Refrigerant R32 as lower GWP working fluid in residential air conditioning systems in Europe and the USA

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Abstract

Because air conditioning and heat pump systems contribute greatly to greenhouse gas emissions, equipment with both lower global warming potential (GWP) working fluids and a higher level of performance should be used. R32 (difluoromethane) has been proposed to substitute R410A, particularly in residential air conditioning (RAC) systems. This study collected the most relevant and recent researches into R32 as a refrigerant so as to assess its viability in RAC systems in both Europe and the USA, as compared to R410A and other lower GWP RAC alternatives.

The R32 value of GWP is 677, which is below the F-gas regulation limit in RAC equipment (750). According to ASHRAE standard 34, R32 is less flammable than hydrocarbons, and the amount of charge permitted for R32 is above the necessary level in RAC equipment. It can be concluded that R32 has significantly good heat transfer characteristics and a level of performance that make it acceptable at low condensing temperatures, thereby avoiding overly high compressor discharge temperatures. Its performance is very similar to that of R410A across the entire operating range, and it is therefore believed that R32 will be utilized in RAC systems in the remaining countries that prioritize lower GWP fluids but are less strict in their security regulations.

To replace R410A under extreme conditions, some system modifications can be conducted, or R32 mixtures with hydrofluoroolefins (HFOs) can be used. Such mixtures achieve a lower performance than R32, but are acceptable replacements when considering their lower GWP compared to that of R32, and similar level of flammability. Finally, other (R32-based) alternative mixtures have also been developed and their behaviours studied under a wide range of operating conditions.

Keywords: review; R32; HFC; GWP; energy efficiency; environment protection.

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Nomenclature

c_p	isobaric heat capacity (kJ kg^{-1} K^{-1})
SC	subcooling degree (K)
D_h	hydraulic diameter (mm)
G	mass flux (kg m^{-2} s^{-1})
m	refrigerant charge (kg)
Q	heat transfer (kW)
q’’	heat flux (kW m^{-2})
RH	Relative humidity (%)
T	temperature (K)
SH	superheating degree (K)
x	vapour quality (-)
Greeks	
Δp	Pressure drop (kPa)
Subscripts	
amb	ambient
c	cooling mode
disc	compressor discharge
dry	dry bulb
h	heating mode
k	condenser, condensing
o	evaporator, evaporating
sat	saturation
wet	wet bulb
Abbreviations	
AHRI	Air Conditioning, Heating, and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
AAD	Average absolute deviation
AC	Air conditioning
BV	Burning velocity
COP	Coefficient of performance
CRC	Conventional refrigeration cycle
EOS	Equation of state
EPA	Environmental Protection Agency

GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Heat pump
HTC	Heat transfer coefficient
HX	Heat exchanger
IHX	Internal heat exchanger
LFL	Lower flammability limit
MIE	Minimum ignition energy
NRC	New refrigeration cycle
ODP	Ozone depletion potential
POE	Polyolester
RAC	Residential air conditioning
UA	Product of the overall heat transfer coefficient and the heat exchanger area
UFL	Upper flammability limit
VI	Vapour injection/injected

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions have increased since the beginning of the industrial revolution, with the most relevant sources in developed countries coming from electricity production, transportation, industry, commercial and residential sectors, agriculture, and land use.

According to different predictions, GHG emissions will be significantly increased in the short term, i.e. relative to the 2010 values, 36.4 billion metric CO_2-eq. tons more than in 2020, and 45.5 billion metric CO_2-eq. tons more than in 2040 [1]. If additional actions are not imposed to reduce GHG emissions, the increase in mean surface temperature globally by 2100 may reach between 2.6 and 4.8 K under the worst-case scenario (compared to pre-industrial levels) [2].

Energy consumption is contributing significantly to climate change [3]. Heating, ventilation, and air conditioning (HVAC) applications used to control offices and room temperatures represent a great portion of the energy consumed in the developed world, as shown in Figure 1 [4]. In the residential sector, which represents 27% of global energy consumption and 17% of CO_2-eq. emissions [5], energy saving in terms of space conditioning can lead to a relevant reduction in CO_2-eq. emissions, particularly in hotter countries [6].

Figure 1. Energy consumption by end users [4] in a) the residential sector and b) office environments.

Increasing the percentage of energy production from renewable sources (solar, wind, geothermal, hydro, etc.) is a proper solution to stopping climate change [7]. However, the development of renewable plants remains slow, and thus measures for curbing energy consumption should be widely introduced. There are several aspects influencing the energy consumption of residential air conditioning systems (cooling and heating load, electricity consumption, outdoor design conditions, etc.) [8]. For example, through proper energy management, energy consumption can be reduced by 14% [9].

Owing to its good thermodynamic properties, hydrochlorofluorocarbon (HCFC) R22 was widely used as the working fluid in air conditioning (AC) and heat pump (HP) systems during most of the 20th century [10]. The application of the Montreal Protocol in developed countries phased out this ozone depleting fluid in newly developed systems [11]. Currently, new AC and HP systems in Europe, the USA, and other developed countries use the chlorine-free hydrofluorocarbon (HFC) R410A (although R22 is still used in developing nations). R22 and R410A, which have been identified as GHG gases [12], contribute largely to climate change when leaked from vapour compression systems because they possess a very high global warming potential (GWP) of 1760 and 1924, respectively [13].

Owing to the large number of air conditioning units installed across the world, residential air conditioning (RAC) systems based on vapour compression systems are the most relevant HFC consumers among all HVAC systems. In 2010, the global HFC consumption from unitary air conditioning (AC) systems was 91 million metric tons of carbon dioxide equivalent ($MMTCO_2$-eq.), i.e. 11% of all heating, ventilation, and air conditioning systems [14]. In 2014, US emissions from residential and light-commercial AC equipment were estimated at 36.7 $MMTCO_2$-eq., or roughly 22% of the nation's total HFC emissions [15]. To achieve an effective reduction of GHG emissions, both R22 and R410A should be completely replaced by lower GWP fluids without lowering the energy efficiency of the vapour compression systems.

Hence, to protect the environment, environmental regulations controlling HFCs in refrigeration and air conditioning systems are being approved. R410A will not be used in European single split air conditioning systems containing less than 3 kg, owing to Regulation (EU) No. 517/2014 [16], which prohibits the use fluorinated GHGs with a GWP of 750 from 1st January 2025. To accelerate the decrease in HFCs, some countries have approved additional HFC retirement measures, e.g. in Spain [17, 18], since 1st January 2016, the use of virgin R410A has incurred a tax rate of 39.50 € per kg.

To replace R410A and R22 in RAC systems, several alternatives have been proposed. In the USA, along with R290 (propane) and R441A, the U.S. Environmental Protection Agency (EPA) has enlisted R32 as an acceptable substitute in residential and light commercial ACs and HPs through its Significant New Alternatives Policy [19]. The lower GWP options available as substitutes to R22 and R410A and their characteristics are listed in Table 1 [20] (carbon dioxide has been discarded in this classification owing to the high equipment costs required).

Table 1. Some lower GWP alternatives to R22 and R410A in residential air conditioners [20].

As can be seen in Table 1, R32 presents a lower flammability than hydrocarbons (R290 and R441A), a lower cost, and higher system efficiency, and therefore is currently the most promising alternative for use in RAC systems. R32 has zero ozone depletion potential (ODP) and a GWP value of 677 (32% of that presented by R410A), which are below the European GWP limit set for RAC equipment. Moreover, as a pure refrigerant, R32 can be more easily recovered from RAC systems than an R410A mixture.

Although it has been available for many years, pure R32 has not been used in RAC systems because RAC manufacturers have preferred R410A. Compared to R410A, R32 offers the disadvantages of being classified as a flammable fluid and higher compressor discharge pressures. However, R32 is currently being reconsidered owing to its lower GWP value and good system performance. In addition, new R32 blends (mixed with hydrofluoroolefins, or HFOs) are being developed to offer further GWP reductions and a trade-off between different characteristics.

Owing to the significant GWP reduction achieved with R32, the environmental benefits derived from the use of this fluid can be significant. This study summarizes the most recent relevant researches regarding the use of R32, and its mixtures, as working fluids for residential AC systems. The strong and weak points of this refrigerant are presented, and methods to overcome them are described. The following section analyses the thermophysical properties of R32 and its proposed mixtures. The security and maintenance characteristics are also revised. Section 4 describes the heat transfer properties during phase changes, and section 5 summarizes the system performance using R32 and its blends. Finally, some concluding remarks are presented in section 6.

2. Analysis of R32 as refrigerant former in lower GWP mixtures

R32 has been traditionally used as refrigerant former for some chlorine-free HFC mixtures (e.g. R407 series, R410A, R427A, and R438A) developed to substitute R22 [21]. In fact, the refrigerant that R32 is intended to replace, R410A, contains 50% R32 (the rest is R125, which is also commonly used as a fire suppressant agent). In the same manner, almost all of the recently proposed lower GWP blends [22] contain R32 in their composition: between 7 and 12% for the alternatives to R134a, between 24 and 40% for the alternatives to R404A, and between 50 and 72.5% for those mixture fluids proposed for substituting R410A. These blends are promising, and the Air Conditioning, Heating, and Refrigeration Institute (AHRI) has enlisted the majority of them as possible low GWP alternatives.

Focusing on the proposed replacements for R410A, as shown in Table 2, the new mixtures have attempted to achieve lower GWP values by replacing R125 with a greater amount of R32 and HFOs, such as R1234yf and R1234ze (E). Moreover, the use of R32 and HFOs as refrigerant formers results in low flammable (A2L) products that can be used in low charge systems. Studies of mixtures containing R32 and R1234ze (E) (among others) were studied in detail by Mota-Babiloni et al. [23].

Table 2. HFC/HFO mixtures proposed to replace R410A.

2.1. R32 Thermophysical properties

R32 was developed a few decades ago, and its properties are well defined. Version 9.1 of REFPROP [24], which is the most recent version, calculates the R32 properties using the Helmholtz-type equation of state (EOS) presented by Tillner-Roth and Yokozeki [25].

Some studies have recently been carried out to reduce the uncertainty in the property calculations. Kagawa et al. [26] concluded that the available EOS (Helmholtz type equations, modified Benedict Webb Rubin equations, and the virial equation) cannot sufficiently represent the R32 isobaric heat capacity behaviour under most conditions. However, they specified the R32 ideal gas and saturated vapour heat capacity curves (at temperatures of 282 to 319 K and at pressures of 1.0 to 2.4 MPa) [27].

The main thermophysical properties of R22, R410A, and their replacements are shown in Table 3. As with R410A replacing R22, R32 cannot be used as a drop-in alternative to either R22 or R410A because it presents remarkable differences in the thermophysical properties (and is slightly flammable). In addition, although the R1234yf GWP is very low (0.4), its thermophysical properties make R1234yf less appropriate than R32 for RAC systems that use R22 or R410A.

Table 3. Main thermophysical properties of R22, R410A, and some alternatives [24].

2.2. Thermophysical properties of R32 blends

At the end of the 20th century, substantial research on R32 mixtures was conducted, and as a result, some HFC mixtures were commercialized (R410A, R407 series). Thus, with good knowledge regarding their behaviour, zero ODP blends have been developed and progressively introduced into heating, ventilation, and air conditioning systems to replace R22 in almost all applications. At the present time, there is a strong interest in defining the properties of new R32/HFC/HFO mixtures (in some cases, adding a small percentage of hydrocarbons) to conduct another large-scale refrigerant substitution, prioritizing the lower GWP, and allowing a slight degree of flammability, as shown in Figure 2.

Figure 2. Evolution of working fluids used in air conditioning systems [28]

The properties of binary mixtures of R32 with HFOs, R1234yf, and R1234ze (E) have been analysed in recent years. Dang et al. [29] correlated the vapour viscosities of different compositions of R32/R1234yf (with R32 mass percentages of 20%, 30%, 40%, and 50%) with the Wilke mixture rule and obtained an average absolute deviation (AAD) of 0.189%. The AAD obtained in REFPROP v9.1 is approximately three times larger, 0.555%. The liquid viscosity measurements [30] of mixtures containing 30%, 50%, and 70% R32 were correlated using a hard sphere method and the Grunberg and Nissan method. The AADs are 2.2% for the hard sphere method, 2.8% for the Grunberg and Nissan method, and 3.5% for REFPROP v9.1.

Kamiaka et al. [31] performed vapour-liquid equilibrium measurements at temperatures from 273 to 333 K for R32/R1234yf at mass fractions of R32 ranging from 20% to 75%. The temperature glide of the refrigerant mixture R32/R1234yf (20/80%) was 8 K, which is significantly larger than that of the other R1234yf/HFC mixtures studied. The optimized AAD obtained with a Helmholtz type EOS was 1.13%, whereas that with REFPROP v9.0 was 3.63%. Akasaka [32] gave an assessment of three thermodynamic models through critical point calculations for ternary and quaternary HFC refrigerant mixtures (including R32) based on Helmholtz energy EOS. The deviations of the critical points are within 1%.

3. Security and maintenance properties

3.1. Flammability

R32 use is limited in certain countries owing to stricter safety regulations. R32 is included in Category 1 of flammable gases (gases at 293.15 K and a standard pressure of 101.3 kPa, which are ignitable when in a mixture of 13% or less by volume in air or have a flammable range with air of at least 12 percentage points regardless of the lower flammable limit) of Regulation (EC) No. 1272/2008 [33]. It is also classified as a lower flammability refrigerant with a maximum burning velocity of 10 cm s^{-1} based on ASHRAE Standard 34 [34] (LFL higher than 3.5% in air by volume but with a heat combustion of lower than 19000 J kg^{-1} when tested at 296.15 K and 101.3 kPa).

The flammability properties of R32 are compared to those of R290 and R1234yf (the other lower GWP alternatives for an RAC) in Table 4 [35]. The minor value of the lower flammability limit (LFL) of R32 compared to hydrocarbons allows a higher refrigerant charge in RAC systems. According to the European standard, EN378-1:2008, for the safety and environmental requirements of refrigeration systems and HPs in a RAC system with a ceiling mounted indoor unit in an occupied room of 9 × 5.5 m^2 in size, the maximum charge of R32 is 8.84 kg, whereas for R290, the value is 0.65 kg [36].

Table 4. Flammability properties of R290, R32, and R1234yf [35].

US EPA allows a notably higher R32 refrigerant charge than R290 and R441A in RAC systems, as shown in Figure 3 [19]. This publication specifies that the LFL of R32 is not reached when the charge size is consistent with the use conditions, i.e. a significant risk of fire is not expected. Moreover, the great differences between R32 and the two aforementioned hydrocarbons are due to a higher LFL and lower burning velocity (BV).

Figure 3. Maximum design charge sizes for [19] a) wall-mounted RAC units, b) ceiling-mounted RAC units, c) portable room RAC units, and d) window RACs.

Boussouf et al. [37] found that the hot plate ignition temperature of R32 is 1037 K, whereas that for R410A was found to be 1063 K (both with an uncertainty of ±10 K). When mixed with polyolester (POE) oil, the ignition temperature of an R32 refrigerant/oil mixture was found to be very close to that of the POE oil (922 K) employed in their study. Jia et al. [38] conducted an ignition experiment using R32, and considered that, in the case of a leak from a running RAC, the indoor environment remains relatively safe. The results show that a spark and candle flame diffuse slightly, but cannot spread effectively. Moreover, approximately 20 min after the exhaust is opened, the refrigerant concentration sufficiently decreases. Imamura et al. [39] experimentally confirmed that, under different conditions, if R32 leaks from a pinhole in a pipe or hose, the possibility of ignition and flame propagation is very small because the zone of flammability is only formed locally, and the burning velocity is much slower than the fluid flow velocity.

Moghaddas et al. [40] studied the laminar burning speeds and flame structures of a mixture with air in spherical and cylindrical vessels of a constant volume coupled with a Schlieren/shadowgraph system, and developed correlations demonstrating the temperature and pressure dependency of the laminar burning speeds, as shown in Figure 4. The conditions for R32 are a temperature range of 350 to 475 K and a pressure range of 2 to 6.8 bar.

Figure 4. Laminar burning speeds of R32/air mixture for T = 350 K and P = 2 bar, and different equivalence ratios [40].

3.2. Toxicity

According to US National Fire Protection Association 704 classification, R32 is safer than R410A in the presence of humans. R32 is classified as a Class A refrigerant (lower chronic toxicity) and its potential health effects (freeze burns, aesthetic effects, and asphyxia) are common to many traditional refrigerants, including R22, R410A, and R134a [41]. Moreover, R32 has the highest acute toxicity exposure limit compared to the other ISO 817 enlisted refrigerants.

Although R32 forms hydrogen fluoride when ignited, the decomposition occurs within the same temperature range as other traditional refrigerants, and the quantity of hydrogen fluoride produced by R32 is much below than that of R22 (5 ppm compared to 70 ppm) and similar to that of R410A. Consequently, in terms of the presence and quantity of the decomposition products, the use of R32 does not provide additional risks compared to other traditional refrigerants [41].

3.3. Material compatibility

R32 is compatible with existing POE lubricants and materials typically used with R410A. In addition, Majurin et al. [42] evaluated the material compatibility of R32 blended with HFO refrigerants so as to characterize the equipment reliability risks associated with the use of next-generation lower GWP fluorinated refrigerant candidates.

As a final safety remark, Belman et al. [43] highlighted the refrigerant charge as a key parameter in vapour compression system applications in the domestic sector. A lower refrigerant charge can reduce the final cost of the system and provide safer and more efficient vapour compression systems.

4. Two-phase flow studies

In general, R32 presents good heat transfer characteristics when compared to traditional refrigerants (HCFCs and high GWP HFCs), and is not penalized by significantly higher pressure drops. The heat transfer and pressure drop characteristics of R32 have been studied inside tubes and channels with different geometries and small diameters. The results and test conditions of such studies are summarized in Table 5.

Table 5. Summary of heat transfer and pressure drop studies for pure R32 and its mixtures.

4.1. Condensation

Liu and Li tested R32 and compared it to R22 for two types of horizontal mini-channels, with circular (D_h of 1.152 mm) and square (D_h of 0.952 and 1.304 mm) sections. The R32 heat transfer characteristics (largest liquid thermal conductivity) are better than those of R22 [44], and the friction pressure drops are very similar (R32 and R22 show almost equivalent pressure gradients) [45].

López Belchi et al. [46] characterized the pressure loss and heat transfer processes for R32 and R410A in aluminium square multiport tubes with a D_h of 1.16 mm (Figure 5). In all tests, the HTC of R32 was higher than the R410A values (higher thermal conductivity), but the pressure drop was up to 25% higher under a high-quality vapour (lower density, which implies a higher velocity).

Figure 5. Experiment results by López Belchi et al. [46] in aluminium square multiport tubes for R410A and R32: pressure drop at a) 308 K and b) 313 K, and HTC at c) 308 K and d) 313 K.

Mancin et al. [47] presented an accurate model for R32 condensation for brazed plate heat exchangers and compared the results with a prototype. Considering a T_{sat} of 309.7 K; SH of 5, 10, 15, and 25 K; G between 15 and 40 kg m^{-2} s^{-1}; and outlet x between 0 and 0.65, the relative deviation was 1.2% and the AAD was 4.7%.

4.2. Evaporation/flow boiling

Matsuse et al. [48] assessed the R32 flow boiling characteristics in a horizontal copper circular tube with a 1.0 mm inner diameter. The range was as follows: G of 30 to 400 kg m^{-2} s^{-1}, x of 0.05 to 1.0, and q'' of 2 to 24 kW m^{-2} at a T_{sat} of 283 K. The characteristics of the boiling heat transfer and pressure drop were clarified based on the measurements and a comparison with the R410A data that were previously obtained.

The two-phase HTC of a zeotropic mixture is always lower than pure R32 owing to the additional mass transfer resistance [49] caused by the volatility difference that suppresses the nucleate boiling and forced convective contributions.

In horizontal microfin tubes, Kondou et al. [50] determined that the evaporation and condensation HTC of pure R32 alone is slightly higher than that of R1234ze(E) owing to its superior thermophysical properties (higher liquid thermal conductivity and larger latent heat of vaporization). R744/R32/R1234ze(E) (9/29/62%) presents the lowest HTC, even though at a G of above 400 kg m^{-2} s^{-1}, the HTC of an R32/R1234ze(E) and R744/R32/R1234ze(E) mixture approaches that of R32 alone. Li et al. [51] studied the heat transfer of R1234yf/R32 mixtures (R32 mass fractions of 20% and 50%) inside a 2-mm diameter smooth horizontal tube. The highest HTC was presented using pure R32. Compared to R1234yf, the HTC of the R1234yf/R32 mixture is only higher at the higher R32 mass fraction (50%) and at a larger G and q''.

Smith et al. [52] provided data for a local two-phase flow boiling HTC and pressure drop for refrigerants R410A, R32, and R1234yf, and two new mixtures, DR-5 [R32/1234yf (72.5/27.5%)] and DR-5A [R32/1234yf (68.9/31.1%)]. The investigation was conducted using a 9.5-mm microfinned tube evaporator with the addition of POE oil. The authors concluded that R32 has up to 40% higher HTC than that of R410A under equivalent conditions (G and q''), and worst results were found for the mixtures, although DR-5 showed closer results to those of R32 at an x of between 0.3 and 0.6.

4.3. Heat transfer enlargement

Wu et al. [53] tested R32 in a mini multichannel flat tube (inner D_h of 1.7 mm) with thirteen 0.16-mm high microfins with a 0° helix angle aligned in the flow direction. The working conditions were as follows: G between 100 and 400 kg m^{-2} s^{-1}, q'' between 10 and 40 kW m^{-2}, and T_{sat} between 283 and 293 K. Compared with a smooth tube, the 0° helix angle microfins can enhance the R32 flow boiling heat transfer by 60% while increasing the pressure drop by 40% on average. For both R410A and R32 [54], the distribution in the vertical header of a reversible microchannel heat exchanger under HP mode will be improved only if G is increased at the top part of the header and a semi-annular flow is avoided.

5. System performance

In section 2, it was shown that R32 presents certain problems in replacing R410A in existing systems owing to the differences between both fluids. However, a CO_2-eq. emission reduction is currently a key factor [55], and R32 and its mixtures offer a great opportunity to reduce the direct emissions in new equipment (or with system modifications) owing to three main factors: a significant GWP reduction compared to R22 (63%) and R410A (66%), lower refrigerant charges, and higher efficiencies in RAC systems.

5.1. Performance and discharge temperature concern of pure R32

The performance of pure R32 has been studied for several R22 and R410A RAC and HP applications (in which a low refrigerant charge is required). The majority of these studies have obtained similar conclusions: R32 shows a good level of performance, but the compressor discharge temperature limits its application. Again, the results and test conditions are summarized in Table 6.

Table 6. Summary of energetic studies for pure R32.

Zilio et al. [56] presented simulations of a packaged air-to-water reversible unit and accepted R32 as a replacement for the cooling mode in R410A designs. In both cooling and heating cases, the R32 capacities are approximately 6% higher than those of R410A. In addition, Barve and Cremaschi [57] obtained a greater heating COP, i.e. COP_h, and cooling capacity, Q_o, and a comparable cooling COP, i.e. COP_c, and heating capacity, Q_k, to R410A. Another conclusion depicted from this study is that the capacity of R1234yf is quite far from that of R410A and cannot be used as a drop-in replacement. Both studies noted an overly high R32 discharge temperature, and recommended a system optimization.

Wu et al. [58] obtained a 3D temperature distribution of a motor-refrigerant in a R32 hermetic rotary compressor. The results (a CFD simulation validated against the experimental results) confirm the excessive temperature of stator winding (under the ASHRAE/T1 condition, this is 8.3 K higher than the maximum acceptable temperature of the most widely used B-class motor insulation). In fact, an overly high discharge temperature and pressure of R32 under extremely high temperature conditions was a concern for the safe operation of the unit, and might be a concern for the compressor lifetime cycle; in addition, it has been the main barrier for the wide and quick introduction of this fluid in air conditioning systems where R410A has typically been used, as shown in Figure 6.

Figure 6. Limiting factors and operating envelopes of a scroll compressor using R32 and R410A [59].

Yang et al. [59] proposed different cycles with modifications to reduce the discharge temperature. A two-phase injection outperforms a liquid injection and two-phase suction in terms of the cooling capacity and COP_c by 12% and 5%, respectively, and significantly decreases the discharge temperature of the R32 scroll compressor (benefited by its significant amount of latent heat).

The ejector in a vapour compression system improves the performance and simplifies the operation and control at the optimum level [60]. Shuxue et al. [61] found that the enhanced vapour injection reduces the discharge temperature by [10, 20] K. In addition, the best range of relative vapour injection mass is [12, 16]% for the best overall cooling and heating performance (it changes the evaporating and condensing temperatures by [0.8, 1] K). Xu et al. [62] found that the capacity and COP (both cooling and heating) improvements using R32 can reach up to 10% and 9% using a vapour-injected HP system. No improvement was found under extreme cooling and heating conditions. Yu et al. [63] proposed a new ejector enhanced vapour compression refrigeration cycle (Figure 7) operating with refrigerant R32, which improves the COP_h and volumetric capacity by more than [8.8, 9.3]% and [13.6, 9.7]%, respectively.

Figure 7. Schematic diagrams for a) ejector expansion refrigeration cycle and b) new ejector enhanced refrigeration cycle proposed by Yu et al. [63].

Finally, the use of an internal heat exchanger (IHX) is not recommended for R32 because it reduces the COP_c and increases the discharge temperature, even though this component can enlarge the energy efficiency for some of its mixtures, as with R407C or R410A [64].

5.2. R32 pure and mixtures

R32 has been traditionally used as a refrigerant former for some chlorine-free HFC mixtures (the most relevant are the R407 series, R410A, R427A, and R438A) that were developed to substitute R22. In the same way, almost all of the recently developed lower GWP blends contain R32 in their composition [65]. In RAC systems, R32 mixtures can substitute either R410A in developed countries or R22 in developing countries, depending on the refrigerant formers and the final composition. The results and test conditions are summarized in Table 7.

Table 7. Summary of energetic studies for mixtures of R32.

5.2.1. R32 pure and mixtures as alternatives to R410A

Using a 10.55 kW HP [66], R32 is superior to R410A in terms of Q_o (4%) and Q_k [4,7. 8]% but presents lower COPs. However, the R32 mixture R447A is also a good R410A alternative that performs better than R410A. Both refrigerants can reduce the amount of optimal charge. These tests have also confirmed that the IHX does not provide significant improvements for R32 or R447A.

In et al. [67] compared R32, R446A, and R410A in a residential HP, as shown in Figure 8. The test conditions for the heating and cooling modes were selected according to the EN14825 standard, matching the system capacity. Compared to R410A, they reached the following conclusions in terms of system operation:

- The optimal refrigerant charges for R32 and R446A were 20% and 10% lower.
- The COP_c of the R32 and R446A systems in standard cooling and heating tests is [104, 110]% and [97, 98]% that of R410A, respectively.
- The discharge temperature for R32 was as high as 356 K, whereas that for R446A was as high as 359 K (under standard cooling and heating modes).
- The compressor input power for the R32 system was lower by a maximum of 9% in seasonal COP_c and 7% in seasonal COP_h relative to those of R410A. For R446A, it was higher by a maximum of 9% in seasonal COP_h and 4% in seasonal COP_c relative to R410A.
- The partial load COP_c under the seasonal COP_c conditions for R32 was higher by [6, 10]%, and for R446A was lower by [1, 8]%. Under the seasonal COP_h conditions it was [2, 12]% higher for R32, and [1, 6]% lower for R446A.
- The overall seasonal COP_c and COP_h were 8% higher for R32 and 1% higher for R446A.

Figure 8. Experimental results in a residential HP [67]: capacity, COP_c, mass flux, and discharge temperature for R410A, R32, and R446A under the standard a) heating mode and b) cooling mode.

Finally, interest regarding R32/Hydrocarbon mixtures has resurged in recent years, although the flammability remains a disadvantage. Yu et al. [68] proposed an azeotropic mixture, R32/R290, for a small-capacity HP system used in high-temperature water heating applications (up to 363 K). In a transcritical cycle, the mixture operates with a high COP_h and volumetric heating capacity superior to those of R125 and R744. Tian et al. [69] also proposed an R32/R290 (68/32%) mixture to replace R410A in RACs. The amount of refrigerant charge is [30, 35]% lower than that of R410A, and the use of microchannel heat exchangers reaches a 34.1% lower charge and 6.8% higher COP_c compared to typical heat exchangers.

5.2.2. R32 mixtures as alternatives to R22

To replace R22, a great number of R32/HFC/HFO and R32/HFC mixtures have been recently proposed. However, in RAC systems that work at elevated ambient temperatures, medium-pressure refrigerants (R444B and R407C) are more efficient than high-pressure refrigerants such as R410A or R32.

Sethi et al. [70] proposed the application of R444B and R407C as working fluids. Finally, the only alternative that reaches the level of performance of R22 is R444B (R32/R152a/R1234ze(E) 41.5/10/48.5%). Abdelaziz et al. [71] presented the results of lower GWP alternatives for R22 and R410A mini split air-conditioning units designed to operate in high ambient temperature environments. Under the ANSI/ASHRAE Standard 37 conditions (Table 8) and compared to the R410A results, R32 showed a significantly better capacity and efficiency, but between 12 and 21 K higher compressor discharge temperatures. Developed and developing HFC/HFO mixtures can also be viable replacements for R22, as shown in Figure 9. The complete list of results obtained through the AHRI tests can be retrieved from [72].

Table 8. Abdelaziz et al.’s [71] test conditions.

Figure 9. Abdelaziz et al.’s [71] results for R22 and its alternatives: a) cooling capacity and b) COP_c.

Studies on HFC mixtures with a higher percentage of R32 or lower GWP HFCs, allowing a higher flammability in the final blend, are still being performed. Lee et al. [73] tested an R32/R152a mixture in a water-source HP bench tester, offering 15% higher efficiency than R22. The amount of charge for the R32/R152a mixture decreased up to 27% compared to that of R22, and the mixture is not flammable at a 36/64% composition. Bansal and Shen [74] tested and modelled a window RAC considering different lower GWP options: R32, a mixture of R32/R125 with a molar concentration of 90/10%, R600a, R290, R1234yf, R1234ze(E), and R134a. R32 offers the highest energy efficiency (4% higher than that of R410A), but the maximum discharge temperature is 366.5 K in an ambient temperature of 308 K. Wu et al. [75] presented the use of R152a/R125/R32 (48/18/34%) as an alternative to R22. Although this mixture showed an 8% lower performance than R22 in an R22 domestic air conditioner, problems related to flammability were not shown, and the leakage does not significantly vary the composition of the mixture.

In a traditional residential air conditioner cycle [76], the (30/70%) R32/R134a mixture has a close performance to that of R22. However, they developed a new refrigeration cycle (composed of a compressor, a phase separator, a subcooler, two condensers, two evaporators, two recuperators, and two expansion valves) that takes advantage of high glides. The maximal COP_c improvement of mixture R32/R134a observed is within a range of [8, 9]% over that of the traditional one, and the volumetric refrigerating capacity can be approximately increased by 9.5%.

6. Conclusions

A reduction in GHG emissions is a priority for stopping climate change. Such a reduction can be achieved through an increase in the energy efficiency and reducing the amount of refrigerant used in air conditioning systems, thereby directly impacting the GWP. R32, with a GWP of 677, is being considered as an alternative to R410A (GWP of 1924) in air conditioning appliances in Europe and the USA. The current state of refrigerant R32 has been presented in this work, and the main conclusions are as follows.

The thermodynamic properties of R32 are well defined, and current studies have focused on defining the most accurate mixture properties achievable. R32 is less flammable than hydrocarbons, and the amount of refrigerant allowed is sufficient to be used in RACs. Its toxicity is below other synthetic fluids, and precautions taken with such refrigerants can also be applied for R32. New HFC/HFC mixtures have a greater content of R32 than old HFC mixtures (R410A), being classified as A2L according to ASHRAE 34 but obtaining allowable compressor discharge temperatures.

Inside the condensation tubes, the HTC of R32 is higher than that of R22 and R410A. For the pressure drop, the highest level observed was in R32 owing to its thermophysical properties. In evaporation studies, an HTC of R32 is significantly higher than that observed with R32 mixtures owing to the glide effects. Pure and blended R32 HTCs have also been compared with R1234yf, which are notably larger than the HFO.

R32 presents a similar or slightly higher performance than R410A in terms of the cooling and heating modes of RACs. However, all studies reviewed herein recommend modifications in the system to reduce dangerous compressor discharge temperatures (particularly under extreme operating conditions). Some advanced systems that inject a liquid, vapour, or two-phase refrigerant have been found in the literature, at levels sufficient to reduce the discharge temperature to admissible levels.

Some R32 mixtures have already been commercialized. R32 mixtures as alternatives to R410A also reduce the compressor discharge temperature, but in some cases, their performances are slightly below than that of pure R32 and cannot produce a benefit in terms of the final CO_2-eq. emissions. R32 is not recommended as a direct replacement for R22, but in mixed form, it shows a similar level of performance and can be considered as a drop-in or retrofit replacement to help non-developed countries phase out this widely used HCFC.

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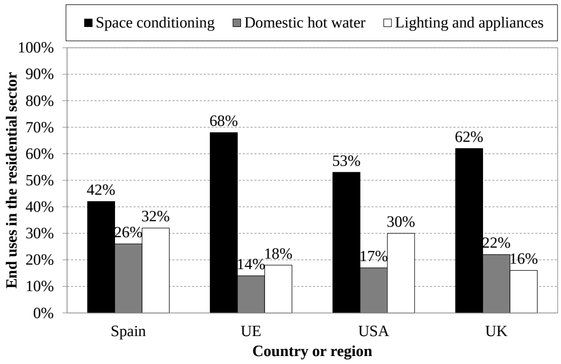

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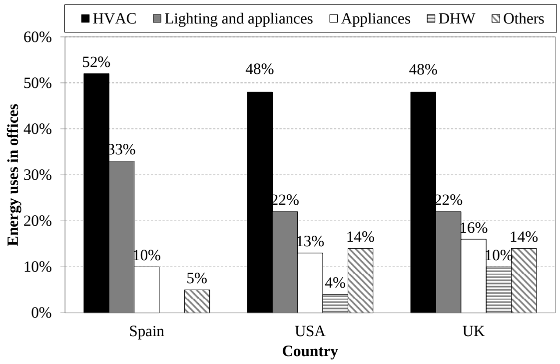

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Figure 1. Energy consumption by end uses [4]: a) in the residential sector and b) in offices.

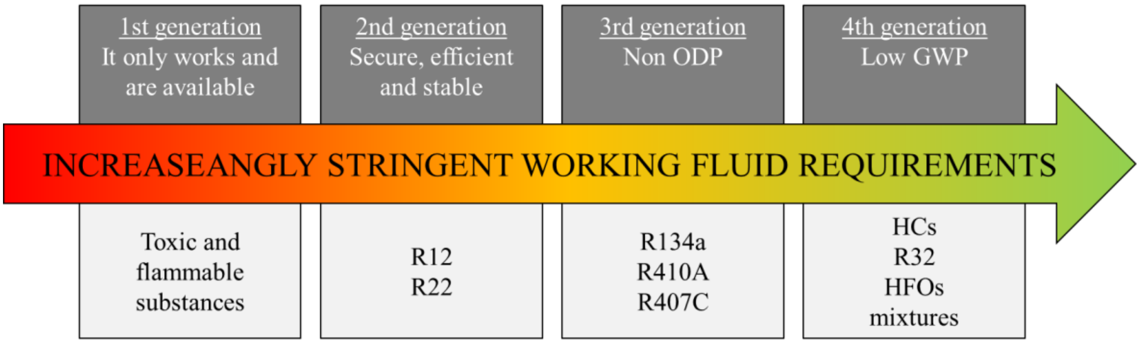


Figure 2. Evolution of working fluids used in air conditioning systems [28].

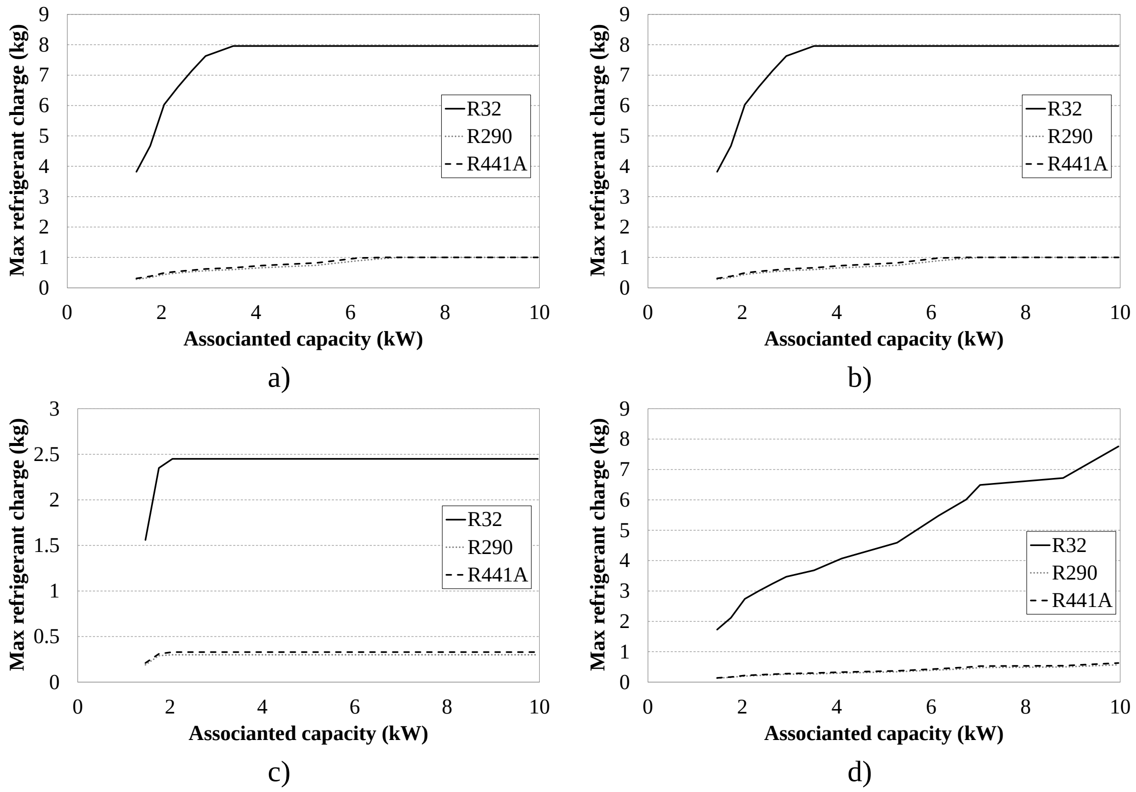


Figure 3. Maximum design charge sizes for [19]: a) wall mounted RAC units, b) ceiling mounted RAC units, c) portable room RAC units and d) window RACs.

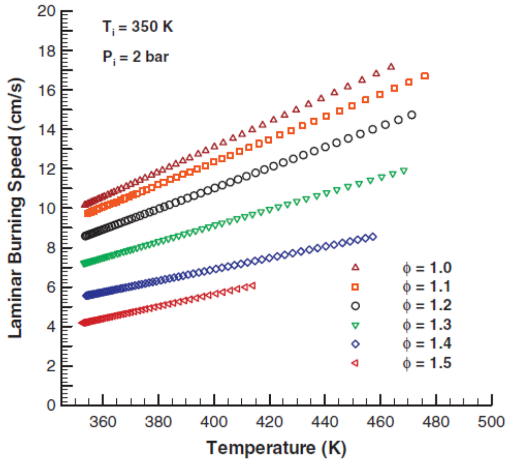
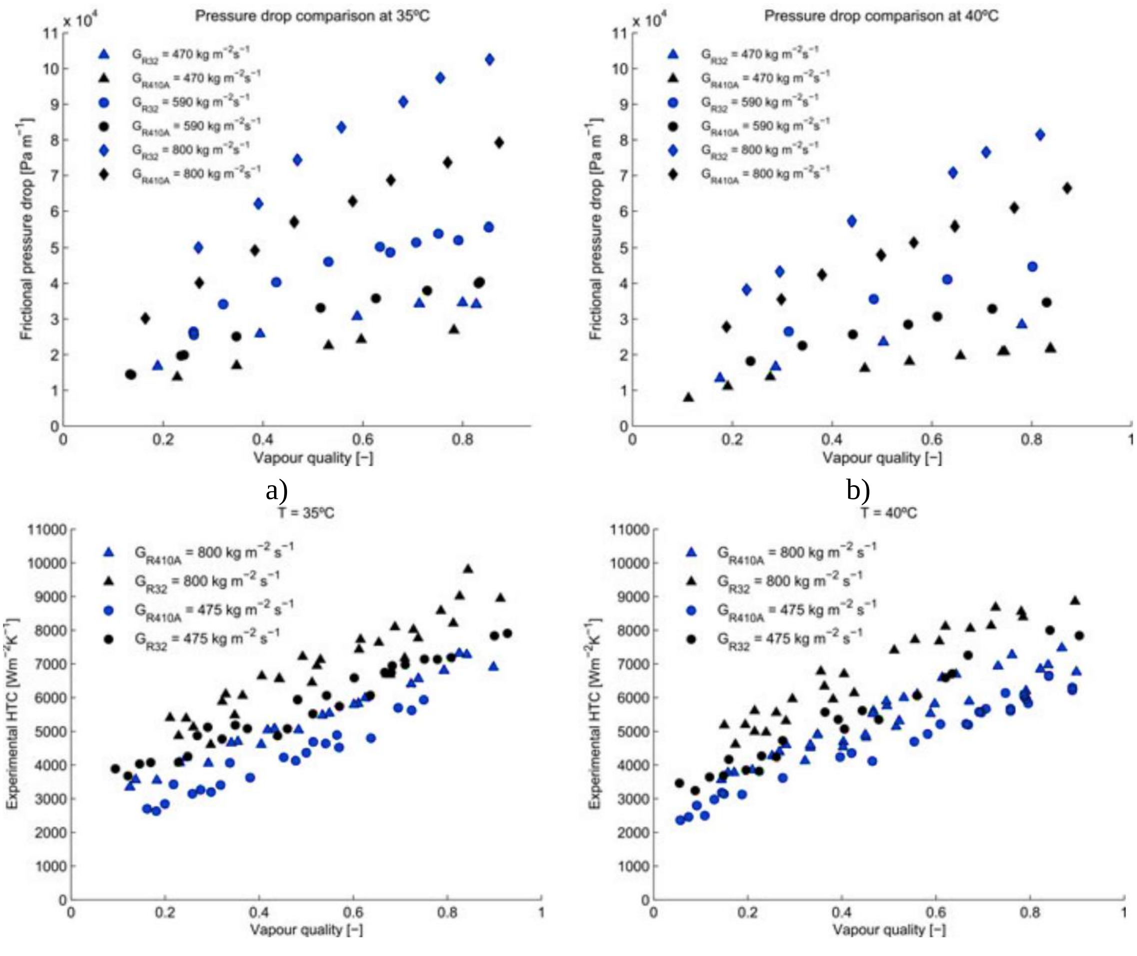


Figure 4. Laminar burning speeds of R32/air mixture for T=350 K and P=2 bar and different equivalence ratios [40].



a) b) c) d)

Figure 5. López Belchi et al. [46] experimental results in aluminum square multiport tubes for R410A and R32: pressure drop at a) 308 K and b) 313 K and HTC at c) 308 K and d) 313 K.

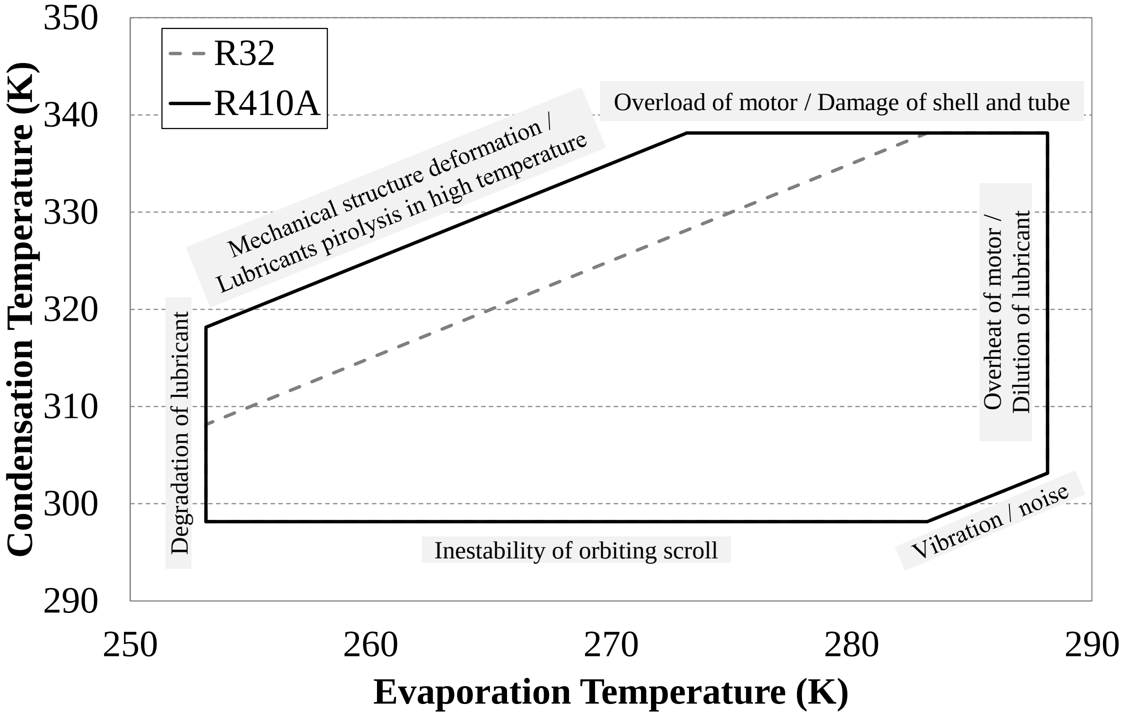
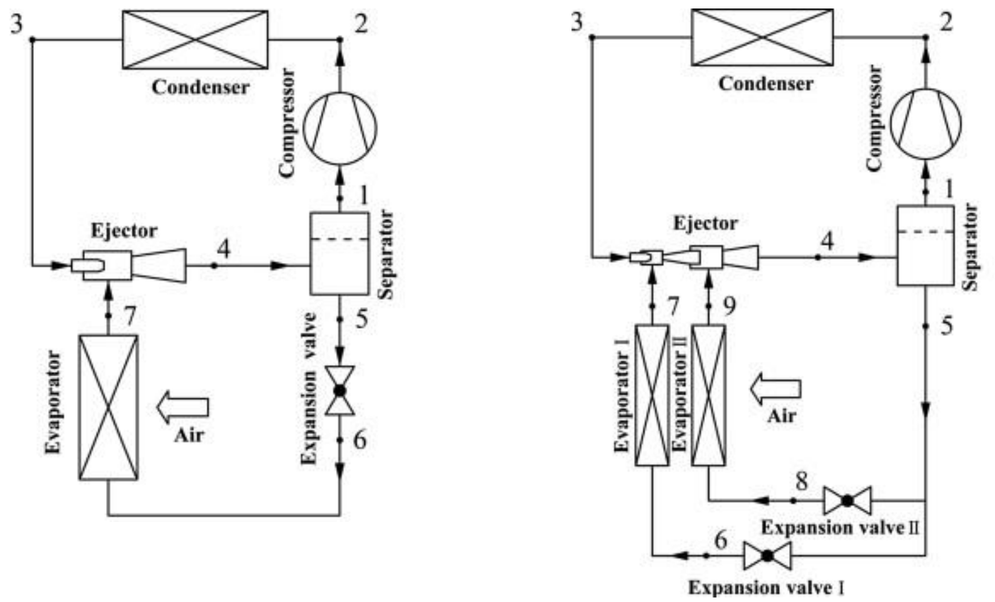
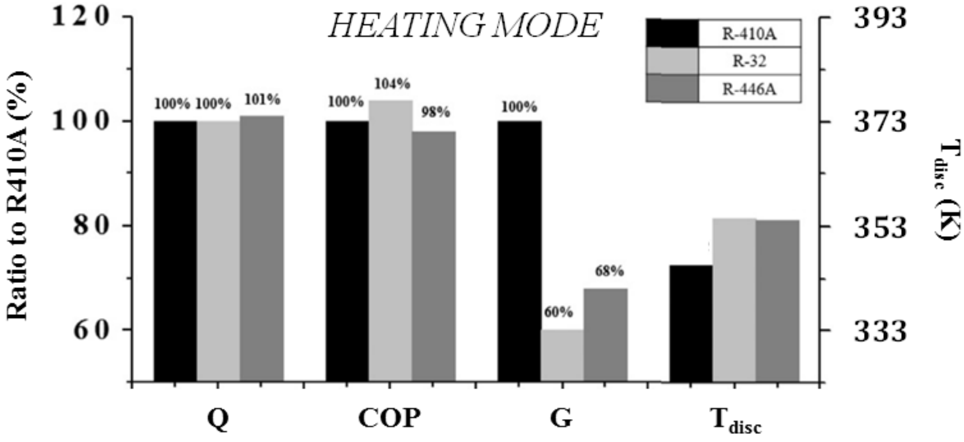


Figure 6. Limiting factors and operating envelopes of the scroll compressor using R32 and R410A [59].



a) b)

Figure 7. Schematic diagrams for: a) ejector expansion refrigeration cycle and b) new ejector enhanced refrigeration cycle proposed by Yu et al. [63].



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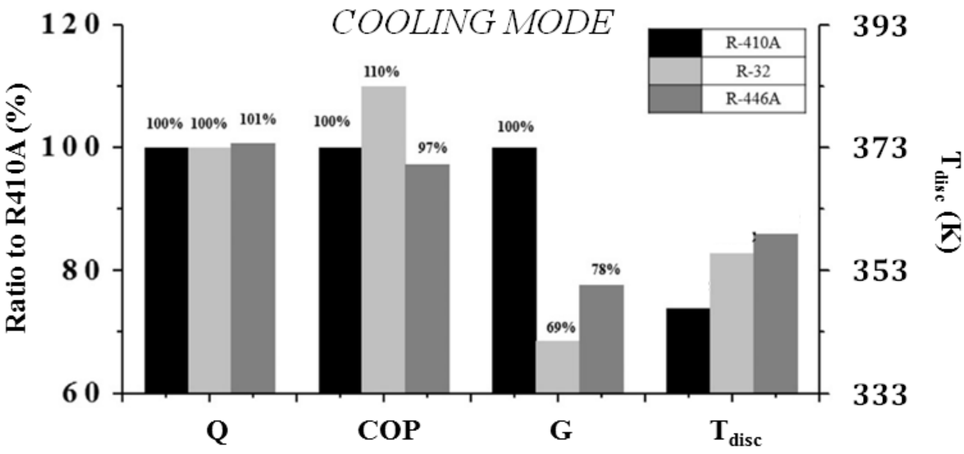

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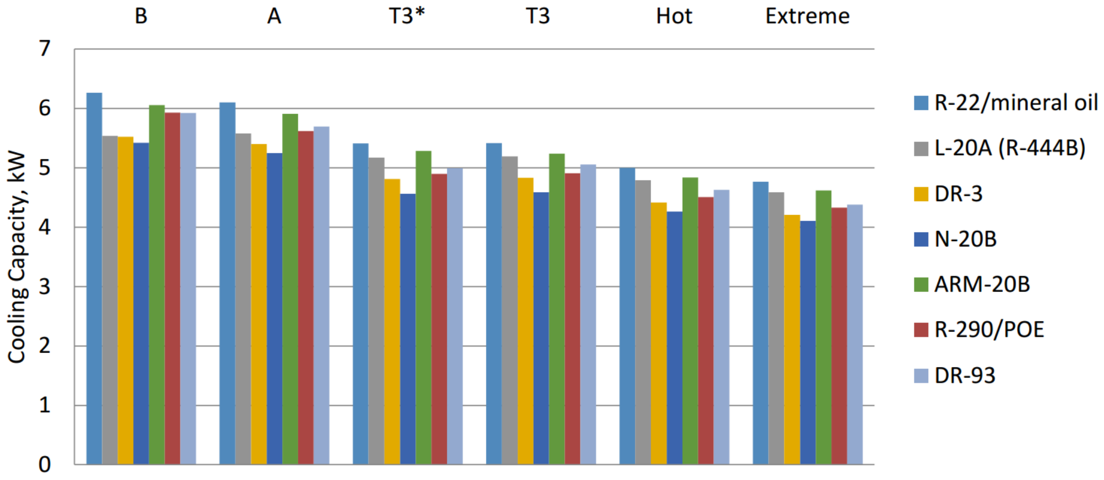
Figure 8. Experimental results in a residential HP [67]: capacity, COP_c, mass flux and discharge temperature for R410A, R32 and R446A under the standard: a) heating mode and b) cooling mode.



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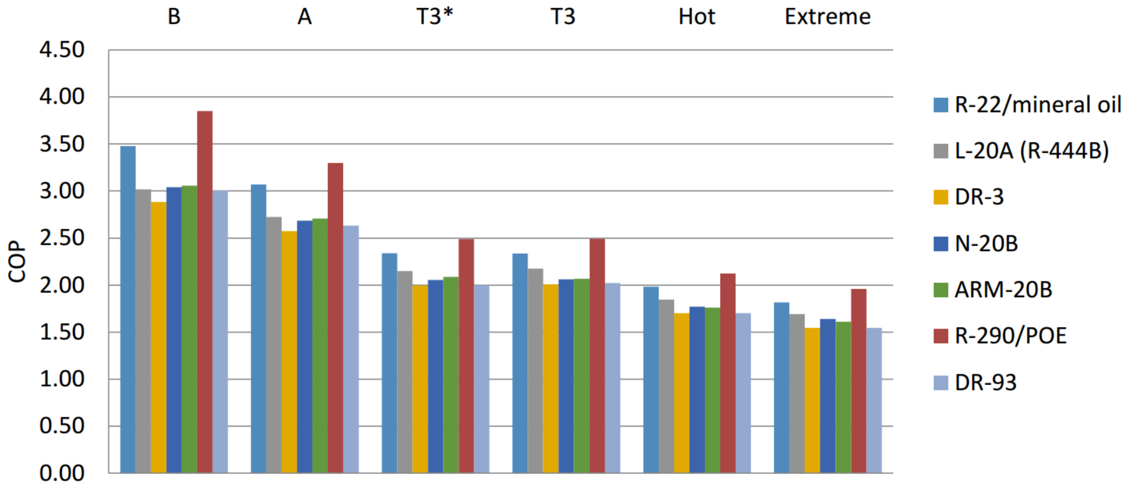

b)

Figure 9. Abdelaziz et al. [71] results for R22 and its alternatives: a) cooling capacity and b) COP_c. Conditions of tests shown in Table 8.

FIGURE CAPTIONS

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Table 1. Alternatives to R22 and R410A in residential air conditioners [20].

Alternative	GWP	Flammability	Equipment cost	Refrigerant cost	Efficiency
R290	3	High (A3)	Low	Low	High
R32	677	Low (A2L)	Low	Medium	High
R441A[a]	1	Medium (A2L)	Low	Medium	High
R1234yf	<1	Low (A2L)	Medium	High	Low

[a] Mixture of R170/290/600a/600

Table 2. HFC/HFO Mixtures proposed to replace R410A.

Mixture	**R125**	**R134a**	**R32**	**R744**	**R1234yf**	**R1234ze(E)**	**R600**
AHRI PHASE I							
ARM-70A		10%	50%		40%		
D2Y-60			40%		60%		
DR-5			72.5%		27.5%		
HPR1D			60%	6%		34%	
R447A	3.5%		68.0%			28.5%	
AHRI PHASE II							
ARM-71A (not yet disclosed)	50%-80%				10%-40%	1%-20%	
DR-5A (R-454B)			68.9%		31.1%		
DR-55	7%		67%		26%		
HPR2A		6%	76%			18%	
L-41-1 (R446A)			68%			29%	3%
L-41-2 (R447A)	3.5%		68%			28.5%	

Table 3. Main thermophysical properties of R22, R410A and some alternatives [24].

Property	**R22**	**R410A**	**R290**	**R32**	**R441A**	**R1234yf**
Critical Temperature (K)	369.30	344.49	369.89	351.26	390.41	367.85
Critical Pressure (kPa)	4990.0	4901.3	4251.2	5782.0	4404.8	3382.2
NBP (K)	232.06	221.53	230.74	221.24	252.52	243.37
Liquid density [a] (kg m^{-3})	1282.0	1170.6	528.8	1055.8	554.0	1176.8
Vapor density [a] (kg m^{-3})	21.13	30.43	10.30	21.98	5.06	17.56
Liquid c_p [a] (kJ kg^{-1} K^{-1})	1.17	1.52	2.49	1.74	2.42	1.29
Vapor c_p [a] (kJ kg^{-1} K^{-1})	0.74	1.13	1.74	1.25	1.66	0.93
Liquid therm. cond. [a] (mW m^{-1} K^{-1})	94.81	103.18	106.05	145.37	109.50	71.51
Vapor therm. cond. [a] (mW m^{-1} K^{-1})	9.40	12.12	15.73	11.72	15.31	11.62
Liquid viscosity [a] (µPa s)	216.33	161.79	125.78	150.74	147.05	208.72
Vapor viscosity [a] (µPa s)	11.36	12.22	7.44	11.50	7.30	10.06
Latent heat of vaporization [a] (kJ kg^{-1})	205.17	221.49	375.08	315.53	382.00	163.39

[a] at 273K

Table 4. Flammability properties of R290, R32 and R1234yf [35].

Fluid	**ASHRAE 34**	**LFL (% v/v)**	**UFL (% v/v)**	**BV (cm s^{-1})**	**MIE (mJ)**
R290	A3	2.5	10	46	0.25
R32	A2L	14.4	29.3	6.7	30
R441A	A3	2.1	- [a]	47.6	- [a]
R1234yf	A2L	6.2	12.3	1.5	5000

[a] Information not published

Table 5. Summary of heat transfer and pressure drop studies for pure R32 and its mixtures.

Reference	**Tube section**	**Conditions**	**Results and comments**
Condensation			
Liu and Li [44,45]	1.152 mm circular, 0.952 and 1.304 mm square	T_{sat}=[303,323] K G=[200,800] kg m^{-2} s^{-1} x=[0.1,0.9]	- HTC ↑ if D_h ↓. - HTC: R152a>R32>R22. - Δp ↑ significantly if x↑. - Δp: R32≈R22>R152a.
López Belchi et al. [46]	1.16 mm multiport minichannel	T_{sat} =[303,308,313,323] K G=[100,800] kg m^{-2} s^{-1} x=[0.05,0.9]	- HTC: R32>R410A, especially at ↓G. - R32 Δp up to 25% higher than R410A at high x.
Evaporation / Flow boiling			
Kondou et al. [50]	5.21 mm horizontal microfin	T_{sat}=283.15 K G=[150,400] kg m^{-2} s^{-1} q''=10 and 15 kW m^{-2}	HTC (by decreasing order): R32, R1234ze(E), R32/R1234ze(E), and R744/R32/R1234ze(E).
Li et al. [51]	2 mm smooth horizontal	T_{sat}=288 K (for =0.5) G=[100,400] kg m^{-2} s^{-1} q''=[6,24] kW m^{-2}	- HTC of mixtures are [20,50]% below than that of R32. - HTC of 20% R32 mixture is [10,30]% less than R1234yf. - HTC of 50% R32 mixture is [10,20]% greater than R1234yf.
Smith et al. [52]	9.5 mm microfinned	T_{sat}=277 and 282 K G=[250,425] kg m^{-2} s^{-1} q''=[10,12] kW m^{-2}	- HTC of R32 up to 40% higher than R410A. - Only DR-5A HTC is close to that of R32 (at some conditions). - Δp: R32>R410A (approx. 20%) but R32<R1234yf. - POE affects more HTC than Δp.

Table 6. Summary of energetic studies for pure R32.

Reference	**System**	**Conditions**	**Results and comments**
Zilio et al. [56]	Packaged air to water reversible unit: - water plate HXs, - scroll compressor.	Standard EN 12900	R32 vs R410A: - Q_o and Q_k 6% higher. - COP_c and COP_h 3% higher. - Seasonal T_{disc} [14.3,16.8] K higher.
Barve and Cremaschi [57]	17.6 kW HP: - hermetic reciprocating compressor, - fin and tube HXs.	T_{amb}=[265,319] K SH>2 K m to max COP at AHRI 210 A	R32 vs R410A: - 10% higher Q_o and Q_k comparable. - Similar COP_c and COP_h [10,17]% higher.
Yang et al. [59]	Low side scroll compressor: - liquid injection, - two phase injection, - two phase suction.	T_k=313, 323 and 333 K T_o=268 K SH=5 K / SC=3 K	- Two phase injection Q_o and COP_c 12% and 5% higher than basic cycle. - T_{disc} decreased = % of liquid injection multiplied by [2.1,2.8] K.
Shuxue et al. [61]	Enhanced VI HP: - R410A scroll compressor, - shell and tube condenser, - plate evaporator.	T_k=313 and 318 K T_o=278 (cooling) and 263, 268 and 273 K (heating) SH=10 K / SC=5 K	- Q_o 4%, Q_k [4,6]% and COP_h 3% higher than single stage system. - T_{disc} [10,20] K lower. - The best range of relative VI mass is [12,16]%.
Xu et al. [62]	R410A HP system: - VI scroll compressor, - fin and tube HXs.	ASHRAE Standard 116. Extended conditions of 319 K (cooling) and 254.4K (heating).	R32 vs R410A: - Single stage system: Q and COP [3,10]% and [2,9]% higher. - VI mode: Q and COP [2,7]% and [1,6]% higher. - No benefits at extreme conditions.
Yu et al. [63]	Ejector enhanced vapor compression cycle.	T_k=[318,328] K T_o=[263,288] K SH=0K / SC=5 K	The R32 COP_h and Q_k are improved by 9% and 11.5%.
Alabdulkarem et al. [66]	10.55 kW HP: - scroll compressor, - fin and tube HXs.	Same as [61]	- R32 Q_o and Q_h 4% and [4,7.8]% higher than R410A. - IHX only improves D2Y60 performance.
In et al. [67]	3.5 kW R410A RAC: - inverter type rotary compressor, - fin and tube HXs.	EN14825 standard	Detailed in text and Figure 8

Table 7. Summary of energetic studies for mixtures of R32.

Reference	System	Conditions	Results and comments
Yu et al. [68]	Transcritical HP with IHX.	T_{disc}=368 K T_o=[263,293] K	R32/R290 (68/32%) COP_h is [8.5,16.8]% and [10.2,23.7]% higher than R125 and R744.
Tian et al. [69]	Wall and floor mounted split RACs: - hermetic rolling rotor compressors, - fin and tube HXs.	Cooling mode: - $T_{dry,in,indoor}$=300 K - $T_{wet,in,indoor}$=292 K - $T_{dry,in,outdoor}$=308 K - $T_{wet,in,indoor}$=297 K - RH_{indoor}=47.2% - $RH_{outdoor}$=40.4% Heating mode: - $T_{dry,out,indoor}$=293 K - $T_{wet,out,indoor}$=278 K - $T_{dry,in,outdoor}$=280 K - $T_{wet,in,outdoor}$=279 K - RH_{indoor}=59.2% - $RH_{outdoor}$=96.7%	R32/R290 vs R410A: - G [30,35]% lower - T_{disc} [0.6,4.8] K higher. - Q_k and Q_o [6.1,16.4]% higher. - COP_c [6,7]% higher. (with microchannel HX) - T_{disc} reduced by 1.39 K - Q_o and COP_c increased by 6.4% and 6.8%.
Sethi et al. [70]	R22 ductless split RAC (cooling only): - fixed speed rotary compressor, - fin and tube HXs.	ISO Standard 5151	R444B vs R22: - Q_o and COP_c ±2%. - 15% lower m. - UA_o similar and UA_k 12% lower. - Lower Δp.
Abdelaziz et al. [71]	Mini split RAC units.	ANSI/ASHRAE Standard 37 conditions	R32 vs R410A: - Q_o and COP_c higher. - T_{disc} [12,21] K higher.
Lee et al. [73]	Water source HP bench tester: - open type variable speed compressor, - double tube HXs.	T_o=266 and 280 K T_c=314 and 318 K	R32/R152a vs R22: - 15% higher COP_c. - m decreased up to 27%.
Bansal and Shen [74]	Window RACs: - Single speed rotary compressor, - fin and tube HXs.	SC=5.6 K / SH=5.6 K	- R32 performance 4% above R410A. - R32 T_{disc} max is 366.5 K at 308 K T_{amb}.
Wu et al. [75]	Xinfei KRF50 chest type AC.	$T_{dry,outdoor}$=308 K $T_{wet,outdoor}$=297 K $T_{dry,indoor}$=300 K $T_{wet,indoor}$=292 K	R152a/R125/R32 COP_c is 8% higher than that of R22.
Chen and Yu [76]	Conventional (CRC) and new (NRC) refrigeration cycles.	T_k=328 K T_o=278 K SH=0K / SC=5 K	R32/R134a (30/70%) vs R22 (CRC): - COP_c 2.6% lower if CRC. - COP_c and Q_o are 1% and 10% higher if NRC.

Table 8. Abdelaziz et al. [71] tests conditions.

Test conditions	**Outdoor** T_{dry} (K)	**Indoor** T_{dry} (K)	T_{wet} (K)	T_{dew}[a] (K)	RH [a]
AHRI B	301.0	299.9	292.6	289.0	50.9%
AHRI A	308.2	299.9	292.6	289.0	50.9%
T3*	319.2	299.9	292.2	289.0	50.9%
T3	319.2	302.2	292.2	286.9	39%
Hot	325.2	302.2	292.2	286.9	39%
Extreme	328.2	302.2	292.2	286.9	39%

[a] Evaluated at 98.6 kPa