Refrigerant Selection for Sustainable Future

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Abstract

Many people perceive that pursuing alternative substance or technology with zero ozone depleting potential (ODP) will be a long-term solution and is the best way to protect the environment since the Montreal Protocol has been enforced to phase out all ozone depleting refrigerants that have been commonly used in air-conditioning. While the consequence of Climate Change issue is better known today, this argument will be challenged because of future sustainability concerns. With reference to the recent scientific findings, it is discussed in this paper through integrated environmental approach. In particular, various approaches in refrigerant selection for air-conditioning use in the building industry are reviewed. Impact of the zero-ODP approach on global warming and energy efficiency will then be debated with reference to competent research or scientific evidence existed in literature. Other possible non-zero ODP options are also evaluated and compared.

Sustainable building, whole building or green building has received more attention nowadays and a lot of building owners are willing to obtain proper certification as a branding effect. Different green building rating systems have been investigated, especially regarding the environmental assessment to refrigerant selection. This paper will be concluded with an environmentally balanced recommendation.

Keywords: Refrigerant selection, HVAC, Energy Efficiency, Sustainability, Environmental policies

1. Introduction

Refrigerant development has a long history. The first generation of refrigerants was introduced in the 1830s, with invention of the vapor-compression machine by Perkins.[1] Most of them are toxic, flammable, or both. Some refrigerants, such as sulfuric (ethyl) ether, ammonia and hydrocarbons were highly reactive. Many accidents occurred as the primary goal was only to provide refrigeration at that time. Later, another goal on durability was added. Propane was marketed as the odorless safe refrigerant.[2] As production increased following World War I, more attention was paid to safety and performance. Fluorinated refrigerants like chlorofluorocarbons (CFCs) came into place following the invention of positive displacement centrifugal compression machines in early 1930s. DuPont's "Freon" products (e.g. CFC-11, CFC-12, HCFC-22) are probably the most well-known fluorocarbon refrigerants for the refrigeration and air-conditioning industry. These refrigerants are stable with low toxicity and flammability. For almost half a century, fluorocarbons have been the dominant choice of refrigerants until they were associated with the "ozone hole" story – the first global environmental problem identified by Molina and Rowland.[3] Since then, a landmark international treaty, i.e. the Montreal Protocol,[4] was set up in 1987 to protect the ozone layer. Chlorinated and brominated refrigerants, along with similar solvents, foam blowing agents, aerosol propellants, fire suppressants, and other chemicals are scheduled to be phased out. Ozone depletion was the only environmental concern at that time.

2. Environmental considerations

Since the only focus was ozone layer protection in late 1980s, European took an aggressive political position and moved quickly to phase out all substances that carry any ozone depletion potential (ODP). This was then adopted by many European firms as their company policy to demonstrate their green image or environmental responsibility.

As a result, the market moved very quickly from CFCs to hydrochlorofluorocarbons (HCFCs) and then hydrofluorocarbons (HFCs) which are zero ODP practically. Unfortunately, this is an unhealthy move or mainly a commercial response rather than being environmentally responsible. Note that the ozone depletion is not the only environmental issue. In fact, zero ODP policy is expensive for energy efficiency and global warming or climate change. For instance, a centrifugal chiller designed for using HCFC-123 as the refrigerant is far more efficient than that designed for HFC-134a. The best to best comparison can be up to 15% difference at the time being. There is potential to increase up to 18% or even higher.[5] This significant difference is not only due to thermodynamic

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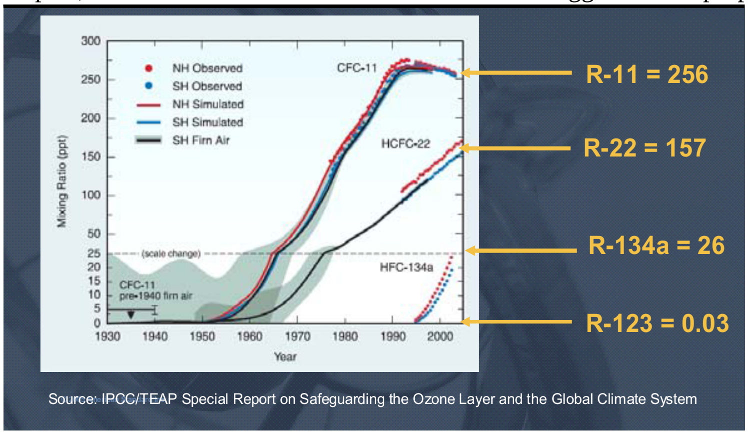
characteristics of the refrigerant itself, which accounts only for 4.5%. Both the outgoing CFC-11 and its replacement HCFC-123 chillers are designed for multistage compression with direct-drive hermetic motor. The multistage-economizer technology would raise the efficiency by 3 to 7%, depending on the number of compression stages and direct-drive, avoiding a 2 to 4% loss in mechanical efficiency inherent to gear-drive compressors. Besides, the actual efficiency in building air-conditioning applications may be combined with reduced energy requirements for associated water circulating pumps as well as optimization with the cooling towers. Best practice examples can be found in China.[6]

Today, global warming is receiving more and more attention. It is believed that global warming has caused climate change. Its impact to the environment is far more significant than ozone depletion. The impact involves not only the scientific aspect, but also socio-economic and political. The associated international treaty "Kyoto Protocol" was signed ten years after the Montreal Protocol but not fully ratified until 2005. The objective of the Kyoto Protocol is to reduce greenhouse gas emissions that are affecting the climate. Evidence showed that the solutions are technically available today and are economically viable. For example, buildings built today are 50% more efficient than most existing buildings built in 1980s in China. Chiller efficiency has been improved 35% over the past 30 years. The minimum U.S. standard for residential air conditioners and heat pumps is 12 SEER (seasonal energy efficiency ratio), though 19 SEER products are commercially available. The United Nations press release for Kyoto Protocol indicated that:

"It (The Protocol) creates new incentives for technological creativity and the adoption of *no-regrets* solutions that make economic and environmental sense irrespective of climate change. Because activities and products with zero or low emissions will gain competitive advantage, the energy, transport, industrial, housing, and agricultural sectors will gradually move toward more climate-friendly technologies and practices."

The "no-regrets" opportunity is known as to invest in the highest possible energy efficiency that pays back through its useful life – basically shifting to a life cycle costing purchasing approach, and away from a first cost approach. Obviously, not all of us purchase this way today.



Source: IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System

Fig.1 Observed global atmospheric concentration trends (from IPCC 2005)

The selection of a good environmental refrigerant today is not as easy as in the 1980's when the only environmental issue of concern was ozone depletion; and merely selecting a zero ODP chemical seemed like the natural choice. HFC-134a refrigerant is a good substitute for CFC-12 that has been phased out under Montreal Protocol; and also it can be one of the viable solutions to substitute some of the applications currently using HCFC-22 that is scheduled to be phased out. However, a recent scientific report [7] showed that the atmospheric concentration of HFC-134a has been increasing dramatically in the past decade as shown in Fig. 1. This is due to several factors, including the use of R-134a in highly emissive applications such as metered dose inhalers, fire suppressants and propellant. Additional emissions can be credited to the automotive industry, which has traditionally struggled to restrict refrigerant leakage for this application. In fact, such alarming observations suggested that proper measures are required to slow down the growth, both its use and emission control. In the same report, however, the atmospheric concentration of HCFC-123 is practically negligible. Possible reasons are discussed below.

HFC-134a has a relatively high global warming potential (GWP), though the ODP is practically zero. The European Union (EU) passed a resolution in March 2006 to ban the use of HFC-134a in mobile air-conditioning (MAC) effective from 1 January 2011. To be more specific, no new vehicles are allowed [8] to use HFC refrigerants with GWP greater than 150. A similar proposal to ban all HFC (as one of the six greenhouse gases being regulated under Kyoto Protocol) refrigerants in stationary air-conditioners by 2010 was voted down earlier. This proposal might be revisited in 2008, depending on the effort made by the industry in HFC refrigerant containment, recovery, certification and reporting.

As shown in Fig.1, the atmospheric concentration of HCFC-123 is only 0.03 ppt (i.e. 867 times lower than HFC-134a) because of its extremely short atmospheric life (1.3 years) and near-zero emission in chiller applications (e.g. 0.5% included refrigerant loss in annual service). This is consistent with the UNEP review of ozone depleting substances (ODSs) published in 2003. It was specifically acknowledged that: [9]

"Refrigerant HCFC-123 has a favorable overall impact on the environment that is attributable to five factors: low ODP, very low GWP, very short atmospheric lifetime, extremely low emissions of current

designs for HCFC-123 chillers, and the highest efficiency of all current options.

Based on integrated assessments, considering the tradeoffs between negligible impacts on stratospheric ozone and important benefits in addressing global warming, these studies recommend consideration of a phase-out exemption for HCFC-123".

3. Safety and other considerations

One of the well-known balance environmental assessments [10] is shown in Fig. 2. A fair side-by-side comparison of ODP and GWP values is suggested. A refrigerant with the lowest resultant environmental impact to ozone depletion and global warming might be the best choice. For instance, HFC-152a has zero ODP and very low GWP. It is an option to substitute HFC-134a for mobile air conditioning (MAC) in vehicles under research in the U.S. as well as in some European countries.[11] However, this chemical is flammable. The safety measure is the key consideration for practical applications; and therefore, it is not considered as a viable option in some countries like Japan. Obviously, it is not a viable solution for large commercial chillers at least in the near future. Thus, environmental aspect should be considered together with the basic criteria such as safety.

Some may suggest HFC-245fa be an option to substitute HCFC-123, but according to the Technical and Economic Assessment Panel (TEAP) for Montreal Protocol: [12]

"HFC-245fa has operating pressures higher than for HCFC-123 and CFC-11 but lower than for HFC-134a. Its use requires redesign of compressors to match its properties, a common requirement for this type of compressor. In addition, the heat exchangers in an HFC-245fa chiller must be designed to meet pressure vessel codes, unlike those for CFC-11 and HCFC-123".

Since the operating pressure of HFC-245fa is higher than atmospheric, achieving near-zero emissions will be more challenging than in HCFC-123 chillers which operate under virtually no pressure and even a slight vacuum because HCFC-123 is a liquid at room temperature, very safe in case of accidental leakage.

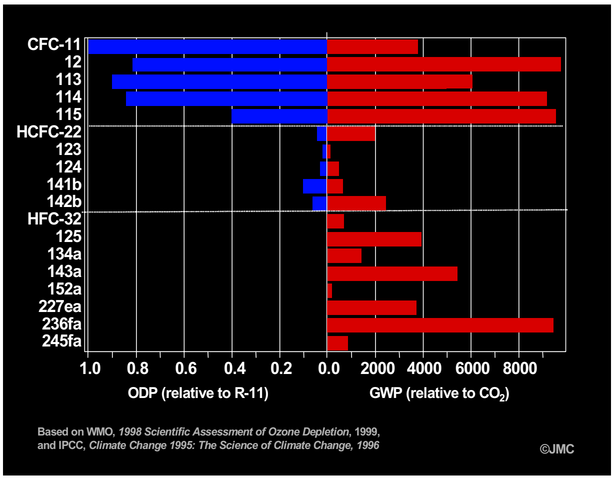


Figure 2: Balanced environmental judgment of common refrigerants (Clam and Didion 1997)

Coupled with relatively high GWP for HFC-245fa of 1020 (HCFC-123 = 76), longer atmospheric life of 7.6 years (HCFC-123 = 1.3 years) and importantly, its lower energy efficiency, HFC-245fa is not an acceptable alternative to HCFC-123.

Hydrocarbons, carbon dioxide, and ammonia are so called "natural refrigerants" which have been suggested as replacements for HFCs and HCFCs in some countries. Unfortunately, carbon dioxide is used for low temperature refrigeration. Although being currently under research by some MAC manufacturers, it is a high pressure gas that is less than half as efficient if compared with R-123. Hydrocarbon refrigerants can be found in some domestic refrigerators from Europe and in a few small stationary air conditioning units where the quantities used are strictly within safe limits due to high flammability in nature. Compared with hundreds of kilograms of charge needed in a chiller, plus significant difference in compressor construction, hydrocarbons are far too risky to be an option.[5]

Ammonia is flammable, as well as a primary eye and upper respiratory tract irritant,[13] which results in regulatory restrictions in many countries which limit its use.

4. Balanced and integrated methodologies

From sustainability point of view, refrigerant selection simply based on zero-ODP or addressing only ozone depletion issue is no longer environmentally responsible. It is at least equally important to address global warming and energy efficiency. Today, engineers and building professionals are challenged by the atmospheric scientists to take a balanced approach in selection of building materials, equipment and systems.

Recently, a prestigious science symposium of UNEP concluded that: [14]

"*We can further protect the ozone layer by accelerating the pace of phase outs. However, the acceleration can consider the impact of greenhouse gas accumulation.*

For example, HCFC-123 could be allowed in specific air conditioning applications where its use promotes superior energy efficiency and assures near-zero refrigerant emissions".

Well attended by atmospheric scientists from Australia, Czech Republic, Egypt, Mexico, Netherlands, Togo, U.K. and U.S., this symposium was chaired by Prof. Molina, who received the 1995 Nobel Prize in Chemistry (with Rowland and Crutzen) for pioneering ozone depletion science.

Green building or sustainable construction is being actively promoted in some countries. For instance, the central government of China is using it strategically to conserve natural resources particularly energy and water. While different country has different rating standard for green building, most of them do contain an environmental assessment of materials, equipment or system selection. HK-BEAM, mainly used in Hong Kong, specifies refrigerants with an ODP of 0.03 or less AND a GWP of 1600 or less.[15] Greenmark, mainly used in Singapore, recognizes refrigerant leak detection system installed to cover high-risk parts of the plant.[16] Greenstar, mainly used in Australia, gives additional credit to hermetic or semi-hermetic chillers with low pressure refrigerant and high efficiency purge.[17]

Leadership in Energy and Environmental Design (LEED) of the U.S. Green Building Council (USGBC) has been used as a standard for green building certification in the U.S. as well as internationally including Canada, China and India. A new environmental assessment on refrigerant selection, that has been adopted since January 2005, was recommended by its Technical and Scientific Assessment Committee (TSAC) after years of research on environmental impact of commonly used HVAC refrigerants.[18] The life-cycle ozone depletion index *LCODI* (in lbCFC-11/RT·year) and life-cycle direct global warming index $LCGWI_d$ (in $lbCO_2$/RT·year) of the refrigerant used by HVAC system for a building, normalized per refrigeration ton of cooling capacity and per year of design equipment life, are calculated by the following two equations respectively.

$$LCODI = \frac{ODP_r \times R_c \times (L_r \times Life + M_r)}{Life} \quad (1)$$

$$LCGWI_d = \frac{GWP_r \times R_c \times (L_r \times Life + M_r)}{Life} \quad (2)$$

where:

GWP_r = Global Warming Potential of Refrigerant, $0 < GWP_r < 12{,}000$ $lbCO_2/lb_r$

ODP_r = Ozone Depletion Potential of Refrigerant, $0 < ODP_r < 0.2$ lbCFC-11/lb_r

L_r = Refrigerant Leakage Rate (% of charge per year) $0.5\% < L_r < 3\%$/Year

M_r= End-of-life Loss (% of charge) 2% < Mr < 10 %

R_c = Refrigerant Charge (lbs refrigerant per ton of cooling capacity) $0.9 < R_c < 3.3$

Life = Equipment Life (Years) 10 < Life < 35 Years

RT = refrigeration ton

Subscript "r" stands for refrigerant, "d" for direct emission.

A performance-based comparison was suggested:

$$LCGWI_d + LCODI \times 100{,}000 \leq 100 \quad (3)$$

The two important factors are the leakage rate L_r and the refrigerant charge R_c. These variables impact the formula significantly and become key areas of contention from the manufacturers. Various refrigerant performance data points are plotted as shown in Fig. 3. Those scored 100 or less with the formula above (or the points under the 100-line) should get the credit. All the refrigerants have some data points lying outside the acceptable region. They are mostly high leak and high refrigerant charge applications.

5. Conclusion

While ideal refrigerants with zero ODP and zero GWP have not yet come to existence, comprehensive assessment, such as the one derived by the TSAC of USGBC, is necessary for a sustainable future. Not only that it is a scientific approach with balanced integrated consideration of the key environmental impacts, but also it has incorporated an important concept of life-cycle impact which is more environmentally responsible, esp. to our future generations. Table 1 summarized the key environmental properties of the refrigerants commonly used by the industry. [19]

Refrigerant selection based on a simple approach of 'zero ODP' will have to pay high cost to both global warming and energy efficiency. Using this single criterion is no longer environmentally acceptable today. The alarming increase in atmospheric concentration of HFC-134a suggested careful considerations of not over-using of any single compound for substituting ODSs.

Based on integrated assessment of ODP, GWP, atmospheric lifetime, energy efficiency and leakage, some HCFC refrigerants such as HCFC-123 has been suggested by atmospheric scientists for longer-term use in specific air conditioning applications where superior energy efficiency with near-zero refrigerant emissions can be achieved.

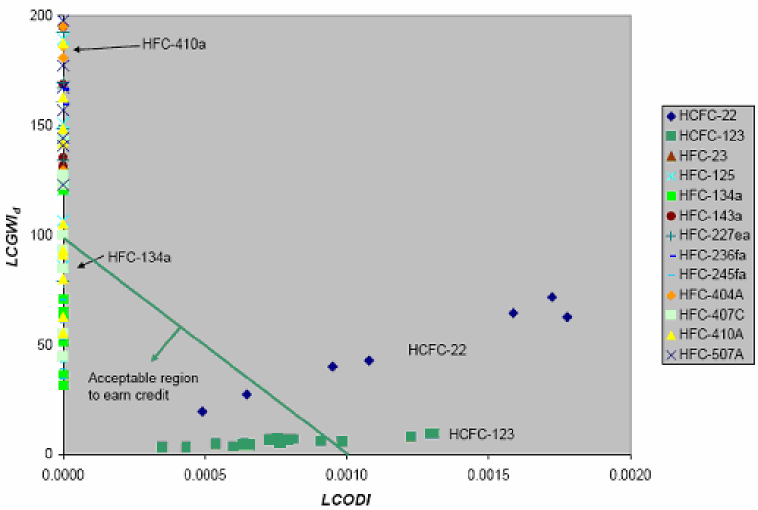


Figure 3: Environmentally balanced assessment of refrigerants (USGBC 2004)

Table 1. Environmental Properties of Common Refrigerants
(WMO 2003)

REFRIGERANT	Ozone Depleting Potential (steady-state)	Atmospheric Lifetime (years)	Global Warming Potential (100-Year)
CFC-11	1 (index)	45	4,680
CFC-12	1.0	100	10,720
HCFC-22	0.05	12	1,780
HCFC-123	0.02	1.3	76
HFC-134a	~0	14	1,320
HFC-23	~0	270	12,240
HFC-125	~0	29	3,450
R-407C (HFC blend)	~0	~29	1,674
R-410A (HFC blend)	~0	~29	1,997

Notes:
a) Source: Montreal Protocol Science Assessment of Ozone Depletion 2002
b) ~0 means practically zero, upper limit of HFC-134a <1.5 × 10^{-5}, HFC-23 <4 × 10^{-4}, HFC-125 <3 × 10^{-5}
c) R-407C and R-410A are blend refrigerants of R-134a, R-32 and R-125. Highest value among the components (i.e. R-125) is considered for the atmospheric lifetime.

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