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R-1234ze for variable speed centrifugal chillers

by

Dr AB Pearson, BSc, BEng, PhD, CEng, FInstR

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Introduction

The proposed phase-down of HFC refrigerants, whether through the Montreal or Kyoto processes or by way of European legislation, has prompted an assessment of alternative fluids for a wide range of applications. Kazakov et al (2012) examined more than 56,000 compounds which they narrowed down to about 1,200 candidates by considering molecular size, component elements, critical temperature, GWP, flammability and toxicity. One of the more difficult challenges has been to find a replacement for R-134a used in small centrifugal compressors as used in water chillers (Hickman, 2012, Wang et al, 2012). The common natural refrigerants ammonia, carbon dioxide, propane and water are not suitable for a variety of reasons. In a Goldilocks-style assessment it can be seen that ammonia is too light, carbon dioxide is too dense, propane is too flammable and water is not dense enough. The use of zeotropic blends is not feasible since the evaporators used in these chillers are usually flooded so any replacement for R-134a would need to be a single compound, or an azeotropic blend.

This paper explains the background to HFC phase-down, describes the steps taken to evaluate alternatives to R-134a in this application and the design modifications required to ensure efficiency and reliability, and gives the results of performance testing in a factory environment and on site. Commercial, technical and legislative barriers to further progress are considered and the next steps to adoption of this technology are discussed. The type of compressor in question was presented to the Institute of Refrigeration by Conry (2009) and has become widely used in North America, Europe, Australia and some parts of Asia, mainly in water cooled chillers, although sometimes in air-cooled units and occasionally in other types of system (Pearson, 2011).

HFC phase-down

Montzka (2012) has commented that although HFCs currently account for less than 1% of the global warming effect of all long term greenhouse gases, the expected rate of rise in demand will result in significantly greater climate impact unless they are replaced by substances with much lower warming potentials. The concept of phase-down, as opposed to phase-out, is that various restrictions are placed on the production and consumption of specific fluids or groups of fluids in order to cap their emissions to some proportion of an established benchmark, but resulting in a residual controlled availability, particularly for essential uses. This mechanism has worked well through the procedures of the Montreal Protocol for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), for example in the use of CFC-12 in medical inhalers or methyl bromide as a pesticide. Phase-down was first raised in 2008 as a mitigation strategy for HFCs, jointly proposed by Mauritius and the Federated States of Micronesia, whose President, Emanuel Mori, when addressing the General Assembly of the United Nations in 2012 said “the biggest challenge we face today in Micronesia is climate change, not just the projections of future loss and damage, but the dangerous impacts that my people are experiencing now as well” (Mori, 2012). Significant weight was added to the Micronesian proposal when Canada, the United States of America and Mexico combined to table a proposal before the meeting of the parties to the Montreal Protocol in Port Ghalib, Egypt in 2009 (Reifsnyder et al, 2009). The North American proposal and the Micronesian proposal are not identical, but they both proposed a reduction of HFC use to roughly 20% of mid 2000s levels by about 2030. Neither proposal has yet been adopted by the Montreal Protocol, having been consistently blocked by a grouping of Article 5 countries including China, India, Brazil and Russia. There is a strong case for regulating HFCs, if they are to be regulated at all, through the Montreal Protocol process (Hufford et al, 2012) since it is concerned primarily with production, consumption, banks and emissions, whereas the Kyoto Protocol process, where HFCs currently sit, is more aligned to managing the reduction of necessary emissions, for example of carbon dioxide from fossil fuel combustion. In considering phase-down proposals it is sobering to note that the original CFC proposals in the 1987 Montreal Protocol mandated a 50% reduction in CFC production and consumption relative to 1986 levels. This quickly changed into a complete ban, so it would be too simplistic to assume that, if either HFC proposal is adopted, the numbers will not change. The targets are unlikely to be relaxed. It seems likely that the European Commission will not wait for the Montreal Protocol Meeting of the Parties to resolve their differences on this issue, but rather will introduce some form of HFC phase-down in the next revision of the f-gas regulations. Again history shows that this is not likely to be a fixed target.

Alternatives in other sectors

The options for refrigerant alternatives to HFCs are compartmentalised by market sector. In small systems hydrocarbons have been widely used in Europe and generally have an excellent safety record. For supermarkets carbon dioxide has been used in a variety of ways and, if the charge can be kept sufficiently low, hydrocarbon offers an efficient and cost-effective option. In large chillers ammonia has been used in a limited number of applications but is not seen as a universal answer and is not generally suitable for use in hermetic or centrifugal compressors. In mobile air-conditioning the situation is more pressing, since the European MAC directive of 2006 required a transition from the current refrigerant, HFC-134a, to something with a global warming potential (GWP) less than 150, on a 100-year time horizon. The automotive industry has responded vigorously to this challenge; originally proposing that enhanced HFC-134a systems would be sufficient, then testing and rejecting several alternatives in quick succession including HFC-152a, carbon dioxide and blends of trifluoroiodide (CF₃I) with a new class of refrigerant known as hydrofluoroolefins (UNEP, 2006). By the time of the 2010 RTOC assessment the picture for mobile air-conditioning was in some ways clearer. HFC-152a was deemed too flammable to be a universal solution, as was HC-290. Several of the blends had been withdrawn due to concerns about toxicity (Low, 2010) but a new single-fluid option had emerged; 2,3,3,3 tetrafluoropropene, also known as HFC-1234yf (Leck et al, 2010). Carbon dioxide was still under consideration and the RTOC report (UNEP, 2010) noted that isomers were also under investigation, including trans-1,3,3,3 tetrafluoropropene, also known as

HFC-1234ze(E), or “ze” for short. These propene-based fluids have become known as HFOs (hydrofluoroolefins) since olefin is an archaic name for an unsaturated hydrocarbon. For the purposes of this paper they will be referred to throughout as “unsaturated hydrofluorocarbons” and abbreviated to “uHFC”. At the time of writing HFC-1234yf has had preferred status among most car manufacturers for about a year, but the debate is not completely over and fears about flammability in “real-world” situations continue to cause concern for some manufacturers.

The emergence of unsaturated HFCs

In 2006 there were no research papers proposing uHFCs as refrigerants and they were not mentioned by UNEP’s Refrigeration Technical Options Committee (RTOC), except as a brief remark as to the possible use of them as blend components (UNEP, 2006). There were no papers on these fluids in the 877 presented to the International Congress of Refrigeration in Beijing in 2007. In 2008 when EN378 was published they were not mentioned in the standard, but by the end of 2010 they were included in the next RTOC report (UNEP, 2010) and one compound, HFC-1234yf, had been added to the interim amendment of EN378, which classes it as an A2 fluid (non-toxic, mildly flammable). The two most commonly mentioned candidate compounds are isomers of tetrafluoropropene; in other words the molecule contains the same elements in the same proportions, but they are arranged differently, producing chemicals that have distinct properties. There are in fact seven isomers of tetrafluoropropene. Some of them, such as the two versions of HFC-1234ze, are “stereo-isomers”, where the elements are connected in the same positions on the carbon “backbone” but in different orientations. The trans-isomer of HFC-1234ze has been commercially available for some time. Koyama et al (2010) note that it was originally developed as a cover gas for the casting of magnesium alloy components and it has also been promoted heavily in Europe as a replacement for R-134a in one-component polyurethane foam since mid-2008 (Bowman and Williams, 2009). It was not initially proposed as a refrigerant, probably because its isomer HFC-1234yf is a much closer match in properties and performance to HFC-134a. The key properties of a few of the uHFC isomers in comparison with CFC-12 and HFC-134a are given in Table 1.

Compound	Formula	Mol. Wt	NBP (°C)	T _{crit} (°C)	P _{crit} (bar g)	P ₀ (bar g)	ΔH ₀ (kJkg ⁻¹)
CFC-12	CCl ₂ F ₂	121	-29.8	+112.0	40.6	2.1	151.5
HFC-134a	CH ₂ FCF ₃	102	-26.1	+101.1	39.6	1.9	197.2
HFC-1234yf	CH ₂ :CF ₂ CF ₃	114	-29.4	+94.8	31.7	2.1	161.5
HFC-1234ze(E)	CHF:CHCF ₃	114	-18.2	+109.6	35.8	1.1	184.5
HFC-1234ze(Z)	CHF:CHCF ₃	114	+9.0	+153.6	38.7	-0.1	c. 225*

Table 1 – Some properties of various possible refrigerants.

Notes: Mol Wt is the molecular weight, NBP is the boiling point at atmospheric pressure, P₀ is the pressure at 0°C saturated and ΔH₀ is the latent heat at 0°C. * ΔH₀ estimated from Koyama et al (2012).

The differences in normal boiling points for the three isomers of HFC-1234 listed is remarkable, showing a greater variance in operating pressure than is seen between R-12 and R-22 or between propane and isobutane. More detail of the difference between “yf” and “ze” is shown in the pressure-temperature relationship in Figure 1.

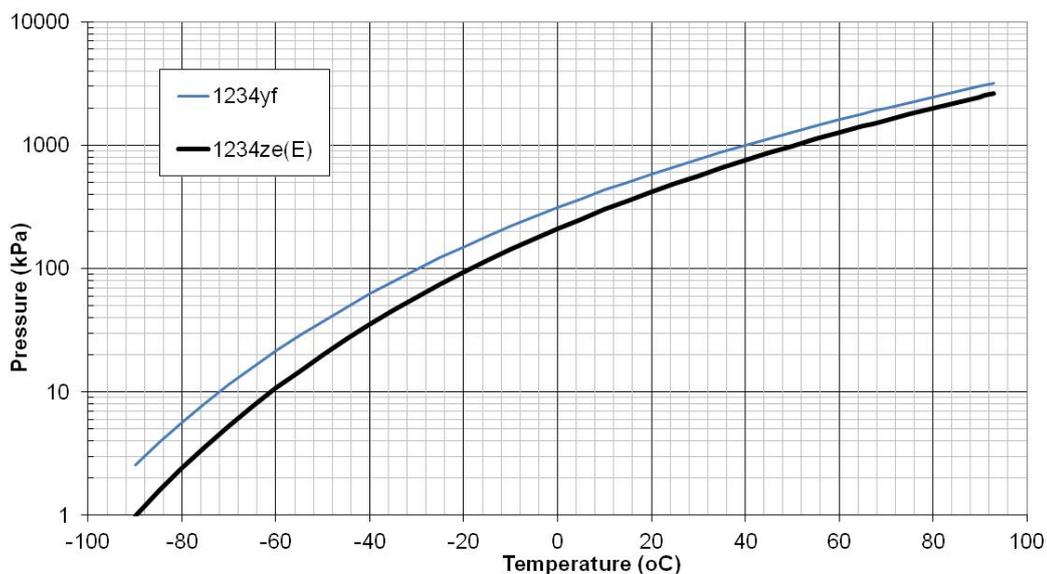


Figure 1 – Pressure – Temperature comparison.

A brief review of literature over the period 2006 to 2012 shows that there are many more references to HFC-1234yf within the refrigeration and air-conditioning field than to any of its isomers. For example the IIR database Fridoc lists 208 results for “1234yf” dating back to 2008 whereas there are only 31 hits for “1234ze” with the earliest being Kuijpers (2009) at the IIR’s Ammonia Technology Conference in Ohrid and the remainder dating from 2010 onwards. In the Kuijpers paper “ze” is mentioned as already commercialised for foams and a possible candidate for refrigeration. Likewise a review of recent Purdue conferences shows that no papers on the subject of HFC-1234ze(E) were presented in 2008, four were presented in 2010 and nine were presented in 2012. The 2010 papers included two (Koyama et al (2010) and Yana Motta et al (2010)) on possible applications – heat pumps and small refrigeration (plug-in) applications respectively. The other two papers provide some thermodynamic properties – McLinden et al (2010) for the pure fluid, including a detailed equation of state, and Akasaka (2010) for mixtures of HFC-1234ze(E) with HFC-32. About half of the papers presented at Purdue in 2012 were for mixtures of HFC-1234ze(E) with HFC-32, mostly by Japanese research teams looking at heat pumps and air-conditioners. Pham and Rajendran (2012) make the point that since “ze” is already commercialised for single component foams and is said to be easier to produce than “yf” it is likely to be cheaper to purchase as a refrigerant. Karber et al (2012) compare fluids for use in domestic refrigerators and note that “ze” requires a significantly higher compressor swept volume to achieve the same cooling capacity. They noted that the energy consumption of the modified “ze” was 15% lower than HFC-134a in one test unit and 5% lower in the other although the compressor run time was 50% higher and 40% higher respectively.

The centrifugal compressor challenge

Only one paper at Purdue last year, Spatz et al (2012), considers the possibility of using HFC-1234ze(E) in centrifugal chillers. They make a useful comparison between HFC-134a and, on the one hand CFC-12 as a sort of yardstick, and on the other hand “ze” and “yf”. They show that CFC-12 was more efficient than the current design of HFC-134a compressor by about 1.3%. The more popular (at least for refrigeration) version of tetrafluoropropene, “yf”, would be about 3.6% less efficient than HFC-134a, but “ze”, not considered elsewhere as a refrigerant, almost exactly matches the efficiency of HFC-134a. The beauty of the small variable-speed centrifugal compressor is that it is not locked in to a fixed swept volume, so the capacity loss associated with “ze” in positive displacement machines can be offset by adjusting the compressor speed. This work was further described at the JRAIA symposium in October 2012.

Parameter	Units	Fixed capacity			Fixed Diameter
		R-12	R-134a	R-1234ze(E)	R-1234ze(E)
mass flow	kg s ⁻¹	14.31	11.33	12.34	8.84
density	kg m ⁻³	20.54	16.86	13.74	13.74
Volume flow	m ³ s ⁻¹	0.70	0.67	0.90	0.64
Impellor speed	rpm	11983	14691	11919	14079
Impellor dia	m	0.255	0.235	0.278	0.235
tip speed	m s ⁻¹	160	181	174	174
Pressure ratio	-	2.34	2.54	2.57	2.57
CoP	-	8.01	7.90	7.91	7.91
Relative CoP	-	101.3%	100.0%	100.1%	100.1%
Relative capacity	-	100.0%	100.0%	100.0%	73.4%

Table 2 – Comparison of design parameters for centrifugal compressors.

(derived from Spatz and Yana Motta, 2012)

Table 2 shows that if the same impellor is used for HFC-1234ze(E) as designed for HFC-134a then the capacity is reduced by 26.6%. Conversely to maintain the same capacity a larger impellor is required, albeit running at lower speed – in this case the diameter is increased from 235mm to 278mm, and the speed is reduced from 14691 rpm to 11919 rpm. This is because the head developed by the compressor is a function of the gas density, the impellor diameter and the speed of rotation. The relationship is shown in equation 1

$$\Delta P \propto \rho(ND)^2 \quad (1)$$

Thus to achieve the same lift with a more dense gas it is necessary to reduce the speed or reduce the diameter of the impellor. The comparison between refrigerants is more complicated because the enthalpy change in the evaporator and the mass flow will also change for a given cooling capacity, as can be seen in the table above. The specific work input to the gas, in kJ per kg of gas flow, is given by equation 2 (Dixon, 1998) where h_o is the stagnation enthalpy, U is the blade speed and c_θ is the tangential gas speed at the exit from the rotor. The subscripts 1 and 2 relate to the inlet and outlet conditions, assuming that the tangential gas speed at inlet is zero.

$$\frac{\dot{W}}{\dot{m}} = (h_{o2} - h_{o1}) = U_2 c_{\theta 2} \quad (2)$$

The stagnation enthalpy is defined as shown in equation 3, where h is the actual enthalpy and c is the gas velocity, and the blade speed is defined in equation 4, where N is the rotational speed and D is the impellor diameter

$$h_o = h + \frac{1}{2} c^2 \quad (3)$$

$$U = ND \quad (4)$$

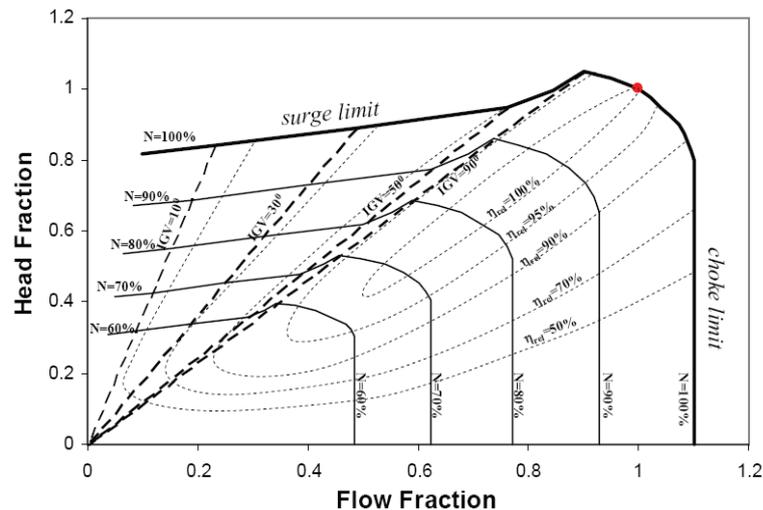


Figure 2 – compressor performance map with variable speed and variable inlet geometry.

(from Brasz and Tetu, 2008)

Equations 2 and 3 show that it is necessary to consider not only the evaporator enthalpy change but also the change in stagnation enthalpy head in the compressor when determining the correct speed and diameter for a different refrigerant. If the compressor generates insufficient pressure lift for the externally imposed lift at the required flow then the flow will be unstable and the machine will surge. There is a limiting flow, the choke line, above which for a given speed, the compressor cannot deliver additional capacity. Brasz and Tetu (2008) showed the effect of varying compressor speed and the effect of adding preswirl (introducing a tangential component to the inlet gas velocity) on the compressor performance map, as seen in Figure 2. The inlet swirl introduces the term U_{IC01} as shown in equation 2a, thus reducing the enthalpy head developed and hence reducing the flow capability and the work input.

$$\frac{\dot{W}}{\dot{m}} = (h_{o2} - h_{o1}) = U_2 c_{\theta 2} - U_1 c_{\theta 1} \quad (2a)$$

This provides a very flexible performance map which allows the centrifugal compressor to operate over a wide range of head (pressure lift) and flow (capacity) requirements (Figure 2). It means however that if the refrigerant is changed then it is necessary to change the software used to control speed and inlet guide vane (IGV) position, otherwise the compressor will operate at the wrong point on the map and will be likely to surge at some point. The safety subroutines used in normal operation to prevent this happening will be ineffective since they would be based on an incorrect map.

Low GWP – a definitive definition

The MAC directive sparked a debate about the meaning of the term “low global warming potential”, since the directive contained a limit of 150. This, it has been said, was to permit the consideration of HFC-152a which has a GWP of 140 and so it is a rather artificial limit since that option is no longer under consideration for MAC due to flammability concerns. However there is a stronger logic to support this rough indicator (Kuijpers, 2011). The current radiative forcing of CFCs in the atmosphere is about 0.3 Wm^{-2} mainly due to CFC-12 which has an atmospheric life of 100 years and a GWP_{100} of 10,900. The analysis considered the radiative forcing effect of CFC-12 emissions before its use was restricted, using 1988 as the base, and equated the “low GWP” tag to an emission of HFC that would result in a forcing of 0.01 Wm^{-2} to 0.02 Wm^{-2} (about 3% – 7% of the forcing effect of the 1988 ODS emissions and about 1% of the forcing effect of all CO_2 emissions). The logic behind this approach was that it did not make sense to replace ozone depleting substances

with fluids which had an equal or greater impact on climate. This comparison indicated that a global warming potential of 100 would equate to the lower forcing figure and 300 would equate to the higher forcing figure in the target band. Thus everything below GWP₁₀₀ of 300 can be considered to be “low GWP” in the context of existing CFC and CO₂ warming activity, and everything below GWP₁₀₀ of 100 can be considered to be “very low GWP”. Since these terms were already widely used it is helpful to provide a scale to calibrate them. The scale was then extrapolated up and down using roughly equal geometric steps to encompass all the refrigerants in common use, together with those proposed for future adoption.

Kuijpers (2011) presented a useful summary of the banding which is summarised in Table 3. Note that in this system everything under 300 is classed as “low GWP” and everything above 1000 is classed as “high GWP”, with further delineation available if required. This classification was criticised in some quarters for the perceived inference that the band from 300 to 1000 was deemed to be tolerable because “moderate” was interpreted as an indication of acceptability. It was also said by some to have too many categories. However it provides a quick and easy ready-reckoner for a complex topic, and has a certain logarithmic appeal. It suggests that the figure of 2150 currently included in the proposed revision to the European f-gas regulations is either rather too loose or slightly too tight, depending on whether the intent is to restrict all “high GWP fluids” or only “very high GWP fluids”. This supports the previous observation that the current GWP cap in the proposed revision to the f-gas regulations is likely to be reduced as time goes by. The only question is “when?”

GWP (100 year time horizon)	Classification	Examples
Above 3000	Very high GWP	R-404A, R-507
Above 1000	High GWP	R-134a, R-410A
Between 300 and 1000	Moderate GWP	R-32
Less than 300	Low GWP	R-152a
Less than 100	Very low GWP	
Less than 30	Ultra-low GWP	CO ₂ , NH ₃ , R-290, R-1234yf

Table 3 – A proposed GWP classification.

The classification uses the 100 year time horizon for GWP. As the atmospheric lifetime of the substances in question is reduced, this measure seems less and less appropriate, however since it is the only metric that is widely used in legislative and industry discussions it is maintained for the purposes of this paper, with the caveat that it may give misleading results in some cases if not considered along with other factors.

Characteristics of unsaturated HFCs

The uHFCs currently proposed as refrigerants are unlike HFCs in several respects, most noticeably flammability, toxicity and global warming potential. It has been observed on several occasions, for example by McLindon et al (2012), that the trade off in designing for low GWP is that the substance is likely to be more flammable. This is because the use of short-lived compounds by definition makes them more reactive.

Flammability – the safety standards used in the design of refrigerating systems class fluids according to three flammability groupings: non-flammable (class 1), mildly flammable (class 2) and highly flammable (class 3). The distinction between class 2 and class 3 is based upon the lower flammable limit (LFL), which gives some indication of how hard the substance is to ignite, and the heat of combustion (HoC), which gives some indication of how much damage it may do when it is ignited. Recently an additional sub-class, known as class 2L has been proposed in order to facilitate the adoption of low GWP, very mildly flammable fluids such as the uHFCs. This additional distinction is based on the burning velocity (BV) of the fluid, that is to say the rate at which a flame front

propagates relative to the unburnt gas ahead of the flame. A substance which has a burning velocity less than 10 cm s⁻¹ is included in sub-class 2L if it fulfils the other requirements for class 2 (LFL > 3.5% and HoC < 19,000 MJ kg⁻¹). In contrast, the hydrocarbons typically have BV greater than 40 cm s⁻¹ but as Takizawa et al (2012) observed this does not mean that the severity of a sub-class 2L fluid fire is one quarter of that of hydrocarbons. The relationship between the burning velocity and the consequences of an ignition is not linear. Above a critical Reynolds number the gas flow in the combustion is turbulent and a far greater amount of combustion energy is transmitted by the growing fireball. The flame Reynolds number (Re) is a function of burning velocity (S_u), the density (ρ_u) and dynamic viscosity (μ_u) of the unburnt gas and the radius of the flame (r_f) as shown in equation 5.

$$Re = \frac{\rho_u r_f S_u}{\mu_u} \quad (5)$$

For HC-290 the critical flame Reynolds number is about 4,100 which is reached at a flame radius of 0.16m, but for fluids with lower burning velocities the critical flame radius is much larger and in practice is not reached in a typical leakage scenario. All of the uHFCs under consideration as refrigerants have extremely low BV, typically less than 3 cm s⁻¹ and so would only exhibit turbulent combustion in exceptionally large flame radii, far greater than could be produced in a refrigerant leak scenario.

Burning velocity indicates not only how much damage may be done by ignition, but also how difficult it is to ignite the fluid, so it would have been possible to achieve the same three class system as before with a simpler method of assessment based solely on BV. Some other uHFCs, such as HFC-1252, are not so mild and would not meet the criteria for class 2. The focus on uHFC fluids has highlighted that the existing method of classifying fluids and designing for their properties is not logical or robust – there is significant room for improvement.

In the same paper Takizawa et al (2012) correlated the burning velocity with accurate measures of minimum ignition energy, E_{min}. They show that if the cooling effect of adjacent material, including the electrodes that provide the ignition, can be reduced then fluids can be ignited with much lower energy sparks than reported in previous test results. The method proposed by Takizawa suggests that E_{min} is about one-quarter of the theoretical values calculated according to gas heating considerations, giving values for the minimum ignition energy of HC-290, HFC-32 and HFC-1234yf of 0.21 mj, 15 mj and 520 mj respectively. In comparison the energy in a spark of static electricity from human touch is typically between 80 mj and 240 mj and a spark plug is typically less than 25 mj.

Toxicity – the uHFC fluids considered as potential refrigerants are in toxicity class A of the EN378 classification. This means that the short term exposure limit is higher than 400ppm and they are deemed safe to use in relatively large quantities. However some fluids, for example HFC-1225, were found to exhibit unacceptable chronic toxicity, so were dropped from the development programme despite being toxicity class A. Again it can be said that the existing method of classifying fluids and designing for their toxicology is not logical or robust and there is significant room for improvement. Neither HFC-1234yf nor HFC-1234ze(E) give cause for concern regarding toxicity, but a further consideration which is currently hotly debated is whether the products of combustion or other degradation should also be considered (AIRAH, 2013). The Honeywell MSDS for “yf” says “risk of formation of toxic pyrolysis products containing fluorine” (Honeywell, 2008a) and the MSDS for “ze” says “Note: hazardous decomposition products formed under fire conditions: to avoid thermal decomposition do not overheat” (Honeywell, 2008b). This has not previously been an issue, although perhaps it should have been once A2 blends of halocarbons became common. It is reasonable to say that the products of combustion of traditional class 2 and class 3 refrigerants would be water and carbon dioxide in the case of hydrocarbons or water and nitrogen in the case of ammonia. However it is difficult to account for all possible products of halocarbon combustion as the circumstances of combustion cannot be fully defined, and prompts the question whether

products of partial combustion should also be considered. This would include carbon monoxide in the case of hydrocarbons and is not feasible in practice. It should also be noted that the combustion products of “yf” and “ze” are less toxic than those of CFC-12 or HCFC-22.

Typically the breakdown of HFC-1234ze(E) in the atmosphere creates trifluoroacetic acid, $\text{CF}_3\text{C}(\text{O})\text{OH}$ (TFA), trifluoroacetaldehyde, CF_3CHO , and formyl fluoride, $\text{HC}(\text{O})\text{F}$ (Javadi et al, 2008). The normal breakdown, which gives HFC-1234ze(E) such a short atmospheric life, is caused by hydroxyl radicals, uncharged OH molecules with a half life of less than a second which are present in the atmosphere in relatively small quantities (roughly a million in each cubic centimetre). The yield of this reaction is said to be virtually 100%, meaning that no other compounds are created. Javadi et al (2008) conclude “In general, unsaturated hfc’s react more rapidly with OH radicals, have shorter atmospheric lifetimes and have lower gwp than saturated hfc’s.” They point out that TFA is a “natural component of the oceanic environment”, not a xenochemical, and so they conclude that “the products of the atmospheric oxidation of trans- $\text{CF}_3\text{CH}=\text{CHF}$ will have negligible environmental impact.” This is supported by Frank et al (2002) who note a uniform distribution of TFA at a level of 200 ng l⁻¹ in oceans throughout the world. Henne et al (2012) studied the possible effect of significant uptake of HFC-1234yf in the European mobile A/C market. They calculated that the maximum level of rainout would be 2500 ng l⁻¹ over the Mediterranean and 2000 ng l⁻¹ over the Czech Republic and Southern Germany. However while this is ten times higher than the previously measured background level it is still at least one order of magnitude less than the no observed effect level.

Global warming potential - at first sight the GWP of HFC-1234ze(E) reported by the WMO (2010) has an value of 6 which places it in the “ultra-low” class described earlier. However if a life cycle approach is adopted, for example as described by Abdelaziz et al (2012), then additional factors must be considered. Since the GWP is most relevant to service work, due to direct emissions, the embedded carbon in the manufacture and supply of replacement refrigerant should also be considered. Accurate figures for the CO_{2eq} emissions in the production of “ze” and “yf” are not yet widely available, but it is regularly reported that they are more difficult and more expensive to produce than HFC-134a (see, for example, UNEP, 2010). Every kilogram of “ze” that leaks from a system requires another kilogram to be manufactured. The leaked kilogram has the direct effect of 6kg of CO₂ (on the 100 year time horizon), but the energy-intensive production of the replacement kilogram will potentially require the emission of much more CO₂ at the time of production, and there may also be fugitive emissions of transitional products during the production process. To provide some numbers to anchor this argument, consider a rough estimate that “ze” production results in 20 kg CO_{2eq} per kg of product and “yf” production results in 30kg CO_{2eq} emission per kg. Thus the “true” GWP of “ze” is 26 (still “ultra-low”) and of “yf” is 34 (now just “very low”). Note also that estimates of the CO_{2eq} emission per kg for HFC-134a production range from 10 kg to 70 kg so the true figures for “yf” and “ze” may be much higher than these anchor numbers. Until large scale production plants are on stream and have been in operation long enough for the process to be fine-tuned it may not be possible to improve on these wild guesses. It should be noted that the same could be said of current saturated HFC production, but since the accuracy of the GWP figures provided in the IPCC fourth assessment report (IPCC, 2007) are given as +/-35% the direct and indirect emissions from production processes have never been an issue before. To put this in context the accuracy of the GWP₁₀₀ figure for HFC-134a in IPCC (2007) is 1430 +/-500 so whether the production effect was a further 10 kg or 70 kg of CO_{2eq} has not been significant up to now.

Design considerations for Centrifugal Compressors

Mechanical – the centrifugal compressor described by Conry (2009) is well suited to this development exercise because it contains a minimum number of moving parts, is variable-speed and is oil-free, so lubricant compatibility is not an issue. The compressor is not hermetic; refrigerant is used to cool the electronic drivers and there are several seals within the compressor body, including some o-rings. The standard compressors (with HFC-134a) use Neoprene rings of type C1278-80 but this is not suitable for use with uHFCs. HNBR elastomer 604-70 has been proven to

be suitable for use with “yf”. However further testing by Honeywell showed unacceptable shrinking and hardening when tested with “ze”. Instead the EPDM elastomer 740-75 was selected. This had shown higher swell rates in immersion tests compared with Neoprene or HNBR. The same material was used for the ball valves and the expansion valve o-rings, which were specially made for this application.

Kinetic - The changes in operating conditions for a centrifugal compressor designed for HFC-134a and operating on either “yf” or “ze” are shown in Table 4. This shows that although the molecular weight is identical for the two isomers the properties which determine the compressor performance are very different. The density and enthalpy differences are the result of the different pressure-temperature characteristics, as shown in Figure 1. Table 4 shows that whereas the density of “yf” at compressor inlet is 20% higher than HFC-134a, the reduction in enthalpy difference means that a much higher mass flow is required and so the volume flow rate is only 11% higher than for HFC-134a. On the other hand “ze” has 20% lower density than HFC-134a but a more comparable enthalpy difference, so the volume flow required is 38% higher. The much higher volume flow requirement means that it is not feasible to use the same impellor for “ze” as was used for R-134a because the large increase in inlet and outlet pressure drop would result in significant inefficiencies and constraints on the operating envelope. It was necessary to use an impellor with larger inlet and outlet paths, and therefore to run the impellor at lower speed to compensate for the increase in diameter. The compressor manufacturer had two similar machines in their standard range; one with a nominal capacity of 300kW and a 87kW motor and one with a nominal capacity of 350kW and a 95kW motor. The solution adopted for the compressor for this exercise was to use the larger impellor and casing but to rate it for the lower capacity.

Suction	Density kg m ⁻³	% diff	Evap Δh kJ kg ⁻¹	% diff	massflow kg s ⁻¹	% diff	Vol flow m ³ s ⁻¹	% diff	Mol mass
HFC-134a	17.04	-	130.0	-	1.92	-	0.113	-	102.03
HFC-1234yf	20.52	+20%	97.1	-25%	2.57	+34%	0.125	+11%	114.04
HFC-1234ze(E)	13.57	-20%	118.2	-9%	2.12	+10%	0.156	+38%	114.04

Table 4 – Characteristic properties for a chiller cycle.

Notes: based on a chiller capacity of 250kW evaporating at 5 °C and condensing at 50 °C

It was also necessary to change the compressor capacity map embedded in the speed control software to ensure that the surge and choke limits were correctly positioned. This is a subtle requirement because it would be possible to test a machine on full load and high lift without any problems, but then to run into surge on site as the operating conditions changed, perhaps many months after apparently successful commissioning, resulting in a sudden unexplained failure in the field.

Electrical – the main concern in adapting the chiller design for “ze” was the low flammability classification of the new refrigerant. A risk analysis was conducted, recognising that the compressor poses an additional hazard with regard to flammability due to the large capacitors incorporated into the variable speed drive. However in consideration of the low burning velocity of the refrigerant and the outdoor location implicit in the design of air-cooled chiller there was no risk of ignition if the chiller was in operation outdoors (the airflow is too high) and no risk of ignition if the chiller was not in operation but located outdoors (the unit is freely ventilated and the temperature is not as high). The risk assessment concluded that operation of outdoor aircooled chillers was acceptable, but until further work was done on ignition and combustion it was not appropriate to use the “ze” refrigerant on a chiller located indoors or within a housing. It was therefore recognised that this refrigerant is not yet proven to be suitable for use in water-cooled chillers. The same analysis was conducted for the other electrical components including the electronic expansion valve and the condenser fans, with the conclusion that there was no risk of ignition.

Chiller Design

The key features of this design of chiller were presented to an Institute conference in 2005 (Pearson, 2005). It is designed to minimise leakage by using sealed components wherever possible, reducing the number of instrumentation points by interfacing directly with the compressor and using welded steel pipe and fittings. The expansion valve is a hermetic design, welded into the pipe and with a single static o-ring seal on the body. The shut-off valves are welded and have a bellows seal on the spindle to eliminate refrigerant leakage. This approach is important when considering a switch to uHFC because the refrigerant price is so much higher than HFC-134a, even though the environmental impact of leakage is less. The condenser coils are oriented vertically along both sides of the unit giving a heat exchange surface over the full length and height of the unit. This also ensures turbulent air movement over all parts of the refrigerant circuit so there is no risk of stagnation in the event of a leak.

The design of condenser header was carefully considered with regard to gas pressure drop. It was estimated that the pressure drop would be approximately 1.9 times higher than for HFC-134a, but since the condenser is relatively short for this model of chiller it was concluded that this would not be a problem. However it was noted that this might be a bigger issue in larger chiller models.

Testing and test results

The compressor (Figure 3) was supplied in the second quarter of 2012 and built into a standard 250kW air cooled unit. It was one of a batch of 20 released by the manufacturer for research and development work in original equipment manufacturers' tests. Unlike the standard HFC-134a units these R&D versions were not CE marked, so were not intended to be placed on the market in the European Union.



Figure 3 – Prototype compressor for HFC-1234ze(E).

To enable a range of ambient temperatures to be tested a frame was constructed around the chiller and the sides were covered by tarpaulins. In this way air coming off the top of the chiller could be partially or completely recirculated to the air on faces of the condenser coils. The tests are conducted inside a large production area (50m x 60m) with a clear internal height of over 30m. A schematic of the test loop is shown in Figure 4 and an overview of the test area is shown in Figure 5. The heat load is provided by a set of gas boilers capable of serving up to 1000kW of heat, with variable speed pumps in the chilled water circulation loop which can be set to match the design water flow requirement.

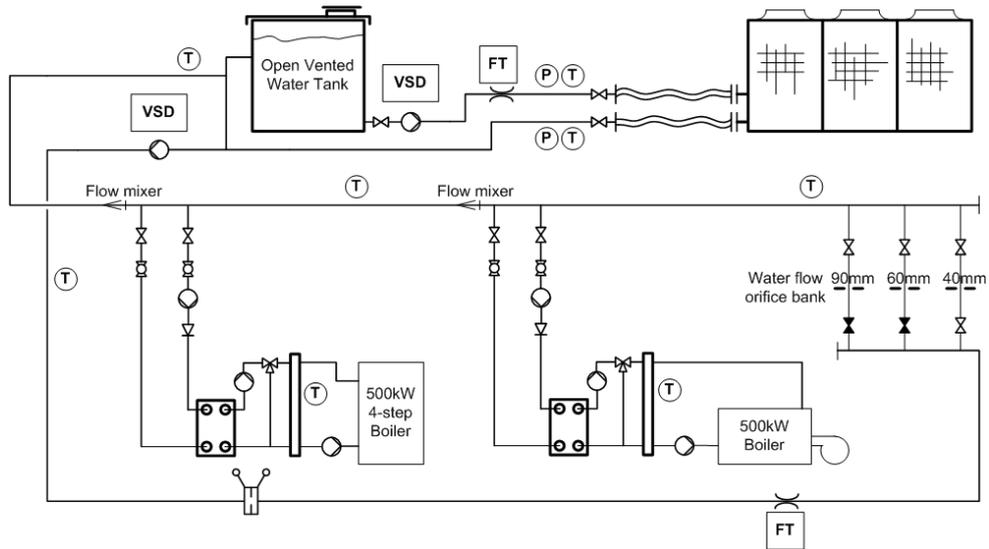


Figure 4 – Schematic of the test loop.

Readings were taken over several days and with a range of air inlet temperatures from 20 °C to 45 °C during which time the background air temperature was around 20 °C. The chiller is designed to give a capacity of 250 kW in an outdoor ambient of 35 °C.



Figure 5 – chiller test set up (without the top tarpaulin).

A summary of the capacity and efficiency results of several days' tests is presented in Figure 6. This shows capacity (blue diamonds) on the left hand vertical axis and coefficient of performance (dark red squares) on the right hand vertical axis.

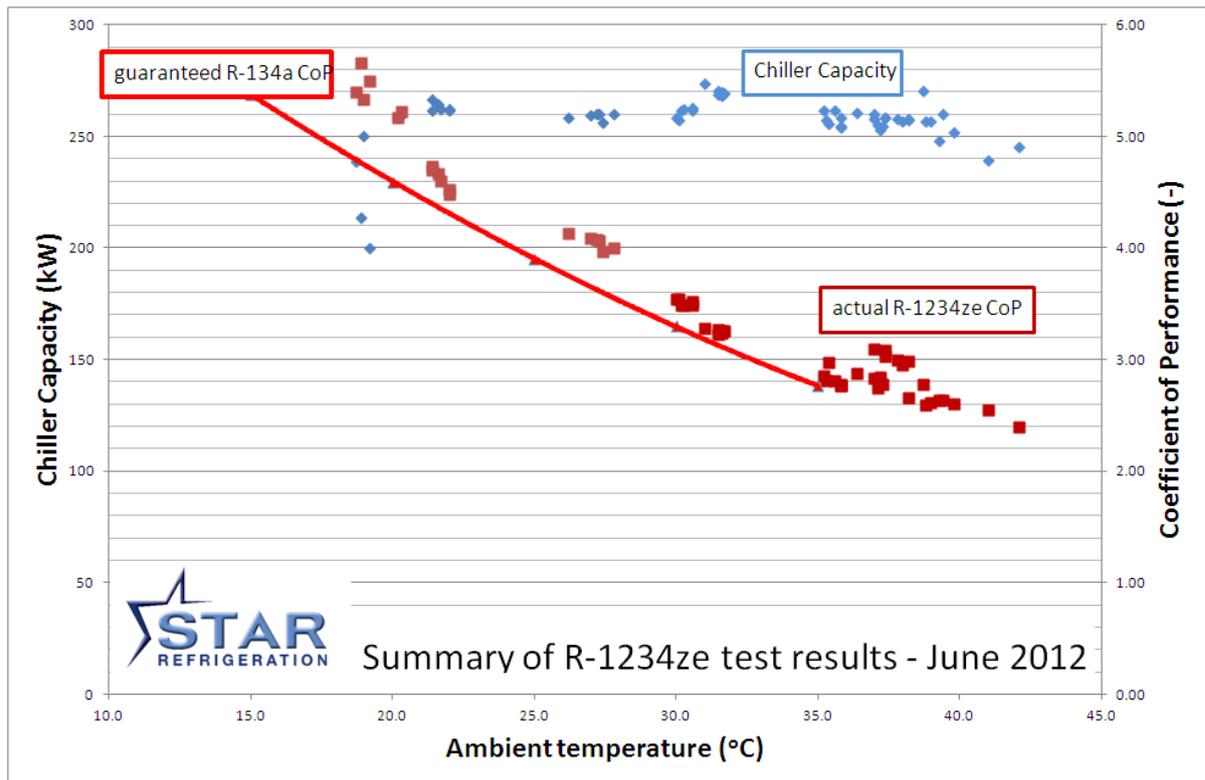


Figure 6 – Capacity and efficiency results.

It can be seen that across the range of ambients from 20 °C to 45 °C the cooling capacity of the unit was almost constant and in all cases exceeded the design capacity except when the ambient was over 40 °C. There were also a few part load tests at 20 °C ambient. The coefficient of performance fell as the ambient increased, as would be expected, but in all cases the CoP exceeded the value that would be guaranteed to a customer for an HFC-134a chiller, as shown by the solid red line. This means that the scatter of HFC-1234ze(E) results are in the same range as would be expected when testing an HFC-134a chiller under identical circumstances.

After the factory tests were completed the unit was shipped to the Honeywell site in Buffalo, NY, where it was installed in the chilled glycol loop serving the laboratory air-conditioning systems. After adjusting for the glycol solution the unit was commissioned in the late autumn and the performance was reconfirmed. Since then it has been shut-down over the winter and will be restarted in a few weeks.

Barriers to Further Progress

Commercial – the compressor is not yet available for sale in the EU as it has not been CE marked. The manufacturer has to satisfy themselves that all aspects of the safety requirements of appropriate legislation are appropriately covered with regard to the flammability of the working fluid. However, since the CE mark indicates conformity to a wide range of European directives including the Low Voltage directive and the Electromagnetic Compatibility directive, an equipment manufacturer wishing to market the (unmarked) R&D compressors in the EU would need to prove conformity to all other requirements of all relevant directives not only the items concerning refrigerant flammability. Therefore the compressors will not sell in Europe in significant numbers until they are suitably CE marked by the compressor manufacturer, which is expected by mid-summer 2013.

The refrigerant was said to be widely available as a foam-blowing component in Europe, but when it came time to buy the refrigerant early in June 2012 it was difficult to get sufficient quantity for this unit (six 40 kg bottles). This was due to the difficulty of supplying product in refrigeration cylinders

from another part of the business which is used to supplying tonnage quantities and does not indicate any expected difficulty in this respect in the long term. There were no concerns about the commercial price or availability of any other components of the system, although the need to fit special o-rings is a slight hindrance.

Technical – there were no unexpected difficulties in operating the chiller with the unsaturated HFC. The evaporator pressure drop was not excessive and the condenser also performed well. The only concern with regard to implementation of HFC-1234ze(E) to existing chillers is that having used the larger compressor body to deliver the nominal duty of the smaller HFC-134a machine, the new compressor cannot be fitted to existing chillers without some site modification of pipework. The two models are tantalisingly similar, with identical foot and suction flange sizes and positions, but the discharge flange, although the same size on both models, is displaced by 6mm on the larger model. A user of an existing HFC-134a chiller is therefore faced with the choice of changing the pipework on his unit to accommodate the different discharge line and maintaining the chiller capacity or retrofitting the existing compressor with new o-rings and new performance map software and accepting a 20% - 25% reduction in capacity, albeit in this case with a substantial improvement in CoP.

Legislative – there are no barriers to the adoption of “ze” as a refrigerant in the European Community even though it is not explicitly listed in the current version of EN378:2008+A1 amendment, 2010. The standard provides a methodology for determining the safety class of any fluid not listed (Annex F of part 1) and following this procedure demonstrates that HFC-1234ze(E) is a class A2 fluid. There are clear rules for applying A2 fluids (Annex C of part 1), which indicate that an air-cooled chiller located outdoors would have no restriction of charge. The requirements for a machinery room are less clear as it is not certain whether the methods applied for ammonia machinery rooms according to part 3 of EN378:2008 would apply in the case of “ze”. This will be clarified in the next version of the standard which is likely to be published in 2014 or 2015 and will probably include the subclass 2L for flammability.

Next steps – The chiller has been out of service for the winter season (the average low temperature in Buffalo in January is -8 °C) but will be recommissioned for the summer season in a few weeks time. It will be monitored over the summer to check for performance and any abnormal operation. The compressor range will be launched (with CE mark) mid-2013. When larger chillers are constructed the condenser and evaporator performance will need to be verified to ensure there is no adverse effect of increased pressure drop.

Conclusions

The phase-down of higher GWP fluids is likely to be introduced in stages over the next five years, either by inclusion in the Montreal Protocol or through European legislation. The extent to which this is applied will depend in part on the availability of alternative technologies. The GWP classification metric proposed in this paper indicates that further restriction beyond the initial proposal is highly probable.

The chiller met our expectations in terms of capacity, performance and control stability. It exceeded expectations on capacity at ambient temperatures above the design point. Provided components are made available at reasonable cost and the refrigerant is also reasonably priced HFC-1234ze(E) will be a suitable ultra-low GWP alternative for HFC-134a in variable-speed centrifugal compressors. The new model of compressor is due to be placed on the market some time over the summer of 2013 and there do not seem to be any technical barriers to this.

The refrigerant cost is likely to remain higher than current HFC-134a prices for a long time, possibly for ever. This increases the importance of leak prevention methods such as those embodied by design in this style of chiller. More information is needed on the true environmental impact of unsaturated HFCs, but the signs so far are encouraging. Flammability is likely not a major concern

based upon recent research on ignition and combustion provided reasonable precautions are followed. Short-term toxic products of combustion remain an issue for large systems but location in the open air provides sufficient mitigation. There is a need to simplify the classification system in safety standards for flammability.

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