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Review Article

Performance Study of Reciprocating Compressor with Eco-Friendly Refrigerant- A Review

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Abstract

This paper represents review with the issue of CFC substitution in small reciprocating compressor for domestic appliance. Most of early effort CFC phase out has been led to HFCs, HCs and their mixture. Performance of reciprocating compressor is increased by using different eco-friendly refrigerants. Performance in term of compressor capacity, compression ratio, volumetric efficiency, isentropic efficiency, refrigeration capacity, compressor work is evaluated for the investigated refrigerant at various evaporating and condensing temperatures. The system performance increases as the evaporating temperature increases, but reduces as the condensing temperature increases. Eco-friendly refrigerant R-134a and R-152a have thermodynamics performance similar to R-12 and also 152a offers the best desirable environmental requirements, Zero ozone depleting potential and very low global warming potential (GWP) while HCs has no ODP and negligible GWP than CFCs/HCFCs and better miscibility with mineral oil and POE.

***Keyword**: Reciprocating compressor, eco-friendly refrigerant, lubricating oil*

1. Introduction

A compressor is considered as the heart of any vapour compression refrigeration system, because It pump the refrigerant through the system similar to the heart which pumps the blood through body. It has higher cost (typically 30 to 40 % of total cost) as compare to other component in VCRS. The function of a compressor is to continuously draw the refrigerant vapour from the evaporator, so that a low pressure and low temperature can be maintained in the evaporator at which the refrigerant can boils extracting heat from the refrigerated space. The compressor then has to raise the pressure of the refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser.

2. Design feature of reciprocating compressor

Reciprocating compressor is an important component of the refrigeration and air-conditioning industry. It is the most widely used with cooling capacities ranging from a few watts to hundreds of kilowatts. Modern day reciprocating compressor are high speed (≈3000 to 3600 rpm), single acting, single or multi-cylinder (up to 16 cylinder) type. The most widely used compressors (for halocarbons) with external derive are open, semi hermetic or bolted hermetic, welded-shell hermetic. Open type compressors the rotating shaft of the compressor extends through a seal in the crankcase for an external derive. Ammonia compressor is manufactured only in the open design because of the incompatibility of the refrigerant and hermetic motor materials. Most automotive compressors are also open-derive type. Hermetic compressors, motor and the compressor are enclosed in the same housing to prevent refrigerant leakage. It is permanently sealed with no access for servicing internal parts in the field, with the motor shaft integral with compressor crankshaft and the motor in contact with the refrigerant. These compressors are used in small systems such as domestic refrigerators, water coolers, air conditioners etc. A semi hermetic compressor also called bolted, accessible, or serviceable compressor. These type of hermetic units, the cylinder head is usually removable so that the valves and the piston can be serviced. Single-stage compressors are primarily used for medium temperature (-20 to 10˚C) and in air conditioning applications, but can achieve temperatures below -35˚C for refrigeration applications with suitable refrigerants. Booster compressor are used for low temperature applications with R-22 or ammonia .integral two stage compressors achieve low temperatures (-30˚C to 60˚C) using appropriate refrigerants within the frame of a single compressor ASHRAE (2008).

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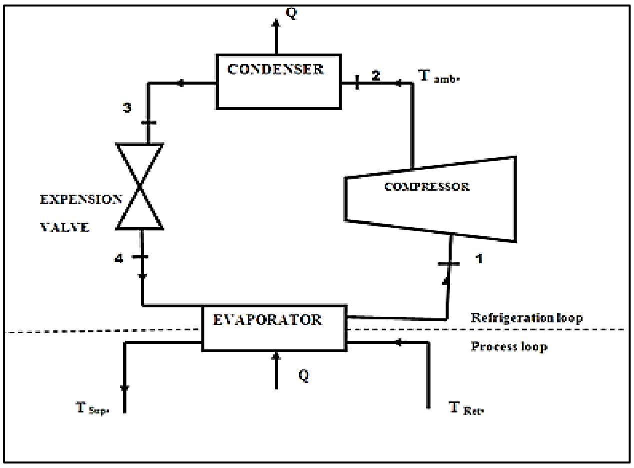


Fig.1 Basic cycle of domestic refrigration system

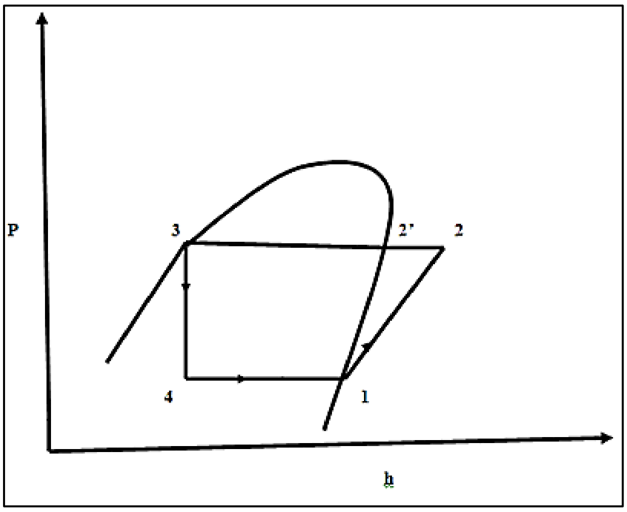


Fig. 2 P-H diagram of domestic refrigration system

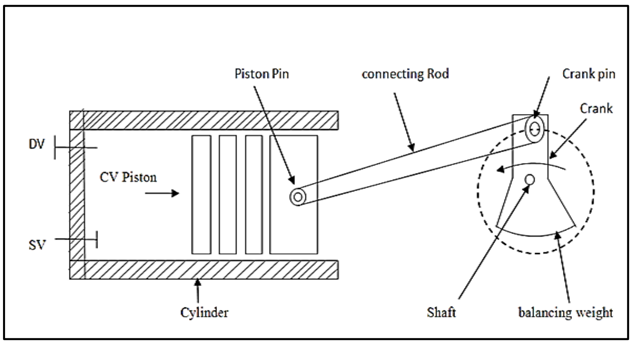


Fig.3 Schematic of reciprocating compressor

3. Improvement in reciprocating compressor

3.1 Special devices in compressor

In many applications, it is necessary to be able to reduce the capacity of the compressor to meet changing process needs. The most commonly capacity control used methods are opening the suction valves by some external force, gas bypassing within the compressor, suction shutoff, gas bypassing outside the compressor and changing compressor speed. Heater is used for remove the frost. When it is possible that refrigerant can accumulate in the compressor crankcase (cold start, gravitation, etc), dilute the oil excessively, and result in flooded starts, a crankcase heater should be used. Internal centrifugal separator-compressors are equipped with antislug devices in the gas path to the cylinders. This device centrifugally separates oil and liquid refrigerant from the flow of foam during a flooded start and thus protects the cylinders. Oil separators are reduced the amount of oil discharged into the system by the compressor and to return oil to the crankcase. ASHRAE (2008)

3.2 Lubricant oil in compressor

In hermetic unit oil is charged only once for the life-time of the unit (minimum five years). It should be chemically stable in the presence of the refrigerant, metals, winding, insulation and extraneous contaminants. The oils of mineral origin contain paraffin's, napthene , aromatics and non-hydrocarbons. Paraffinic and naphthenic oils are saturated. They have excellent chemical stability but poor solubility for refrigerants such as R-22, R-502, etc. and are poor lubricants. Aromatics have good solubility and lubrication properties. Non-hydrocarbons are the most reactive but are good for lubrication. The limited solubility of mineral oil with R-22 and R-502 originally led to the investigation of synthetic lubricants. In more recent times, the lack of solubility of mineral oils in no chlorinated fluorocarbon refrigerants, such as R-134a and R-32, has led to the commercial use of some synthetic lubricants.

Gunderson and Hart (1962) describes a number of commercially available synthetic lubricants such as synthetic paraffin's, polyglycols, dibasic acid easters, nonpentyl easters, silicones, silicates easters and fluorinated compound. At recent time three most commonly used synthetic lubricants are alkylbenzene, for R-22 and R-502 service, and polyglycols and polyol easters, for use with R-134a and refrigerant blends using R-32. ASHRAE (2006)

3.3 Lubricant selection factor

Miscibility/solubility is one of the key factors to selection of lubricant. Life of any compressor depends upon the miscibility of oil. The refrigeration oil shall have such several features that miscibility is good at low temperature and chemical reactions do not occur in spite of contacting with refrigerant at high temperature different oil is used with different refrigerants with CFC-12 and HFC-134a refrigerants synthetic oil is used which may be hazards for human health mineral oil provides better miscibility with new refrigerants like R-152a and HC refrigerants. POE oil is used with azeotropic refrigerants like R-401a,R-404a,R-407c,R-410a.minral and POE oil are environmental friendly oils, compressor works economically with these refrigerants less power is consumed and COP is increased.

Table 1 Mutual solubility of refrigerants and mineral oil ASHRAE (2006) [0]

Completely miscible	Partially miscible			Immiscible
	High miscibility	Intermediate miscibility	Low miscibility	
R-11	R-123	R-22	R-13	Ammonia
R-12		R-114	R-14	CO_2
R-113			R-115	R-134a
			R-152a	R-407C
			R-C318	R-410A
			R-502	

4. Literature review

Fabian Fagotti compared the performance parameter of reciprocating compressor using R-12, R-134a, R-152a,R-290,R-600,and R-600a.and considering Compressors with the same ideal refrigerating capacity. Finally it is concluded that HC290 shows superior performance Characteristics. R.C.Prasad *et al*. compare the performance of vapour compression refrigeration system using HFC-134a and CFC-12.It is found that the HFC-134a is slightly interior to the CFC-12 due to a higher exergy loss with HFC-134a. C. Aprea *et al*. Compared the performance of R-22 and its drop-in-substitute R-407C in a vapour compression refrigeration plant using a semi-hermetic compressor in a purpose built rig . His results have revealed that R-22 performs better than R-407C. C.Aprea *et al*. evaluated the energetic performances when the compressor refrigeration capacity is controlled varying its speed. And these energetic Performances have been compared with most suitable substitutes (R-507,R-407C,R-417A) of the R-22.and found that R-407C is the better substitutes of R-22 Comparison to other refrigerant. E.Navarro *et al*. carried out the comparison between R-407C and propane on five positive displacement hermetic reciprocating compressors covering different capacities, displacement ,Stroke to bore ratio, and number of cylinder .The found that COP improvement of 9% when using propane instead of R-407C. Marie- Eve Duprez *et al*. calculates the mass flow rate and power consumption by developing thermodynamically realistic models of the two types of compressors(reciprocating and scroll compressor) with using R-134a, R-404A, R-22, R-12,and R-407C.finally he found that average discrepancies on mass flow rate and power consumption for reciprocating compressor are 1.10% and 1.69%.and for scroll compressors the average discrepancies on mass flow rate and power are 2.42% and 1.04% .E . Navarro *et al*. carried out the performance of a series of compressors with different capacities and geometries working with propane as refrigerant .and also compared the propane and R-407C for one compressor. B.O.Bolaji provided study is carried out of reciprocating compressor performance using five ecofriendly refrigerants(R-23,R-32,R-134a,R-143a, R-152a) in comparison to R-12 .his results shows that only COP of R-134 andR-152a is close to R-12 with 6.6% and 3.1 % reduction respectively. Refrigeration capacity of R-152a 4.9%higher than of R-12.and volumetric efficiencies obtained 75.8%, 74.4%, and 77.9% for R-12, R-134a, and R-152a respectively. Finally he is found that R-134a and R-152a are the best substitutes of R-12. B.O.Bolaji designed and developed a refrigerator that is work with R-134a and Its performance compared with R-152a and R-32.and he found that average COPof 152ais 4.7% higher than that of R-134a while average COP of R-32 is 8.5% lower than that of R-134a .and system consumed less energy when 152a was used. Enrico, Da Riva *et al*. carried out performance of a semi-hermetic reciprocating compressor working with propane as the refrigerant and compared the performance both with and without an internal heat exchanger between the vapour suction line and liquid line, at different settings of expansion valve. Without the IHX suction superheating was varied from 4 k upto14 k, while with the IHX suction superheating varied from 20 K up to 35 K. The suction superheating is to improve volumetric efficiency and global efficiency.

Table 2 Theoretical and Experimental investigations for Eco-friendly refrigerant

AUTHOR	APPROCH	OBJECT	RANGE OF PARAMETERS	REFRIGERANT	CONCLUSION	REMARK
Fagotti F (1994)In. Comp. Engg. Con.	Computer simulation	Performance Evaluation of reciprocating compressors operating with Hydrocarbon Refrigerants	V_p=5.0 cm^3	R-12	HC-290 Shows Superior Performance Characteristics.	HC-290 is a Flammable refrigerant.
			T_c=54.4˚C	R-134a		
			T_e= -40˚C to 20˚C	R-152a		
			T_{sup} =32.2˚C	R-290		
				R-600		
				R-600a		
Prasad R.C. et al.	Computer Simulation	Simulation of a vapour Compression Refrigeration cycles using HFC-134A	Q= 1KW	R-12	Performance of HFC-134a is slightly less than R-12.and Total Exergy loss of the actual system increases when R-134a is used instead of R-12.	Actual cycle has-been used with heat exchanger.
-1999			T_e=0 to -20˚C	R-134a		
Heat& mass transfer			T_c = 40˚C ,η_v=0.7 L= 4m ,			Total exergy loss is due to the expansion device and compressor.
			D_i =10mm, d_o=16mm			
			$T_{Cold\ room}$=0˚C			
			$T_{Environ.}$=25˚C			
Apera et al.(2003)	Experimental analysis	Performance Evaluation of R-22 and R-407C in a vapour compression plant with reciprocating Compressor.	T_e = -30 to -5˚C	R-22	It revealed that R-22 performs better than R-407C.	R-22(1790) has higher GWP.
Applied Thermal Engineering			T_c = 35˚C	R-407C	R-22 has isentropic efficiency 6-14% and Volumetric efficiency 3-7%better than of R-407C.	
			Q =1.6 - 5 KW			
			$T_{w\ out,\ co}$=			
			28-42˚C			
Apera et al.(2004)	Experimental analysis	An evaluation of R-22 substitutes performances regulating continuously the compressor refrigeration capacity.	Current frequency varies 30 -50 Hz.	R-22	Volumetric efficiency and isentropic efficiency of R-407C is better than R-507 and R-417A.	R-407C has lower GWP (1700).
Applied thermal Engg.			Nominal frequency =50Hz,	R-407C		
			T_e = -20 to 10˚C ,	R-417A	R-407 allows the highest energy saving after that R-22.	
			T_c =35˚C	R-507		
			Q = 1.4 to 4.4KW			
			$T_{cold\ store\ air}$ =0˚C			
			$T_{outdoor\ air}$ =32˚C			
Navarro E et al (2005)In. J. Of refrigeration	Experimental analysis	Test result of performance and oil circulation rate of commercial reciprocating compressors of different Capacities working with propane as refrigerant.	T_e = -25 to -20˚C,T_c= 35,50,65˚C,	R-290	COP improvement of 9% when using Propane instead of R-407C.	Suitability of Propane as refrigerant in Combination with POE oil.
			SO =30.23mm	R-407C		
			LO =30.10mm			
			ST=38.23mm			
			LT =38.10mm			
			LF=38.10mm			

Duprez et al.(2007) In. J. of refrigeration	Thermodynamically realistic modelling	Modelling of reciprocating and scroll compressor	P_{max} =10 KW T_e = -20 to 15˚C T_c =15 to 60˚C	R-134a R-404a R-22 R-12 R-407C	Mass flow rate of scroll compressor higher and power consumption is lower (except that of R-407C) than of reciprocating compressor.	In scroll compressor R-134a have lower mass flow rate and lower power consumption as compare to other refrigerant.
Navarro et al.(2007) In .j .refrigeration	Model analysis	Performance analysis of a series of hermetic reciprocating compressor working with R-290 and R-407C.	SO=30.23mm LO=38.10mm ST=30.23mm LT=38.10mm T_{sup}=11.1 K P_r =2 to 7	R-290 R-407C	Compressor efficiency of R-290 is higher. . But Volumetric efficiency of R-290 is lower .	R-290 has lower GWP as compare to 407C.
Bolaji B.O.(2010) Journal of power and Energy	Experimental Analysis	Analysis of reciprocating compressor performance with ecofriendly refrigerant.	V_p =30.4 cm^3 P = 0.746 kw P_r = 2.4-3.8 P_d =5-30˚C	R-12 R-23 R-32 R-134a R-143a R-152a	R-134a and R-152a will perform better.	R-152a has lower GWP .
Bolaji B.O.(2010)Journal energy	Experimental analysis	Study of R-152a and R-32 to replace R-134a in Domestic refrigerator.	Q=12L, m=60g, 80g, 100g, 120g. T e =-5 to 35˚C	R-152a R-134a R-32	R-152a is the good alternative of R-134a.	Performance of R-134a is better than R-32. GWP of 32 has lower.
Da Riva et al. (2011)In.J.refrigeration	Experimental Analysis	Performance of a semi-hermetic reciprocating compressor with propane and mineral oil.	P_e =4.4 bar to 5.2 bar P_c =13.8-19.6 bar	R-22 R-290 R-134a R-600a	Test has been Performed both with and without IHX. With IHX, displays higher efficiency.	With IHX, suction superheating is increases.

5. Refrigerant progression

The historic progression of refrigerants encompasses four generations based on defining selection criteria. Calm (2010)

5.1 Past refrigerant

Mechanical refrigeration has been around since the mid 19th century. The first refrigerant used was ether employed by Jacob Perkins in 1834 in his hand operated vapour compression machine. In the earlier days, CO_2 was first used as a refrigerant in 1866. and ammonia (NH_3) in 1873. other chemicals used as vapour compression refrigerants included chymgene petrol ether and naphtha), SO_2(R-764) and methyl ether. In 1926, Thomas Midgely developed the first CFC (Chlorofluorocarbons), R-12. CFCs were nonflammable, non-toxic (when compared to Sulfur Dioxide) and efficient. Commercial production began in 1931 and quickly found a home in refrigeration. For technical reasons that will be discussed later, several refrigerants became very popular in air conditioning including CFC-11, CFC-12, CFC-113, CFC-114 and HCFC-22.

5.2 Present refrigerant

In mid of 20th century it is found that ozone layer is depleting because of some CFC and HFC refrigerants which is very harmful for environment and human health. To reduce ozone depletion potential (ODP) new refrigerants are produced which are using in present trends. At the end of 20th century these refrigerants were banned by Kyoto protocol for safety reason.

Table 3 Historic progression of refrigerants

GENRATION	SELECTION CRITERIA	REFRIGERANTS
1830s-1930s	Whatever worked	Primarily familiar solvents and other volatile fluids including ethers,R-717,R-744,SO_2 (R-764),methyl format (R-611),HCs, H_2O (R-718),CCL_4(R10),HCCs, other natural refrigerants.
1931-1990s	Safety and durability	Primarily CFCs, HCFCs, HFCs, ammonia, water.
1990-2010s	Stratospheric ozone protection	Primarily HCFCs, HFCs, ammonia, water, HCs, and CO_2.
2010-?	Global warming mitigation (No ODP,low GWP,and high efficiency)	Hydrofluoro-olefins (HFOs),ammonia ,CO_2, HCs, water.

Table 4 Properties of past refrigerant

REFRIGERANT	FORMULA	NBP(˚C)	CT(˚C)	APPLICATION
R-11	CCl_3F	23.8	198	A low pressure Refrigerant. Commercial plants with centrifugal compressors.
R-12	CCl_2F_2	-30	112	Small plants with reciprocating compressors. Used in domestic /commercial refrigeration Car air-conditioning
R-22	$CHCl_2F_2$	-40.8	96	Packaged air-conditioning units where size of equipment and economy are important
R-500	$C Cl_2F_2$ -73.80% CH_3CHF_2 -26.20%	-33	102.1	Offers apron 20% more refrigeration capacity than R-12 for same compressor.
R-502	$CClF_2$ -48.80% $CClF_2CF_3$ -51.20%	-45.6	90	More refrigeration than R-22. Reciprocating low temperature application.
R-717	NH_3	-33	133	Large industrial plants. Since it attacks copper, used in open-type reciprocating or screw compressors and steel pipes.

Table5 Properties of present refrigerants

ASHRAE#	TYPE	COMPONENT (WEIGHT)	ODP	GWP	LUBRICANT	INTENDED APPLICATION
R-507	HFC Blend	125/143a(50/50)	0	3300	POE	Refrigeration, Transport
R-404A	HFC Blend	125/143a/134a(44/52/4)	0	3260	POE	Refrigeration, Transport
R-422A	HFC/HC Blend	125/134a/600a (85.1/11.5/3.4)	0	3013	POE(Mineral oil)	Refrigeration, (Retrofits)
R-422D	HFC/HC Blend	135/134a/600a (65.1/31.5/3.4)	0	2232	POE(Mineral oil)	Refrigeration, (Retrofits)
R-410A	HFC Blend	32/125 (50/50)	0	1730	POE	A/C
R-134a	HFC	Pure	0	1300	POE	Transport ,food service
Low GWP	Synthetic	TBD	0	~5-40	POE	Automotive TBD
R-744	CO_2	Pure	0	1	POE	TBD

Table 6 Properties of future refrigerant

REFRIGERANT	NBP(˚C)	CT(˚C)	ODP	GWP
R-227ea	-15.6	102.8	0	3500
R-236fa	-1.4	124.9	0	9400
R-245fa	15.1	154.1	0	950
R-125	-48.1	66.2	0	3400
R-143a	-47.2	72.9	0	4300
R-23	-82.1	25.9	0	12000
R-32	-51.7	78.2	0	550
R-134a	-23	119	0	1300
R-152a	-24	113.3	0	140
R-718	99.97	373.95	0	0
R-717	-33	133	0	0
R-744	-54	31	0	1
R-290	-42	97	0	20
R-600a	-12	135	0	20
R-407C	-44	87	0	1700
R-410A	-51	72	0	1730

5.3Future refrigerant

US Environmental Protection Agency (EPA) have identified new chemicals that appear to be good alternatives to CFC and HCFC refrigerants. The chemical include HFC-227ea, HFC-236fa, HFC-245fa, HFE-125, and HFE-143a. HFC-236fa is a near drop –in replacement for R-114 used in chillers, HFC-227ea and HFE-143a are the best alternatives for R-12, HFC-245fa is potential good alternatives for R-11 used in chillers.R-23, R-32, R125, R-134a, R152a are the alternatives for R-12 in domestic refrigerator.

5.4 Eco-friendly refrigerant

Hydrocarbon refrigerant are environmentally friendly, non toxic, non-ozone depleting replacement for chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs). From a chemical point of view, a hydrocarbon is the simplest organic compound, consisting entirely of hydrogen and carbon. Hydrocarbons (HC) are naturally occurring substances. The majority can be found in crude oil, where decomposed organic matter provide an abundance of carbon and hydrogen .The hydrocarbons that can be used as a refrigerant in cooling & heating applications are R170-Ethane-C_2H_6,, R260-Propane-C_3H_8,R600-N-Butane-C_4H_{10},R600a-Isobutane (2-Methylpropane)-C_4H_{10} , R1270-Propylene (propane)-C_3H_6 and R1150-Ethylene-C_2H_4 .

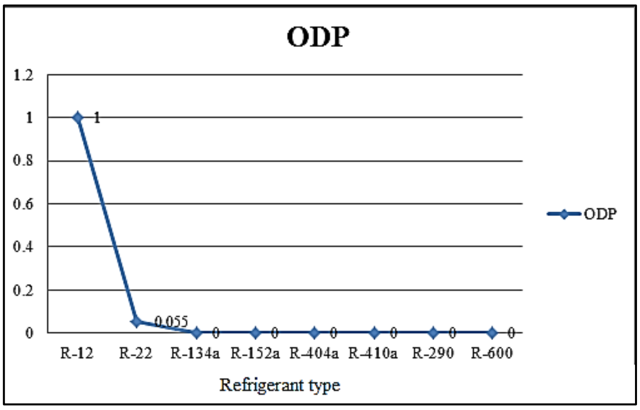
However, the most commonly used HC refrigerants are propane (mainly in commercial & industrial freezers, air conditioning & heat pumps) and isobutene (in domestic refrigerators &freezers)

6. Environment concerns

By the mid-1970s concerns began to surface about the thinning of the ozone layer and whether CFCs may be in part responsible. This led to the rectification of the Montreal protocol in 1987 that required the phase out of CFCs and HCFCs. New solutions were developed with HFCs taking on a major role as refrigerants. In the 1990s global warming arose as the new threat to the wellbeing of the planet. While there are many contributors to global warming, refrigerants were again included in the discussion because air conditioning and refrigeration are significant energy users (about 1/3) and many refrigerants are themselves greenhouse gases.

6.1 Ozone depletion potential (ODP)

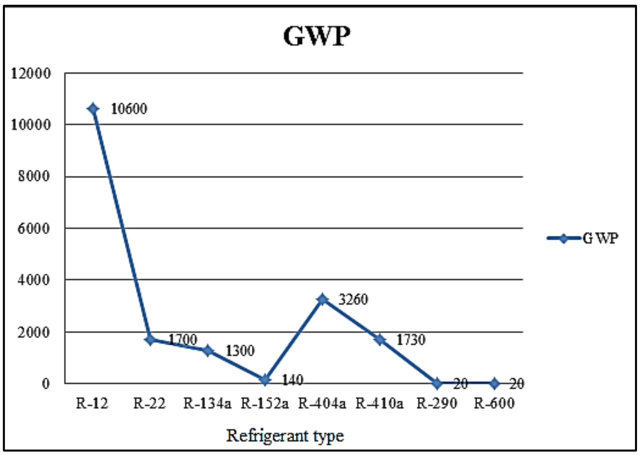
ODP is an index of a substance's ability to destroy atmospheric ozone. Table 5 & 6 lists the ODP for many common refrigerants. R-11 and R-12 have the highest potential (1.0). While the ODP of a refrigerant does not affect its performance as a refrigerant, it is a key parameter. All refrigerants with any ODP either have been or will be phased out as required by the Montreal Protocol. Any new refrigerant /product development must be based on refrigerants with no ODP.



Graph 1 ODP for common refrigerants

6.2 Global warming potential (GWP)

GWP is an index of a substance's ability to be a greenhouse gas. The GWP is relative to the warming effect of a similar mass of carbon dioxide for a 100 year time-frame. Carbon dioxide is used as the reference gas because it has the greatest net impact on global warming. Halocarbon refrigerants typically have higher GWPs than carbon dioxide but are in much smaller quantities.



Graph 2 GWP for common refrigerants

Most environmentally friendly HFCs these natural refrigerants are valid alternatives. The graphs 1 and 2 show a comparison of the impact of hydrocarbon refrigerants vs. HCFC and HFC's on Ozone Depletion Potential (ODP) and Global Warming. HCFC's such as the phased-out R-22 have an ODP of 0.01 to 0.1 and are categorized as "class I I Substances by the EPA. All HFCs have 0 ODP while they have higher GWP.

Conclusion

This review invested an eco-friendly, energy efficient, user friendly, safe, and cost-effective alternative refrigerant for reciprocating compressor. In accordance with Montreal and subsequent protocols on substances that deplete the Ozone layer, CFC's and HCFCs refrigerants are subjected to total phase-out in a scheduled time frame.R-22 have capped and banned in 2010 except small a amount for service.R-290,R-134a,R-404A,R-407C,R-410A and R-507 are the refrigerants will end up replacing various application of R-22. Propane (R-290) is a halogen-free substance with no Ozone –depletion potential and low-direct GWP. Propane is widely available and is a low-cost substance. The operating pressure of refrigeration system with propane is similar to R-22. R-290 used as refrigerant are highly flammable but can be good refrigerant. Abnormal refrigerant foaming reduces the lubricant's effectiveness in cooling the motor windings and removing heat from the compressor. Different type of oil is using with new refrigerants which are less toxic non-flammable having better miscibility than the synthetic oil which is highly toxic and flammable.

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