-energy explicit model and the Peng-Robinson EoS in the thermodynamic property calculations for R1234yf + R1243zf, R1234yf + R600a, and R1243zf + R600a binary subsystems. The symbols and acronyms are defined in the Nomenclature.

Property	Number of experimental data	Temperature range [K]	Reference	Helmholtz	Peng-Robinson
R1234yf + R1243zf					
pvTz	41	367.24 – 373.93	Yang et al. (2022)	AARD (p) = 0.97 %	AARD (p) = 4.18 %
VLE	20	293.41 – 353.74	Yang et al. (2022)	AARD (p) = 0.52 %	AARD (p) = 0.75 %
VLE	41	283.15 – 323.15	Fedele et al. (2023d)	AARD (p) = 0.16 % AAD (y) = 0.0016	AARD (p) = 0.95 % AAD (y) = 0.0028
Speed of sound	153	243.45 – 348.45	Lombardo et al. (2024)	AARD (c) = 1.02 %	AARD (c) = 11.85 %
R1234yf + R600a					
pvTz	101	270.11 – 300.21	Zhang et al. (2018)	AARD (p) = 0.16 %	AARD (p) = 0.28 %
pvTz	96	303.15 – 383.15	Brown et al. (2017)	AARD (p) = 1.11 %	AARD (p) = 1.04 %
VLE	60	283.15 – 323.15	Hu et al. (2014)	AARD (p) = 0.18 % AAD (y) = 0.0033	AARD (p) = 0.53 % AAD (y) = 0.0044
R1243zf + R600a					
Liquid density	54	283.15 – 423.15	Menegazzo et al. (2025)	AARD (p) = 0.08 %	AARD (p) = 2.43 %
pvTz	66	303.15 – 383.15	Tomassetti et al. (2019)	AARD (p) = 0.33 %	AARD (p) = 0.35 %
VLE	50	253.15 – 293.15	Deng et al. (2020)	AARD (p) = 0.38 % AAD (y) = 0.0027	AARD (p) = 0.80 % AAD (y) = 0.0057
VLE	53	283.15 – 323.15	Menegazzo et al. (2024b)	AARD (p) = 0.27 % AAD (y) = 0.0029	AARD (p) = 0.70 % AAD (y) = 0.0043

Table 9

Vapor-liquid equilibrium properties determined from the two-phase pvTz measurements for R1234yf (1) + R1243zf (2) + R600a (3) ternary system (reported in Table 5) by using the “flash method” with the multi-fluid Helmholtz-energy explicit model and the Peng-Robinson EoS. The symbols T, p_{calc}, x and y are the temperature, calculated pressure, and calculated mole fractions of the liquid and vapor phases, respectively.

T [K]	Helmholtz					Peng-Robinson				
	p _{calc} [kPa]	x ₁	x ₂	y ₁	y ₂	p _{calc} [kPa]	x ₁	x ₂	y ₁	y ₂
z ₁ = 0.1109 and z ₂ = 0.4127										
263.15	193.8	0.0868	0.3759	0.1446	0.4642	193.1	0.0881	0.3699	0.1435	0.474
268.15	230.2	0.0834	0.3671	0.1394	0.4599	229.1	0.0847	0.3604	0.1389	0.4685
273.15	271.2	0.0797	0.3565	0.1339	0.4542	269.4	0.0809	0.3493	0.134	0.4615
278.15	316.9	0.0758	0.3440	0.1283	0.4468	314.4	0.0768	0.3363	0.1288	0.4527
283.15	367.3	0.0715	0.3292	0.1225	0.4373	364.0	0.0724	0.3215	0.1233	0.4421
288.15	422.6	0.0671	0.3123	0.1165	0.4256	418.2	0.0678	0.3050	0.1176	0.4293
z ₁ = 0.1687 and z ₂ = 0.6433										
262.84	201.1	0.1511	0.6672	0.1759	0.6335	202.8	0.1496	0.6663	0.1765	0.6338
263.15	203.4	0.1510	0.6673	0.1757	0.6338	205.1	0.1495	0.6664	0.1763	0.6341
268.15	243.2	0.1483	0.6697	0.1722	0.6387	245.1	0.1465	0.6682	0.1726	0.6389
z ₁ = 0.3627 and z ₂ = 0.2943										
260.15	188.6	0.2995	0.2884	0.3789	0.2958	187.7	0.2889	0.2768	0.3830	0.2991
263.15	209.7	0.2903	0.2841	0.3725	0.2957	208.4	0.2787	0.2708	0.3757	0.2980

The binary interaction parameters (k_{ij}) for the Peng-Robinson EoS coupled with the van der Waals one-fluid mixing rules were determined from the thermodynamic properties of the binary subsystems available in the literature. The datasets used in the regression of k_{ij} are reported in Table 8. Their values were obtained by minimizing the root mean square of the available properties and are equal to 0.0076177 for R1234yf + R1243zf, 0.0946285 for R1234yf + R600a, and 0.08345245 for R1243zf + R600a.

Table 8 presents a comparison between the average absolute relative deviation (AARD) of the literature thermodynamic properties provided by the multi-fluid Helmholtz-energy explicit model and the Peng-Robinson EoS with the regressed parameters. As expected, the former model is generally more accurate than the Peng-Robinson EoS. This is especially true for the liquid density and speed of sound measurements.

The values of pressures (p_{calc}) and mole fractions of the liquid and vapor phases (x_i and y_i) of the ternary mixture calculated by means of the “flash method” are reported in Table 9. The deviations between the experimental and calculated pressures are shown in Figs. 3a and 3b for the Helmholtz-energy explicit model and the Peng-Robinson EoS, respectively. The results indicate that the selected models ensure an accurate description of the two-phase measurements, providing an average absolute relative deviation of the pressure (AARD(p)) of 0.96 % for the multi-fluid Helmholtz-energy explicit model and AARD(p) of 0.69 % for the Peng-Robinson EoS. Considering that the parameters of

the models were not determined on the basis of the proposed experimental data, this outcome demonstrates the reliability of both models in the description of the thermophysical properties of the studied ternary system.

Vapour-phase pvTz calculations

As for the two-phase region, the measurements performed in the superheated vapour region were utilized to assess the capability of the multi-fluid Helmholtz-energy explicit model combined with existing BIPs to predict the thermodynamic properties of the ternary system. In addition, they were also compared with the calculations provided by the Peng-Robinson EoS extended through the van der Waals one-fluid mixing rules with the regressed k_{ij} . Deviations between experimental data and model calculations were analyzed in terms of specific volume and pressure, revealing that the selected models provide a satisfactory prediction of the vapour-phase properties. Deviations in terms of pressure as a function of temperature are shown in Figs. 4a and 4b for the Helmholtz-energy explicit model and the Peng-Robinson EoS, respectively. Specifically, the calculated vapour-phase pvTz data provided by the multi-fluid Helmholtz-energy explicit model showed an AARD of 0.64 % for specific volumes and an AARD of 0.59 % for pressures. Instead, the Peng-Robinson EoS yielded AARDs of 0.66 % and 0.61 % for the specific volumes and pressures, respectively. These deviations

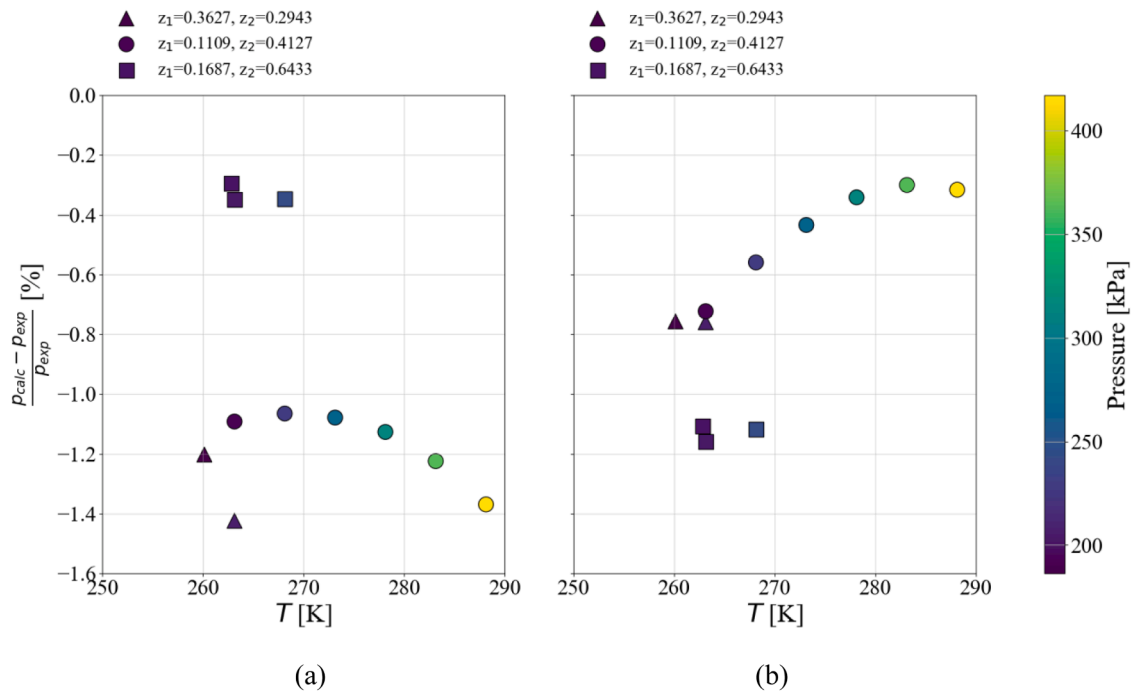


Fig. 3. Deviations in pressure (p) between the experimental data in the two-phase region and the up-to-date models for the ternary mixture with: (a) Helmholtz-energy explicit model, (b) Peng-Robinson EoS with van der Waals one-fluid mixing rules. The symbols T and z are the temperature and overall mole fraction, respectively.

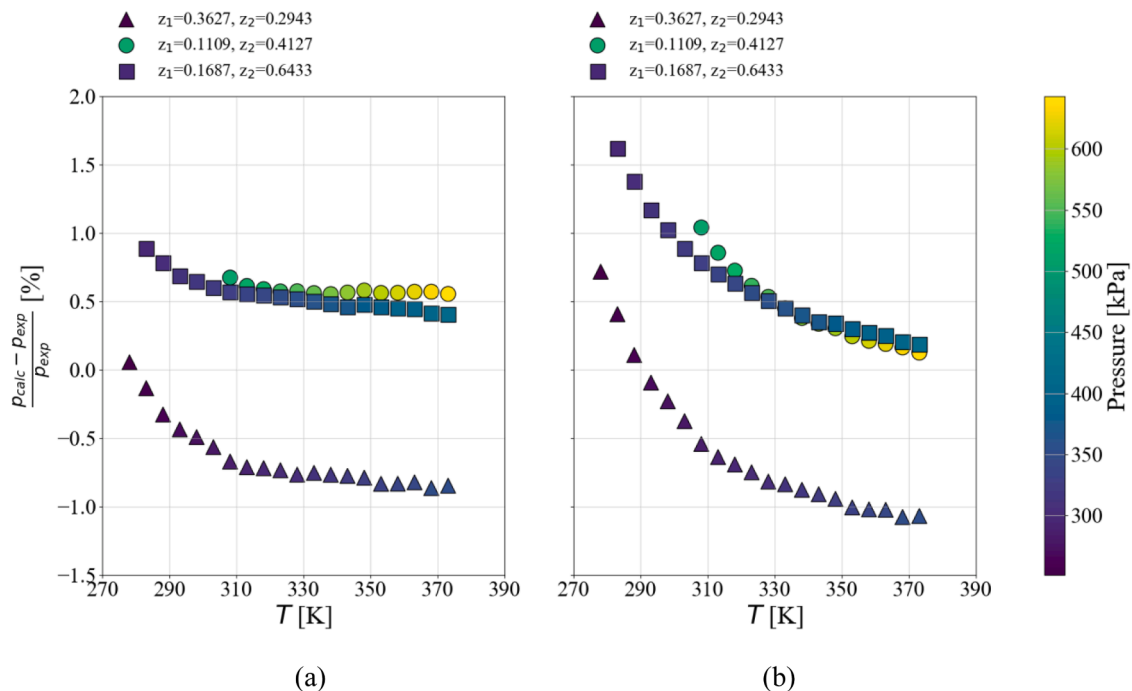


Fig. 4. Deviations in pressure (p) between the experimental data in the superheated vapour region and the up-to-date models for the ternary mixture with: (a) Helmholtz-energy explicit model, (b) Peng-Robinson EoS with van der Waals one-fluid mixing rules. The symbols T and z are the temperature and overall mole fraction, respectively.

confirm the accuracy and reliability of the chosen models, even though the parameters were not directly fitted using the current experimental dataset. Finally, although both models ensured low deviations for the vapour-phase and two-phase thermophysical properties of the studied ternary system, the developed Helmholtz-energy explicit EoSs can be considered more suitable for heat pump system simulation and

optimization, as they also provide more accurate descriptions of the thermodynamic properties of binary subsystems, as shown in Table 8.

Simulation results

As previously mentioned, the ternary mixture was tested across all

Table 10

Environmental, safety and thermophysical properties of R1234yf, R1243zf, R600a and baseline fluid R410A. The symbols are defined in the Nomenclature.

Environmental and safety properties (Intergovernmental Panel on Climate Change (IPCC), 2021; ANSI/ASHRAE Standard 34-2019, 2019)						
Refrigerant			R1234yf	R1243zf	R600a	R410A
GWP			<1	<1	5	2088
ODP			0	0	0	0
ASHRAE Safety class			A2L	A2	A3	A1
Thermophysical properties (Lemmon et al., 2018)						
Property	T [K]	State	R1234yf	R1243zf	R600a	R410A
M [kg kmol ⁻¹]	—	—	114.04	96.051	58.122	72.58
T _{NBP} [K]	—	—	243.67	247.73	261.401	221.5
T _c [K]	—	—	367.85	376.93	407.81	344.49
p _c [MPa]	—	—	3.38	3.52	3.63	4.9
ΔH _{vap} [kJ kg ⁻¹]	275.15	Liquid	162	199.3	352.44	218.85
	308.15	Vapor	136.88	172.09	317.53	168.81
p _{sat} [MPa]	275.15	Liquid	0.34	0.29	0.17	0.85
	308.15	Vapor	0.89	0.78	0.46	2.14
ρ [kg m ⁻³]	275.15	Liquid	1170	1041.9	578.28	1161.9
	308.15	Vapor	50.3	35.51	11.99	87.46
μ [mPa·s]	275.15	Liquid	0.2	0.2	0.2	0.2
	308.15	Vapor	0.01	0.01	0.01	0.01
λ [W m ⁻¹ K ⁻¹]	275.15	Liquid	0.07	0.08	0.09	0.1
	308.15	Vapor	0.015	0.02	0.02	0.02
c _p [kJ kg ⁻¹ K ⁻¹]	275.15	Liquid	1.3	1.38	2.29	1.53
	308.15	Vapor	1.12	1.17	1.88	1.69

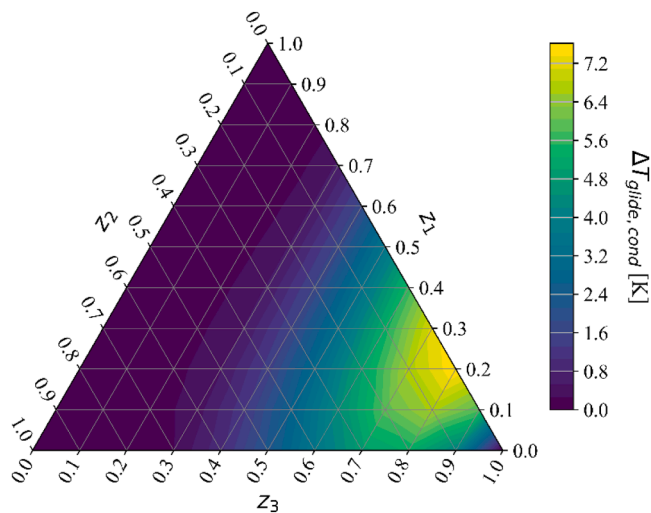


Fig. 5. Results obtained in terms of temperature glide at the condenser ($\Delta T_{\text{glide,cond}}$) for the various compositions given as mole fraction z_1 of the ternary mixture R1234yf (1) + R1243zf (2) + R600a (3) at $T_{\text{air}} = 293.15$ K.

possible compositions in comparison to R410A under typical residential heating scenarios.

Table 10 presents essential environmental, safety, and thermophysical properties of R1234yf, R1243zf, and R600a, compared to the baseline refrigerant R410A, at representative evaporating and condensing temperatures used in this study: 275.15 K and 308.15 K, respectively. This initial comparison provides insights into operational aspects that are not directly addressed in this study, such as components compatibility and stability. As illustrated in the table, R1234yf exhibits a lower molar mass (M) and consequently a lower enthalpy of vaporization (ΔH_{vap}) relative to R410A. However, incorporating R1243zf and particularly R600a, which possess more favourable properties in this context compared to R410A, can enhance the overall mixture performance. Furthermore, all three fluids—R1234yf, R1243zf, and R600a—show lower vapor densities compared to R410A, leading to reduced mass flow rates processed by the compressor. Consequently, the compressor must handle larger volumes, necessitating more substantial

components and larger heat exchange surfaces, as will be demonstrated later in this study. Additionally, similar viscosity (μ) and thermal conductivity (λ) values suggest that heat exchanger performance will remain comparable. Finally, the fluids' comparable isobaric specific heats (c_p), particularly higher for R600a, should result in similar discharge temperatures, thus limiting compressor stress and ensuring refrigerant and oil stability.

Simulation results for temperature glide at the condenser, COP, and VHE are presented in Figs. 5, 6 and 7, respectively. For COP and VHE, the data are provided for each of the source temperatures considered, relative to the baseline values obtained for R410A.

Concerning the performance trends of COP (Fig. 6), and VHE (Fig. 7), both parameters exhibit mutually consistent behaviours. The observed performance, both in absolute terms and relative to R410A, improves slightly at higher evaporating temperatures. Specifically, COP variations range from approximately +4.7 % (occurring at an air temperature of 258.15 K) to +7.9 % (occurring at 290.15 K), compared to R410A. Conversely, VHE consistently ranges between −64.9 % and −59.40 % relative to R410A, with a relatively stable behaviour across the considered source conditions. These results for VHE align with expectations, given the lower latent heat of vaporization common to R1234yf, R1243zf, and R600a, and the comparatively reduced heating capacities of R1234yf and R600a with respect to R410A.

The optimal molar composition resulted to be 83 % of R1234yf, 5 % of R1243zf and 12 % of R600a. Table 11 summarizes the most interesting performance indicators for the simulated boundary conditions. These compositions not only represent optimal choices under the different operating conditions but also correspond closely to near-azeotropic mixtures, as evident from Fig. 5. Moreover, the calculated NFI was equal to 19.10, leading to a A2L refrigerant in terms of safety.

As presented in Table 11, the optimal results achieved are remarkably similar across the four conditions studied, consistently featuring minimal concentrations of R1243zf at approximately 5 %. This finding suggests that even a binary mixture of R1234yf + R600a could potentially substitute R410A for residential heating scenarios, aligning with experimental evidence presented by Lombardo et al. (2025) in comparisons to R134a. To demonstrate so, further simulations were run under the same temperature conditions for the binary mixture R1234yf + R600a (0.88/0.12 mol fraction). Given the similar thermophysical properties of R1234yf and R1243zf, as well as the near-azeotropic behaviour of the R1234yf + R1243zf mixture, the molar share of R1243zf was substituted with an equivalent amount of R1234yf. As can be seen from Table 12, the results obtained for this binary system are almost identical to those of the ternary mixture R1234yf + R1243zf + R600a (0.83/0.05/0.12). For the binary mixture, the NFI is equal to 17.20, which is slightly lower than that of the ternary mixture.

The data in Table 11 also indicate that the mixture demonstrates superior COP performance compared to R410A exclusively at T_{air} equal to 275.15 K, 280.15 K, 285.15 K, and 290.15 K, with deviations ranging from −1 % (at $T_{\text{air}} = 258.15$ K) up to +3 % (at $T_{\text{air}} = 290.15$ K). Conversely, due to previously discussed factors such as vapor density, heat capacity, and latent heat, the mixture consistently underperforms relative to R410A in terms of compressor power requirement (W_{comp}) and volumetric heating effect (VHE). Specifically, compressor power increases between +2 % and +8 %, while VHE decreases by approximately 60 %.

The reduced VHE observed with the proposed refrigerant mixture implies a need for larger compressor displacement to maintain comparable performance, with potential implications for efficiency, equipment cost, and system footprint. Additionally, the increased mass flow rate associated with the lower specific refrigeration effect of the mixture may lead to higher refrigerant velocities in both piping and heat exchangers. This rise in velocity directly corresponds to greater pressure drops, which can degrade system efficiency and potentially exceed design limits in standard heat exchanger and piping geometries. To mitigate such losses, the use of larger heat exchanger surfaces, or alternatively

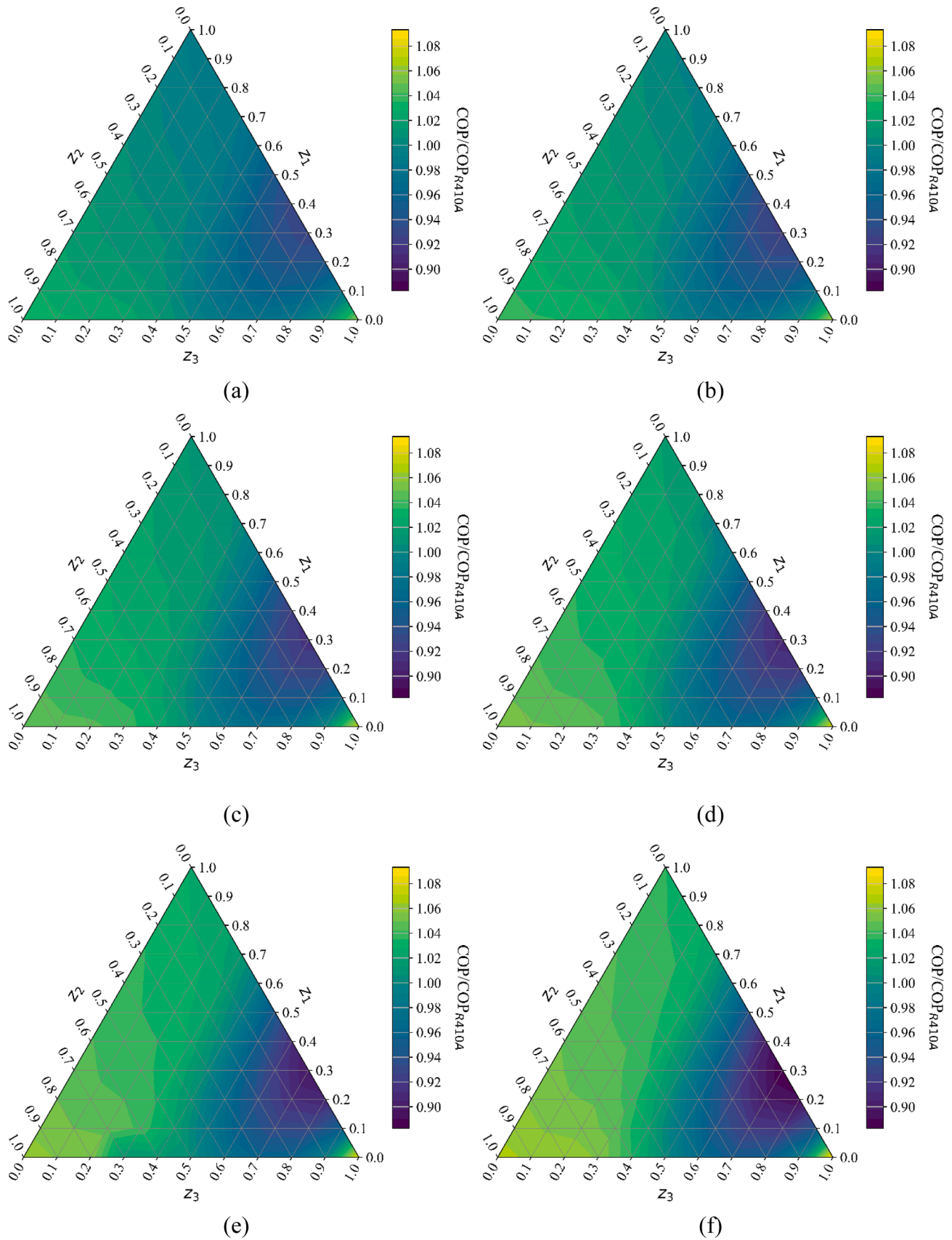


Fig. 6. Results obtained in terms of coefficient of performance (COP) for the various compositions given as mole fraction z_i of the ternary mixture R124yf (1) + R1243zf (2) + R600a (3) at: a) $T_{air} = 258.15$ K, b) $T_{air} = 266.15$ K, c) $T_{air} = 275.15$ K, d) $T_{air} = 280.15$ K, e) $T_{air} = 285.15$ K, f) $T_{air} = 290.15$ K.

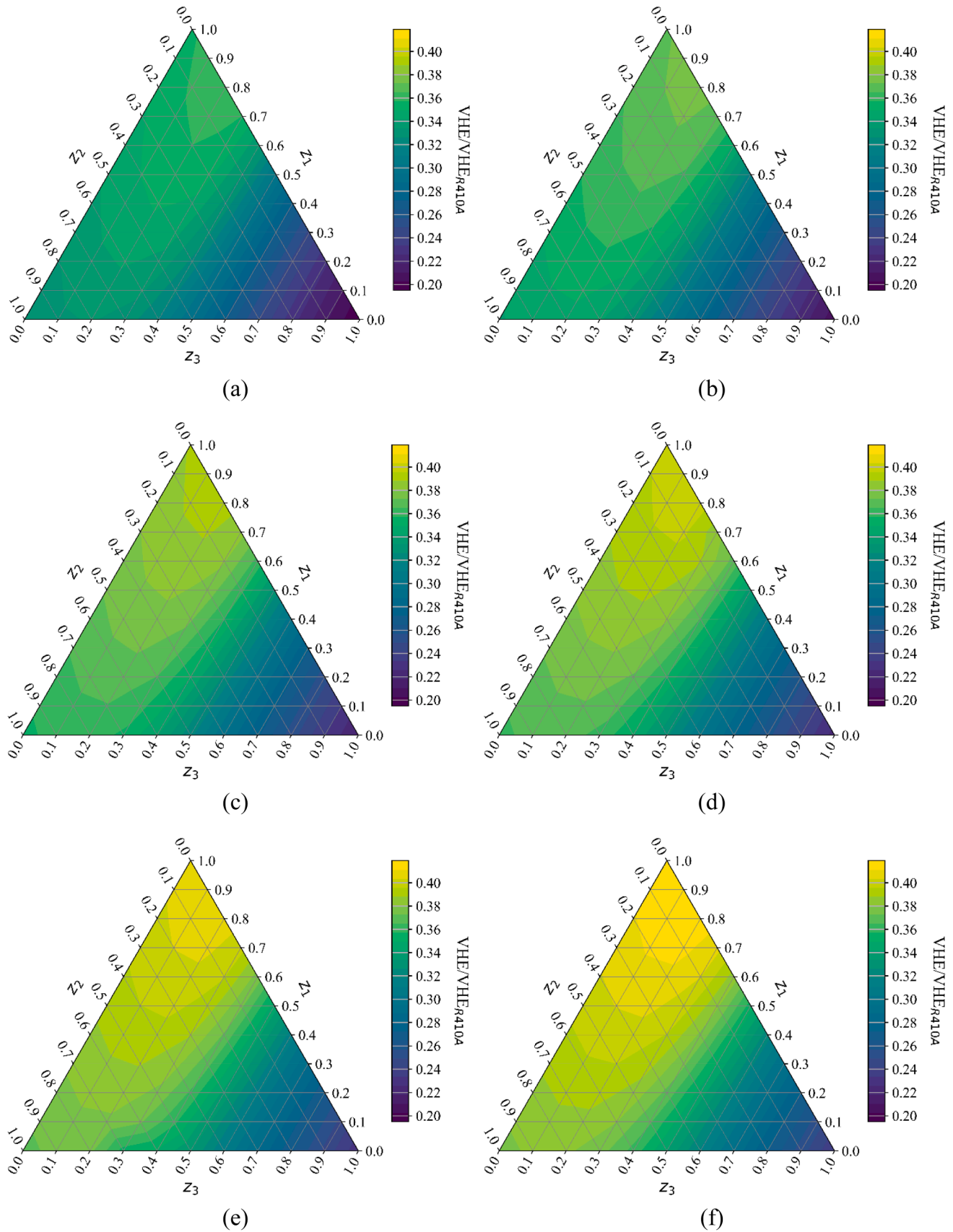


Fig. 7. Results obtained in terms of volumetric heating effect (VHE) for the various compositions given as mole fraction z_i of the ternary mixture R1234yf (1) + R1243zf (2) + R600a (3) at: a) $T_{air} = 258.15$ K, b) $T_{air} = 266.15$ K, c) $T_{air} = 275.15$ K, d) $T_{air} = 280.15$ K, e) $T_{air} = 285.15$ K, f) $T_{air} = 290.15$ K.

Table 11

Relative performance indicators and compressor discharge temperatures (T_2) for the mixture R1234 + R1243zf + R600a (83/5/12 molar based) and R410A. The symbols T_{source} , COP, W_{compr} and VHE are the source temperature, coefficient of performance, compressor power, and volumetric heating effect.

T_{source} [K]	COP/ COP _{R410A}	$W_{\text{compr}}/$ $W_{\text{compr,R410A}}$	VHE/ VHE _{R410A}	T_2 [K]	$T_{2, \text{R410A}}$ [K]
258.15	0.99	1.01	0.36	334.85	379.85
266.15	1.00	1.02	0.37	331.95	370.35
275.15	1.01	1.04	0.39	329.35	360.85
280.15	1.02	1.05	0.40	328.15	355.95
285.15	1.03	1.06	0.41	327.15	351.45
290.15	1.04	1.07	0.41	326.15	347.25

Table 12

Performance metrics for the binary mixture R1234yf + R600a (0.88/0.12). The symbols T_{source} , COP, W_{compr} and VHE are the source temperature, coefficient of performance, compressor power, and volumetric heating effect.

T_{source} [K]	COP/COP _{R410A}	$W_{\text{compr}}/W_{\text{compr,R410A}}$	VHE/VHE _{R410A}
258.15	0.99	1.02	0.36
266.15	1.00	1.03	0.38
275.15	1.01	1.05	0.39
280.15	1.02	1.05	0.40
285.15	1.02	1.06	0.41
290.15	1.03	1.07	0.42

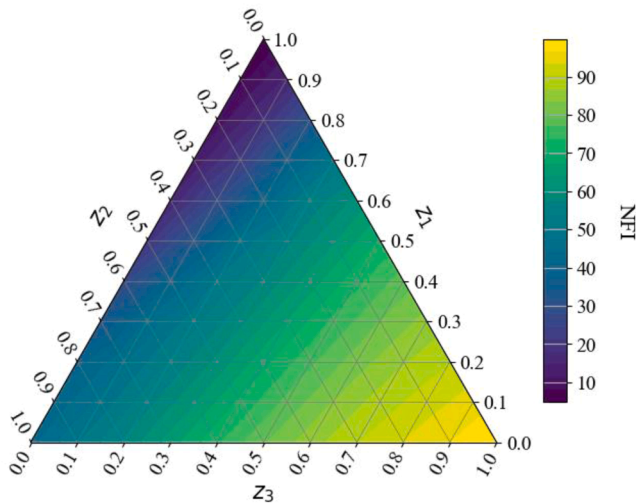


Fig. 8. Normalized Flammability Index (NFI) for the various compositions given as mole fraction z_i of the ternary mixture R1234yf (1) + R1243zf (2) + R600a (3).

enhanced designs may be required to maintain effectiveness without compromising performance. However, these solutions come with their own cost and design trade-offs. While a full hardware redesign and cost-benefit analysis are beyond this study's scope, these findings offer preliminary guidance for future system-level adaptations, highlighting the technical and economic trade-offs between improved environmental performance and the adjustments required in system components. In fact, they make clear the need to reassess the refrigerant circuit design from compressor sizing to heat exchanger configuration.

Overall, considering the comparable COP values and distinct environmental benefits, the proposed mixture could indeed represent a viable alternative to R410A for residential heating applications, contingent upon careful selection and optimization of cycle components. This is especially true when sustainability is a design priority.

Although the share of R600a in the mixture is particularly reduced, a higher percentage of R600a would have led to a significant drop in terms

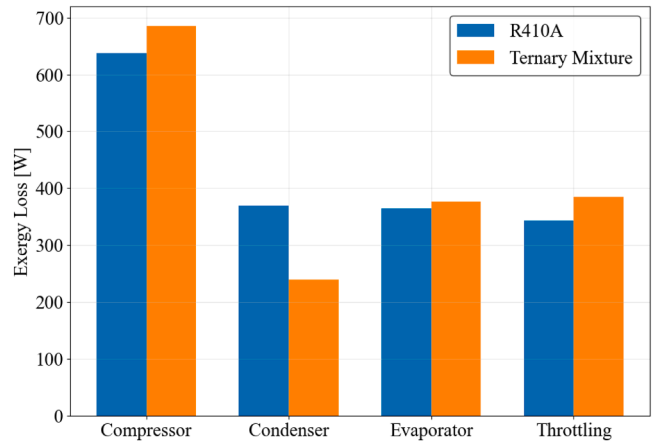


Fig. 9. Exergy loss comparison between the ternary mixture R1234yf + R1243zf + R600a (83/5/12) and R410A considering an external air-source temperature equal to 275.15 K.

of energy performance and volumetric effect. A higher isobutane content would necessitate a larger displacement compressor, further increasing equipment cost and system complexity.

Moreover, based on the normalized flammability index (NFI), which is an empirical metric that estimates the flammability of refrigerants integrating key parameters—such as heat of combustion, the lower flammability limit, and laminar burning velocity—the selected mixture can be considered mildly flammable A2L, thanks to a $NFI < 50$, which makes it more suitable to residential applications compared to HCs. Obviously, specific experimental investigations focused on flammability are necessary to verify this outcome. Anyway, the proposed mixture requires careful handling to prevent fire hazards. This includes using explosion-proof electrical components, ensuring proper ventilation in enclosed spaces, and employing specific technologies to reduce the flammability risk by lowering the gas-to-oxygen ratio below the lower flammability limits (Cheekatamarla and Sharma, 2024). The distribution of NFI as composition of the ternary mixture changes is shown in Fig. 8.

Further interesting insights have been obtained from the exergetic analysis of the ternary mixture and the baseline R410A. Fig. 9 shows the results for an external air-source temperature equal to 275.15 K, while Table 13 shows the results for all the simulated boundary conditions. Considering the four components of the thermodynamic cycle, the ternary mixture resulted in increased exergy losses for every component, but the condenser. For the ternary mixture, the compressor resulted to be the most penalized component from the exergetic point of view: the compressor power required by the ternary mixture led to increased exergy losses, considering the same isentropic efficiency. Conversely, the exergy losses at the condenser were always lower for the ternary mixture. This is due to the high compressor discharge temperature encountered with R410A (reported in Table 12), which worsens the heat transfer at the condenser. It is worth noting that, despite the exergy losses at compressor, evaporator and throttling valve were always higher for the ternary mixture, the overall exergy losses with the ternary mixture were greater than R410A only with the coldest external air-source temperature and almost identical at 266.15 K. For the other cases, the total exergy losses resulted lower for the ternary mixture with respect to R410A.

Conclusions

HFO/HCs refrigerant mixtures present significant potential as environmentally sustainable alternatives to hydrofluorocarbon (HFC) refrigerants such as R410A, which currently dominates residential heating applications. This study evaluated the thermodynamic performance of

Table 13
Exergetic analysis results for the baseline R410A and the ternary mixture R1234yf + R1243zf + R600a (83/5/12).

	Exergy losses [W]									
	Compressor		Condenser		Evaporator		Throttling valve		Total	
Source Temperature [K]	R410A	Ternary mixture	R410A	Ternary mixture	R410A	Ternary mixture	R410A	Ternary mixture	R410A	Ternary mixture
258.15	769.5	873.0	441.7	241.1	338.6	348.8	535.8	659.5	2085.7	2122.5
266.15	712.7	788.6	404.8	239.2	351.4	362.4	442.2	522.4	1911.1	1912.6
275.15	637.2	685.5	369.2	239.3	365.1	376.2	343.5	384.5	1715.0	1685.6
280.15	590.1	625.1	352.0	240.2	372.5	383.3	292.6	316.3	1607.1	1564.9
285.15	539.6	562.8	336.4	241.6	379.6	389.9	244.7	254.4	1500.3	1448.7
290.15	485.8	498.9	322.5	243.3	386.5	396.1	200.3	199.1	1395.1	1337.4

the ternary mixture R1234yf + R1243zf + R600a, aiming to identify an optimal composition capable of substituting R410A in residential heat pumps. Experimental *p*vTz properties measured across both two-phase and superheated vapor regions demonstrated that existing BIPs for multi-fluid Helmholtz-energy explicit models can accurately predict ternary mixture properties, achieving deviations lower than 1 % for both pressures and specific volumes. Cycle simulations under typical air-to-water heat pump operating conditions indicated that the ternary mixture composition requires careful balancing to optimize performance metrics, as none of the pure fluids simultaneously maximized COP and VHE. Optimized simulations highlighted that compositions with minimal amounts (~5 %) of R1243zf yielded the best trade-off between COP, volumetric capacity, and temperature glide, suggesting that even the binary azetropic mixture of R1234yf and R600a might be effective substitutes. Despite a decrease in VHE and a subsequent increase in compressor power requirements compared to R410A, the proposed mixture demonstrated slightly higher COP values, especially at higher ambient temperatures. Other interesting insights came from the exergetic analysis, which highlighted the opportunity for further optimization at the compressor and suggested an improved heat transfer at the condenser with respect to the baseline R410A. Ultimately, this work emphasizes the feasibility of the studied ternary refrigerant mixture as an alternative for residential heat pump systems, contingent upon optimized system design, component selection adjustments, and detailed safety considerations due to mild flammability.

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CRedit authorship contribution statement

S. Tomassetti: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **G. Lombardo:** Writing – review & editing, Writing – original draft, Visualization, Software. **D. Menegazzo:** Writing – review & editing, Writing – original draft, Software, Methodology.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ijrefrig.2025.11.030](https://doi.org/10.1016/j.ijrefrig.2025.11.030).

References

Abas, N., Kalair, A.R., Khan, N., Haider, A., Saleem, Z., Saleem, M.S., 2018. Natural and synthetic refrigerants, global warming: a review. *Renew. Sustain. Energy Rev.* 90, 557–569. <https://doi.org/10.1016/j.rser.2018.03.099>.

Akasaka, R., Lemmon, E.W., 2025. A Helmholtz Energy equation of State for 3,3,3-trifluoroprop-1-ene (R-1243zf). *Int. J. Thermophys.* 46, 23. <https://doi.org/10.1007/s10765-024-03481-6>.

Albà, C.G., Alkhatib, I.I., Vega, L.F., Llovel, F., 2024. Mapping the flammability space of sustainable refrigerant mixtures through an artificial neural network based on molecular descriptors. *ACS. Sustain. Chem. Eng.* 12, 11561–11577. <https://doi.org/10.1021/acssuschemeng.4c01961>.

ANSI/ASHRAE Standard 34-2019, Designation and safety classification of refrigerants, 2019.

Apra, C., Mastrullo, R., Renno, C., 2004. An analysis of the performances of a vapour compression plant working both as a water chiller and a heat pump using R22 and R417A. *Appl. Therm. Eng.* 24, 487–499. <https://doi.org/10.1016/j.applthermaleng.2003.10.006>.

Arami-Niya, A., Xiao, X., Al Ghafri, S.Z.S., Jiao, F., Khamphasith, M., Pouya, E.S., Sadaghiani, M.S., Yang, X., Tsuji, T., Tanaka, Y., 2020. Measurement and modelling of the thermodynamic properties of carbon dioxide mixtures with HFO-1234yf, HFC-125, HFC-134a, and HFC-32: vapour-liquid equilibrium, density, and heat capacity. *Int. J. Refrig.* 118, 514–528.

Ardizzoni, G., Cavazzini, G., Pavesi, G., 2015. Adaptive acceleration coefficients for a new search diversification strategy in particle swarm optimization algorithms. *Inf. Sci.* 299, 337–378.

Arp, H.P.H., Gredelj, A., Glüge, J., Scheringer, M., Cousins, I.T., 2024. The global threat from the irreversible accumulation of trifluoroacetic acid (TFA). *Environ. Sci. Technol.* 58, 19925–19935. <https://doi.org/10.1021/acs.est.4c06189>.

Bell, I.H., 2022. Mixture models for refrigerants R-1234yf/134a, R-1234yf/1234ze(E), and R-134a/1234ze(E) and interim models for R-125/1234yf, R-1234ze(E)/227ea, and R-1234yf/152a. *J. Phys. Chem. Ref. Data* 51. <https://doi.org/10.1063/5.0086060>.

Bell, I.H., Lemmon, E.W., 2016. Automatic fitting of binary interaction parameters for multi-fluid helmholtz-energy-explicit mixture models. *J. Chem. Eng. Data* 61, 3752–3760. <https://doi.org/10.1021/acs.jced.6b00257>.

Bell, I.H., Riccardi, D., Bazyleva, A., McLinden, M.O., 2021. Survey of data and models for refrigerant mixtures containing halogenated olefins. *J. Chem. Eng. Data*.

Bobbo, S., Nicola, G., Di Zilio, C., Brown, J.S., Fedele, L., 2018. Low GWP halocarbon refrigerants: a review of thermophysical properties. *Int. J. Refrig.* 90, 181–201. <https://doi.org/10.1016/j.ijrefrig.2018.03.027>.

Bobbo, S., Zilio, C., Scattolini, M., Fedele, L., 2014. R1234yf as a substitute of R134a in automotive air conditioning. Solubility measurements in two commercial PAG oils. *Int. J. Refrig.* 40, 302–308. <https://doi.org/10.1016/j.ijrefrig.2013.08.002>.

Brown, J.S., Coccia, G., Tomassetti, S., Pierantozzi, M., Di Nicola, G., 2017. Vapor phase pvtz measurements of binary blends of 2,3,3,3-tetrafluoroprop-1-ene + isobutane and trans-1,3,3,3-tetrafluoroprop-1-ene + isobutane. *J. Chem. Eng. Data* 62, 3577–3584. <https://doi.org/10.1021/acs.jced.7b00564>.

Brown, J.S., Di Nicola, G., Fedele, L., Bobbo, S., Zilio, C., 2013. Saturated pressure measurements of 3,3,3-trifluoroprop-1-ene (R1243zf) for reduced temperatures ranging from 0.62 to 0.98. *Fluid Ph. Equilib.* 351, 48–52. <https://doi.org/10.1016/j.fluid.2012.09.036>.

Calleja-Anta, D., Nebot-Andres, L., Sánchez, D., Cabello, R., Llopis, R., 2022. Drop-in substitutes for R-600a. Experimental evaluation and optimization of a commercial fridge. *Appl. Therm. Eng.* 211, 118490. <https://doi.org/10.1016/j.applthermaleng.2022.118490>.

Calleja-Anta, D., Sánchez, D., Nebot-Andrés, L., Cabello, R., Llopis, R., 2023. Alternative mixtures to R-600a. Theoretical assessment and experimental energy evaluation of binary mixtures in a commercial cooler. *Int. J. Refrig.* 152, 83–92. <https://doi.org/10.1016/j.ijrefrig.2023.05.009>.

Cheekatamarla, P., Sharma, V., 2024. Mitigation of safety and environmental challenges posed by refrigerants. *Results. Eng.* 23, 102381. <https://doi.org/10.1016/j.rineng.2024.102381>.

Dai, B., Dang, C., Li, M., Tian, H., Ma, Y., 2015. Thermodynamic performance assessment of carbon dioxide blends with low-global warming potential (GWP) working fluids for a heat pump water heater. *Int. J. Refrig.* 56, 1–14.

Deng, Z., Xu, G., Sun, S., Zhao, Y., Dong, X., Gong, M., 2020. Isothermal (vapour-liquid) equilibrium for the binary {isobutane (R600a)+ 3, 3, 3-trifluoropropene (R1243zf)} cc system at temperatures from 253.150 to 293.150 K. *J. Chem. Thermodyn.* 150, 106177.

- Di Nicola, G., Giuliani, G., Passerini, G., Polonara, F., Stryjek, R., 1998. Vapor-liquid equilibrium (VLE) properties of R-32 + R-134a system derived from isochoric measurements. *Fluid Ph. Equilib.* 153, 143–165. [https://doi.org/10.1016/S0378-3812\(98\)00407-5](https://doi.org/10.1016/S0378-3812(98)00407-5).
- Di Nicola, G., Polonara, F., Ricci, R., Stryjek, R., 2005. PVTx measurements for the R116 + CO₂ and R41 + CO₂ systems. New isochoric apparatus. *J. Chem. Eng. Data* 50, 312–318.
- Domanski, P.A., Brignoli, R., Brown, J.S., Kazakov, A.F., McLinden, M.O., 2017. Low-GWP refrigerants for medium and high-pressure applications. *Int. J. Refrig.* 84, 198–209. <https://doi.org/10.1016/J.IJREFRIG.2017.08.019>.
- Domanski, P.A., McLinden, M.O., 2025. Updating the limited options for low-global-warming-potential refrigerants. *Int. J. Refrig.* 178, 410–417. <https://doi.org/10.1016/j.ijrefrig.2025.07.011>.
- ECHA - European Chemical Agency, 2025. Per- and polyfluoroalkyl substances (PFAS). <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas> (Accessed 2 September 2025).
- EN European Standard, 2022. EN 14511-3:2022 air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors - part 3: test methods.
- European Parliament, Council of the Europe, 2024. Regulation (EU) 2024/573 of the European parliament and of the council of 7 February 2024 on fluorinated greenhouse gases, amending directive (EU) 2019/1937 and repealing. Regulation. (EU) No 517/2014.
- Fedele, L., Trini Castelli, S., Ielpo, P., Zilio, C., Bobbo, S., 2023a. The environmental impact of HFOs from TEWI to PFAS. A review, in: international institute of refrigeration (IIR) (Ed.), refrigeration science and technology proceedings. Vol. 2, pp. 398–408. 10.18462/iir.icr.2023.0442.
- Fedele, L., Lombardo, G., Greselin, I., Menegazzo, D., Bobbo, S., 2023b. Thermophysical properties of low GWP refrigerants: an update. *Int. J. Thermophys.* 44, 80. <https://doi.org/10.1007/s10765-023-03191-5>.
- Fedele, L., Bobbo, S., Menegazzo, D., De Carli, M., Carnieletto, L., Poletto, F., Tarabotti, A., Mendrinis, D., Mezzasalma, G., Bernardi, A., 2023c. Energetic analysis of low global warming potential refrigerants as substitutes for R410A and R134a in ground-source heat pumps. *Energies* 16, 3757. <https://doi.org/10.3390/en16093757>.
- Fedele, L., Lombardo, G., Menegazzo, D., Scattolini, M., Bobbo, S., 2023d. Isothermal (Vapour + Liquid) equilibrium measurements and correlation of the binary mixture {3,3,3-trifluoropropene (HFO-1243zf) + 2,3,3,3-tetrafluoropropene (HFO-1234yf)} at temperatures from 283.15 K to 323.15 K. *Int. J. Thermophys.* 44, 83. <https://doi.org/10.1007/s10765-023-03192-4>.
- Gaur, A.S., Fitiwi, D.Z., Curtis, J., 2021. Heat pumps and our low-carbon future: a comprehensive review. *Energy Res. Soc. Sci.* 71, 101764. <https://doi.org/10.1016/j.erss.2020.101764>.
- Giuliani, G., Kumar, S., Polonara, F., 1995. A constant volume apparatus for vapour pressure and gas phase P-v-T measurements: validation with data for R22 and R134a. *Fluid Ph. Equilib.* 109, 265–279. [https://doi.org/10.1016/0378-3812\(95\)02727-V](https://doi.org/10.1016/0378-3812(95)02727-V).
- Heath, E.A., 2017. Amendment to the Montreal Protocol on substances that deplete the ozone layer (Kigali Amendment). *Int. Leg. Mater.* 56, 193–205. <https://doi.org/10.1017/ilm.2016.2>.
- Henne, S., Shallcross, D.E., Reimann, S., Xiao, P., Brunner, D., O'Doherty, S., Buchmann, B., 2012. Future emissions and atmospheric fate of HFC-1234yf from mobile air conditioners in europe. *Environ. Sci. Technol.* 46, 1650–1658. <https://doi.org/10.1021/es2034608>.
- Heredia-Aricapa, Y., Belman-Flores, J.M., Mota-Babiloni, A., Serrano-Arellano, J., García-Pabón, J.J., 2020. Overview of low GWP mixtures for the replacement of HFC refrigerants: r134a, R404A and R410A. *Int. J. Refrig.* 111, 113–123. <https://doi.org/10.1016/j.ijrefrig.2019.11.012>.
- Hu, P., Chen, L.X., Chen, Z.S., 2014. Vapor-liquid equilibria for binary system of 2,3,3,3-tetrafluoroprop-1-ene (HFO-1234yf) + isobutane (HC-600a). *Fluid Ph. Equilib.* 365, 1–4. <https://doi.org/10.1016/j.fluid.2013.12.015>.
- Intergovernmental Panel on Climate Change (IPCC), 2021. Climate Change 2021 – The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <https://doi.org/10.1017/9781009157896>.
- Kim, M., Mulroy, W., Didion, D., 1994. Performance evaluation of two azeotropic refrigerant mixtures of HFC-134a with R-290 (Propane) and R-600a (Isobutane). *J. Energy Resour. Technol.* - Trans. ASME.
- Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., 2018. NIST Standard Reference Database 23: reference Fluid Thermodynamic and Transport Properties-REFPROP, version 10.0, National institute of standards and technology. 10.18434/T4/1502528.
- Lombardo, G., Menegazzo, D., Vallesse, L., De Carli, M., Poletto, F., Bobbo, S., 2025. Exploring low-GWP alternatives for heat pumps: a drop-in comparative study of R1234yf/R600a and R134a. *Int. J. Thermophys.* 46, 1–19.
- Lombardo, G., Menegazzo, D., Wedler, C., Fedele, L., Bobbo, S., Trusler, J.P.M., 2024. Speed of sound measurements and correlation of {x 3,3,3-trifluoropropene (HFO-1243zf) + (1-x)2,3,3,3-tetrafluoropropene (HFO-1234yf)} with x = (0.2856, 0.5054, 0.8418) at temperatures from 243.15 K to 348.15 K and pressures up to 90 MPa. *Int. J. Thermophys.* 45, 34. <https://doi.org/10.1007/s10765-023-03321-z>.
- Lueken, D.J., Waterland, R.L., Papasavva, S., Taddonio, K.N., Hutzell, W.T., Rugh, J.P., Andersen, S.O., 2010. Ozone and TFA impacts in North America from degradation of 2,3,3,3-tetrafluoropropene (HFO-1234yf). A potential greenhouse gas replacement. *Environ. Sci. Technol.* 44, 343–348. <https://doi.org/10.1021/es902481f>.
- Luo, J., Ye, Z., Zhao, Z., Yang, K., Zhang, S., Wang, Q., 2023. Vapor-liquid equilibrium measurement and heating performance modeling on eco-friendly zeotropic blends of CO₂/R1234ze(Z) and CO₂/R1336mzz(E). *Appl. Therm. Eng.* 229, 120576. <https://doi.org/10.1016/j.applthermaleng.2023.120576>.
- McGillen, M.R., Fried, Z.T.P., Anwar, M., Kuwata, K.T., Martin, C.M., O'Doherty, S., Pecere, F., Shallcross, D.E., Stanley, K.M., Zhang, K., 2023. Ozonolysis can produce long-lived greenhouse gases from commercial refrigerants. *Proc. Natl. Acad. Sci. U.S.A.* 120, e2312714120. <https://doi.org/10.1073/pnas.2312714120>.
- McLinden, M.O., Huber, M.L., 2020. (R)Evolution of refrigerants. *J. Chem. Eng. Data* 65, 4176–4193. <https://doi.org/10.1021/acs.jced.0c00338>.
- Menegazzo, D., Lombardo, G., Bobbo, S., Fedele, L., De Carli, M., Bordignon, S., Poletto, F., Mendrinis, D., Bortolin, A., Bernardi, A., 2024a. Monitoring of two ground-source heat pumps working with R454B and R600a in a pilot facility.
- Menegazzo, D., Lombardo, G., Fedele, L., Bobbo, S., Kim, M.S., Jeong, Y., Lee, S., 2024b. Isothermal (vapor + liquid) equilibrium measurements and correlation of the binary mixture 3,3,3-trifluoropropene (R1243zf) + isobutane (R600a) at temperatures from 283.15 to 323.15 K. *Int. J. Refrig.* 161, 62–70. <https://doi.org/10.1016/j.ijrefrig.2024.02.032>.
- Menegazzo, D., Lombardo, G., Vallesse, L., Scattolini, M., Bobbo, S., Fedele, L., 2025. Experimental compressed liquid density measurements and correlation of the binary mixture {3,3,3-trifluoropropene (R1243zf) + isobutane (R600a)}. *Int. J. Refrig.* 172, 64–74. <https://doi.org/10.1016/j.ijrefrig.2025.01.013>.
- Mickoleit, E., Breitkopf, C., Jäger, A., 2021. Influence of equations of state and mixture models on the design of a refrigeration process. *Int. J. Refrig.* 121, 193–205. <https://doi.org/10.1016/j.ijrefrig.2020.10.017>.
- Mota-Babiloni, A., Navarro-Esbrí, J., Barragán-Cervera, Á., Molés, F., Peris, B., 2015. Analysis based on EU Regulation No 517/2014 of new HFC/HFO mixtures as alternatives of high GWP refrigerants in refrigeration and HVAC systems. *Int. J. Refrig.* 52, 21–31. <https://doi.org/10.1016/j.ijrefrig.2014.12.021>.
- Nair, V., 2021. HFO refrigerants: a review of present status and future prospects. *Int. J. Refrig.* 122, 156–170. <https://doi.org/10.1016/j.ijrefrig.2020.10.039>.
- Palm, B., 2008. Hydrocarbons as refrigerants in small heat pump and refrigeration systems - a review. *Int. J. Refrig.* 31, 552–563. <https://doi.org/10.1016/j.ijrefrig.2007.11.016>.
- Peng, D.-Y., Robinson, D.B., 1976. A new two-constant equation of State. *Ind. Eng. Chem. Fundam.* 15, 11–18. <https://doi.org/10.1073/pnas.15.1.11>.
- Poling, B.E., Prausnitz, J.M., O'Connell, J.P., 2001. *The Properties of Gases and Liquids*, 5th ed. McGraw-Hill.
- Polonara, F., Kuijpers, L., Peixoto, R., 2017. Potential impacts of the Montreal Protocol Kigali Amendment to the choice of refrigerant alternatives. *Int. J. Heat Technol.* 35, S1–S8. <https://doi.org/10.18280/ijht.35Sp0101>.
- Singh, R.R., Papanastasiou, D.K., 2021. Comment on "scientific basis for managing PFAS as a chemical class. *Env. Sci. Technol. Lett.* 8, 192–194. <https://doi.org/10.1021/acs.estlett.0c00765>.
- Toleikyte, A., Roca Reina, J.C., volt, J., Carlsson, J., Lyons, L., Gasparella, A., Koolen, D., De Felice, M., Tarvydas, D., Czako, V., Koukoulakis, G., Kuokkanen, A., Letout, S., 2023. The heat pump wave opportunities and challenges. <https://doi.org/10.2760/27877>.
- Tomassetti, S., Coccia, G., Pierantozzi, M., Di Nicola, G., Brown, J.S., 2020a. Vapor phase and two-phase PvTz measurements of difluoromethane + 2,3,3,3-tetrafluoroprop-1-ene. *J. Chem. Thermodyn.* 141. <https://doi.org/10.1016/j.jct.2019.105966>.
- Tomassetti, S., Perera, U.A., Di Nicola, G., Pierantozzi, M., Higashi, Y., Thu, K., 2020b. Two-phase and vapor-phase thermophysical property (pvTz) measurements of the difluoromethane + trans -1,3,3,3-tetrafluoroprop-1-ene binary system. *J. Chem. Eng. Data* 65, 1554–1564. <https://doi.org/10.1021/acs.jced.9b00995>.
- Tomassetti, S., Pierantozzi, M., Di Nicola, G., Polonara, F., Brown, J.S., 2019. Vapor-phase PvTz measurements of binary blends of cis-1, 2, 3, 3-pentafluoroprop-1-ene + isobutane and 3, 3, 3-trifluoropropene + isobutane. *J. Chem. Eng. Data*.
- UNI Ente italiano di normazione, 2016. UNI TS 11300-4:2016 Prestazioni energetiche degli edifici - parte 4: utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria.
- United Nations Environment Programme, 2024. Global Status Report for Buildings and Construction: beyond foundations: mainstreaming sustainable solutions to cut emissions from the buildings sector. Nairobi.
- Yang, K., Zhao, Z., Liu, Y., Wang, Q., Jiang, L., Xue, Z., Luo, J., 2024. Energy, exergy, economic and environmental studies on a nonflammable eco-friendly mixture for efficient heating in cold regions. *Energy Convers. Manage* 321, 119031. <https://doi.org/10.1016/j.enconman.2024.119031>.
- Yang, Z., Valtz, A., Coquelet, C., Wu, J., Lu, J., 2022. Critical properties and vapor-liquid equilibrium of two near-azeotropic mixtures containing HFOs. *Int. J. Refrig.* 138, 133–147. <https://doi.org/10.1016/j.ijrefrig.2022.03.027>.
- Zendehboudi, A., 2025. Thermo-economic evaluation of low-GWP CO₂-based zeotropic mixtures in space heating heat pumps with and without internal heat exchanger. *Int. J. Refrig.* 173, 1–17. <https://doi.org/10.1016/j.ijrefrig.2025.01.036>.
- Zhang, H., Li, H., Gao, B., Zhong, Q., Wu, W., Liu, W., Dong, X., Gong, M., Luo, E., 2018. Gaseous densities of 2,3,3,3-tetrafluoroprop-1-ene (R1234yf) and isobutane (R600a) binary system: measurements and a preliminary Helmholtz equation of state. *Int. J. Refrig.* 95, 28–37. <https://doi.org/10.1016/j.ijrefrig.2018.07.029>.
- Zhang, N., Li, B., Feng, L., Dai, Y., 2021. Research on the thermophysical properties and cycle performances of R1234yf/R290 and R1234yf/R600a. *Int. J. Thermophys.* 42, 123. <https://doi.org/10.1007/s10765-021-02875-0>.