

Compressor Lubrication –the key to Performance

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ABSTRACT

Today, Low Global Warming Potential Refrigerants are being evaluated, optimized and applied. Higher-pressure refrigerants, refrigerant blends, and new chemical families of refrigerants are candidates. Compressor designs and system components are being evaluated to deliver the desired capacity, efficiency and reliable performance for intended applications.

Once the Refrigerant family is chosen based on Environmental and Heat transfer properties, System Chemistry between the Refrigerant and Lubricant families are scrutinized for optimum miscibility and solubility. These directly affect the Phase separation between the 2 liquid phases and reduction of viscosity. Over the entire Operating Envelope, the “oil return” and “viscosity reduction” problems are assessed. Compatibility aspects between chemicals (Refrigerants, Lubricants) and materials of construction (metallic, polymeric, elastomeric) are verified to avoid failures in use. System Components, compressor bearings, expansion devices and heat transfer coils are adversely affected due to contaminants circulating in systems. Rust, Copper plating, Formicary corrosion, elastomer swelling are example. Advances in Analytical Chemistry Techniques help the compressor and system manufacturers characterize the problems. Further, System Chemistry guides selection of lubricant additives.

This presentation explains how lubricant selection is accomplished using Tribology and System Chemistry aspects.

Key words: Compressor, Lubrication, Tribology, Stability,. Miscibility, Solubility, System Chemistry, Daniel Plot, Stribeck curve, Life Testing

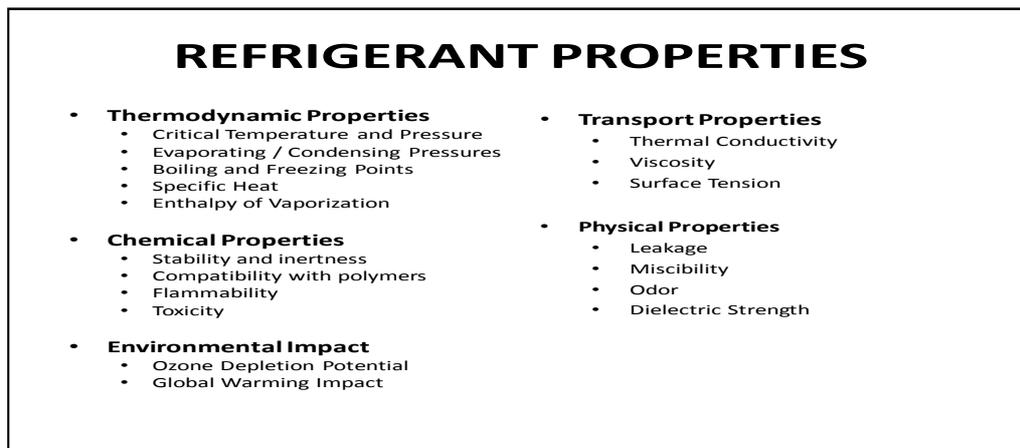


1. Introduction

- Refrigerant capacity and efficiency are the targets for each application category: car air conditioning, domestic refrigerators and freezers, air-conditioners, heat pumps and commercial refrigeration.
- Lubrication is the key to the Performance of a Reliable Air-conditioning and Refrigeration Compressor.
- Hermetic System Chemistry is a science needed from the beginning to assure thermal and chemical stability, compatibility with all materials of construction, miscibility/solubility during the selection of lubricant family, life testing with the selected formulated lubricants. Operating envelope and contaminants are parameters used in all chemistry evaluations. After acceptable system chemistry screening tests, Tribological evaluation tests are performed. Bench Lubricity Tests and Compressor Life Tests are the next step, [1,2]
- Lower GWP (Global Warming Potential) refrigerants such as HFO1234yf, HFO1234ze, HFC32, CO₂, Propane, Isobutane and their blends are of current interest. Lubricants such as Mineral Oil, Alkyl benzene, Polyalphaolefin, Polyalkalyneglycol, Polyolester and Polyvinyl ether are being evaluated to obtain desired net viscosity for specific applications.

2. Refrigerants

2.1 Refrigerant Properties



2.2 Chemical Families, GWP, and Applications

Currently lower GWP refrigerants such as HFO1234yf, HFO1234ze, HFC32, CO₂ and Hydrocarbons are being evaluated. Refrigerant Blends with HFC, HFO, and Hydrocarbons with 2 to 7 components are being provided by Refrigerant Manufacturers as Low GWP alternatives. Applications cover a wide range, from single stage vapour compression cycle to multi stage in refrigeration, heat pump and air-conditioning systems. The temperature range spans from extra low evaporating temperatures in medical systems to high condensing temperature in high ambient countries. Selection of Refrigerant starts with the operating envelope of the end product and the lubricant selection follows.

3. Tribology

The Lubricant Selection and Optimization Step require the use of fundamentals of Tribology (Friction, Lubrication and Wear). It requires thorough understanding of contact surfaces, materials, types of motion, loads and speeds. Characterization of “wear modes” is the goal for various surface techniques from simple visual, optical microscopy to Scanning Electron Microscopy. The wear modes are adhesive wear, abrasive wear, fatigue wear, fretting wear, corrosive wear, and erosive wear. The very first step in understanding lubrication needs is to understand the role

of contacting surfaces and the materials. The analyst has a wide range of techniques depending on the need for depth of penetration, special resolution, and tribological applications. Light microscopy is useful for 200nm character and size of wear topography; and able to see surface film colour; SEM is good for 500 nm and microstructure of developing wear scar together with elemental analysis of transfer products as they are produced. SIMS provides 500nm resolution and surface chemistry analysis in vacuum. Atomic Force Spectroscopy has better resolution in the Nano range (0.1nm) and provides three-dimensional Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM). The compressor designer has to confirm the wear regimes of interest. The Stribeck Curve is the Road Map.

3.1 Surface Characterization and wear

Every application has Surfaces in Contact, and a Relative Motion. (e.g., sliding, rolling and impacting). The Surface is not simple , nor it is flat. All engineering surfaces have a roughness and this plays an important role in tribology. The Surface layer : on the top is the Lubricant film, then underneath is Adsorbed Contaminants, Oxide , “Disturbed Material” . Underneath these 4 is the Bulk Material . The film thickness of the lubricant is a few orders of magnitude over that of surface roughness (This ratio is called Lambda). The wear regimes can be based on the ratio; less than 1.2 is boundary lubrication; 1.2-3.0 is mixed or thin film lubrication; greater than 3 is full film hydrodynamic lubrication. [3.]

3.2 Analytical Tools

The following table provides all tools available in Surface Analysis. [4]

Analytical method	Maximum depth of penetration	Spatial resolution	Tribological applications
Auger	0.5–1.5 nm	1000 nm	Metal transfer, surface segregation Magnetic recording surface inspection Analysis in vacuum
XPS	1.5–7.5 nm	1–4 nm	Lubricant reaction products chemistry Analysis in vacuum
Ellipsometry	400–500 nm	1 nm	Transparent solid film thickness Analysis in air
Raman	400–500 nm	10 nm	Organic film thickness and chemistry Analysis in air
Rutherford backscattering	2 μ m	10 nm	Surface film thickness composition
SIMS	Sputters 0.5 nm	500 nm	Surface chemistry Analysis in vacuum
<i>In situ</i> SEM wear test		500 nm	Microstructure of developing wear scar Elemental analysis of transfer products as they are produced Analysis in vacuum
Light microscopy		200 nm	Character and size of wear topography surface film color Nomarski texture
Fourier transform infrared spectroscopy		2000 nm	Chemistry of organic films: polymer transfer and boundary lubrication Analysis in air
Atomic force microscopy		0.1 nm	Friction forces on the atomic level Atomic level surface roughness
Profilometer		0.1–25 μ m	Surface roughness by stylus Micro-topography of surface finish and wear

Surface Analytical Tools Used in Tribology [4]

3.3 Types of Wear (modes)

Adhesive wear occurs when two smooth bodies are slid over each other, and fragments are pulled of one surface to adhere to the other. These fragments may come off the surface on which they are formed and be transferred back to the original surface, or else form loose wear particle.

Abrasive wear occurs when a rough hard surface, or a soft surface containing hard particles, slides on a softer surface, and ploughs a series of grooves in it. This material from the grooves is displaced in the form of wear particles, generally loose ones.

Surface fatigue wear is observed during repeated sliding or rolling over a track. The repeated loading and unloading cycles to which the materials are exposed may induce the formation of surface or subsurface cracks, which eventually will result in the break-up of the surface with the formation of large fragments leaving large pits in the surface.

In each case, the root cause should be identified; for example, in many cases of abrasive wear, by re-examination of test samples, the origin of the wear particles needs to be identified; if these are contaminants that can be filtered, the designer has an option to select type and location of filter ahead of this component; however, if the abrasive particles are by-products from wear, for example, stiffeners used in plastic/elastomers, the design option may be different.

If fretting wear is observed, eliminating slip at the interface or use of solid film lubricants is helpful.

If corrosive wear is observed, the root cause of corrosion such as acidic or oxidative environment should be investigated and eliminated; for example, copper plating on critical bearing surfaces can be eliminated using an acid catcher in the lubricant.

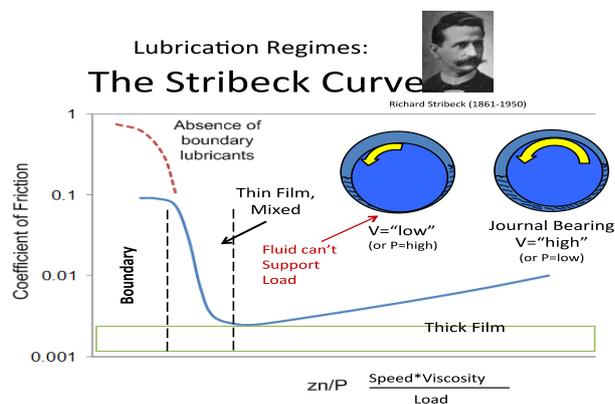
The investigator's goal is to identify the wear mode and its mechanism; this is an iterative process and may take time and other resources.

4. Lubrication Regimes and Stribeck Curve

4.1 Stribeck Curve is a plot of Friction Coefficient versus Hydrodynamic parameter (fluid viscosity times relative speed divided by load). The various regimes covered are: Boundary Lubrication (BL), Mixed Lubrication (ML), Elastohydrodynamic Lubrication (EHL) and Hydrodynamic Lubrication [3,5]

4.2 Transition Diagram is a plot of Load Carrying Capacity F (N) versus Sliding Speed (m/s). Three regions separated by two transition curves are shown. (These regions are governed by the measured friction-time characteristics). Region I/II represents Safe region with negligible wear rate. The lubricating conditions in this region are BL, ML and EHL. Region III is to be avoided due to incipient or micro scuffing. The third region III is an Immediate Failure Region by scuffing. [6]

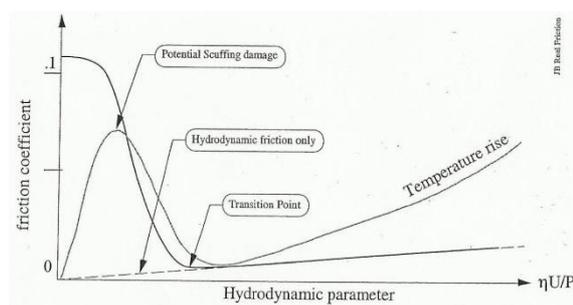
4.3 Stribeck curve



Source : S.Shaffer [3]

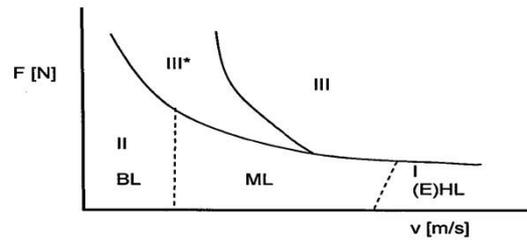
4.4 Scuffing

Temperature Rise and Scuffing



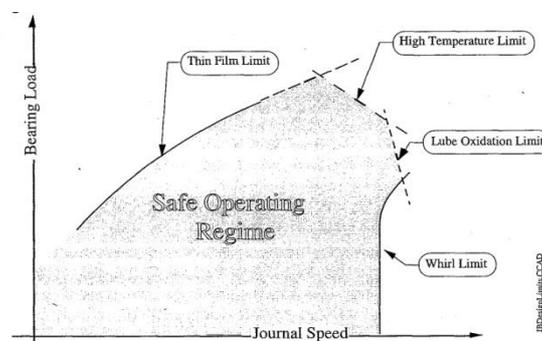
Source: J. L. Tevaarwerk[5]

4.5 Transition Diagram Combined with Stribeck Curve



Source: [6]

4.6 Safe Operating Regime



Source: J. L. Tevaarwerk[5]

5. LUBRICANTS and ADDITIVES

5.1 Lubricants

Lubricants are used in bearing designs to reduce friction and wear; other functions in a compressor application are sealing of clearances, noise control cooling and transport debris away from Interface.heat transfer. Lubricants used in hermetic compressors are selected based on their viscosity and lubricity primarily; other relevant properties are chemical stability, thermal stability, low hygroscopicity, thermal conductivity, electrical resistivity, environmentally acceptable, compatible with elastomeric and polymeric components, soluble with refrigerant gas and non-deposit forming. The compressor manufacturer is ultimately responsible to determine acceptable values for the above list of properties.

In the Refrigeration & Air-Conditioning industry, the following is a list of unique needs of a lubricant: low temperature properties (low pour point, low wax), chemical stability, known partial miscibility with refrigerants and known solubility of refrigerants. The selection of lubricant is based on the three factors, miscibility, solubility and net viscosity.

5.1.1 Lubricant Families and The six chemical families of Lubricants in Air Conditioning and Refrigeration are: Naphthenic Mineral Oil , Alkyl benzene (Polyalphaolefin, Polyalkyleneglycol, Polyolester and Polyvinyl ether The available viscosity grade ranges from 10 cSt to 220 cSt (centi stokes). Viscosity Index(VI) is indicative of viscosity change over a temperature range .(40 Deg.C to 100 Deg.C). The pressure viscosity coefficient is a measure of effect of pressure on viscosity. This is relevant in elastohydrodynamic lubrication regime.

5.1.2 Lubricant Properties vary with the chemical family; the properties oil interests are viscosity, viscosity index, pour point and pressure viscosity coefficient. This figure compares 6 families belonging to 32 VG (viscosity grade).

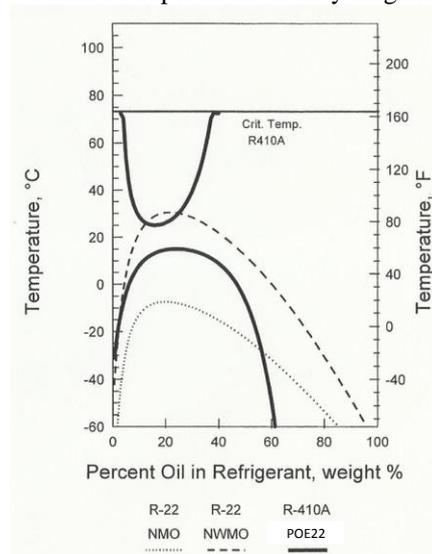
WORKING FLUID COMBINATIONS								
REFRIGERANTS	R11, 12, 22, 502	R123	R134a	R407C, R410A	R404A, R507A	NH ₃	CO ₂	HC Mixture
Lubricants Application	MO	AB	PAG	POE	POE	MO	PAO	MO
	AB		POE	PVE	PVE	AB	MO	AB
	PAO		PVE	AB (?)	AB (?)	PAG	POE	
			AB				PAG	

Note: Viscosity Grades range from 10 cSt to 100 cSt depending on family; refer to ISO 6743-3

5.1.3 Lubricity Additives are based on their functionality : Anti Wear (AW), Extreme Pressure (EP), and Friction Modifier (FM). AW usually is made from P chemistry (e.g. TCP, tricryslphosphate and BTTP, butyl teraphalatephosphate); EP is made from P and Cl chemistry .[8]

5.2 Miscibility and Solubility

5.2.1 An example of miscibility diagram for R410A and POE 22 is compared with R22 and two Mineral Oils.



5.2.2 This miscibility/immiscibility has the following implications. At compressor, oil pick up location at start up and net viscosity (of the 2 phases mentioned above), foaming tendencies at start up decompression are affected. In suction line accumulators, location of oil return hole and its size is affected. The solubility affects net viscosity (reduction); this effect may help oil return but adversely affect lubrication. Also, solubility affects explosive decompression of elastomeric components and may result in foaming.

Viscosity selection depends upon minimum film thickness, maximum allowable viscous drag, minimum sealing, minimum flow rate and minimum variation within the operating envelope (temperature, pressure and refrigerant flood back). Viscosity index takes care of the change of viscosity along with temperature. Solubility and Daniel Plot takes into account solubility, and percentage lubricant

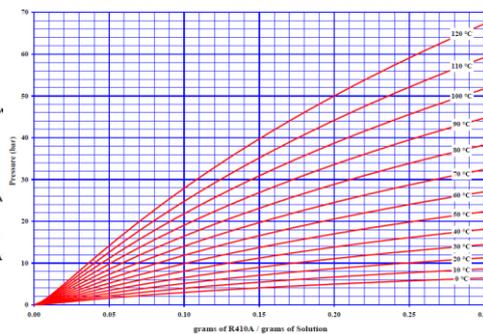
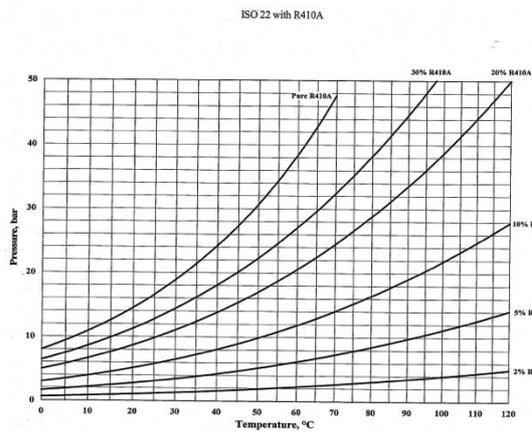
6. Daniel Plots

Pressure versus Temperature is a measure of Solubility. Temperature versus % lubricant in refrigerant is another plot. Density versus temperature for pure Lubricant and with dilution of 5%, 10%, 15% and 20% refrigerant is also needed. Daniel Chart is Kinematic Viscosity versus Temperature from 100% lubricant, 95%, 90% and to

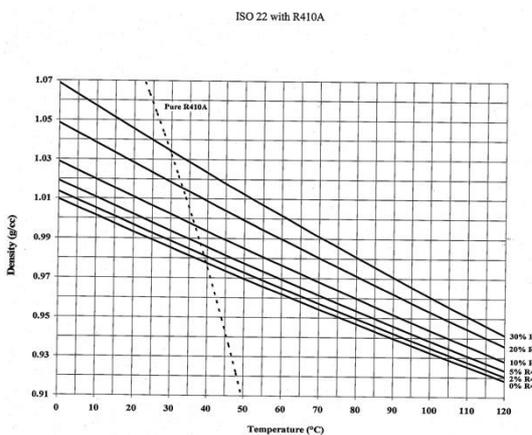
85% .In Daniel Chart, constant pressure Isobaric) curves are incorporated to show the effect of pressure (typically 10bar, 15,25 and 35 bar).

The customer, for any operating point (e.g.: sump condition or at the bearing condition) can estimate the net kinematic viscosity in cSt. for comparison of different lubricant families and viscosity grades

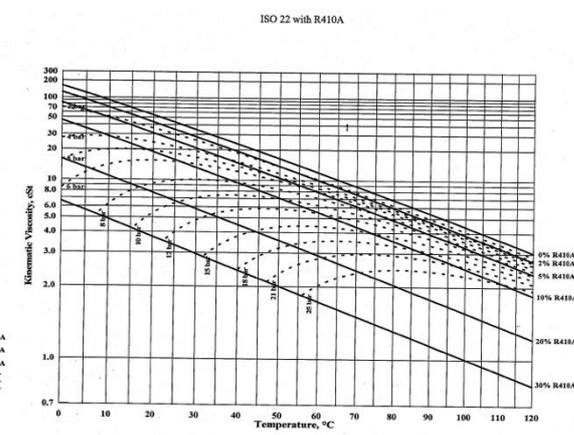
6.1-6.4, The Daniel Plot of R410A with a 22 cSt POE is derived from refrigerant solubility data, density data and viscosity data versus temperatures. The combined PVXT data is called Daniel Plot and includes isobaric curves.[8]



Solubility (Pressure versus Temperature) Pressure versus % Refrigerant Concentration

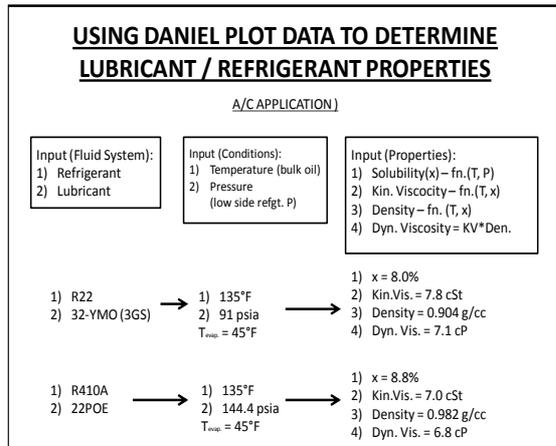


Density Data



Pressure-Viscosity-Composition-Temperature

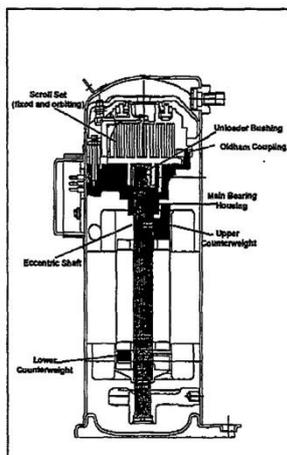
6.5 Determination of net viscosity using Daniel Plots



7. Quantifying Wear

The prerequisite to understanding how compressor components perform starts with detailed knowledge of Material, type of motion and extent of motion. Schematic of a Scroll Compressor and the key wear components are provided as an example. Measurements at contact points as a function of time are critically needed to understand Break-in wear and wear during operating life.

7.1 Schematic of a Scroll Compressor



7.2. Key Wear Components in a Typical Scroll Compressor

Table 1. Key Wear Components In A Typical Scroll Compressor

Key Component	Contact Areas	Material	Mating Surface
Scrolls	Tips	Cast Iron	Bases (other scroll)
	Bases		Tips (other scroll)
	Thrust Area (Orbiting scroll)		Main Bearing Housing Thrust Surface
Oldham Coupling	Tabs (loaded side)	Diecast Aluminum based alloy	Scroll Key Slots
Drive Shaft	Flat	Heat Treated Carbon Steel	Unloader Bushing Flat
Unloader Bushing	Inner Surface	Steel Powder Metal	Shaft Drive Flat
Drive Bearing	Inner Surface	Composite PTFE/Bronze liner with steel backing	Unloader Bushing OD
Floating Seal	Outer and Inner Lip	PTFE based	Fixed Scroll
Top Cap	Muffler Plate	Carbon Steel	Seal Face

8. Lubricity Bench Tests and compressor tests

8.1 Bench lubricity tests such as Falex Pin on V block, Block on Ring, Four Ball, Cameron-Plint are performed depending upon the type of motion. Materials of the wear couple can be changed. Lubricant manufacturers screen

different base stocks and then different additives. They are inexpensive, relatively short duration and provide excellent value as a screening and ranking tool. The results are useful but may not be correlated to specific wear couple inside a compressor.

8.2 Recently, a High Pressure Tribometer with pin on disk method was developed to handle pressures up to 13.8Mpa and Transcritical CO₂ applications have been evaluated..[9]

9.Current Work on Lubricants for Low GWP Refrigerants including Propane and CO₂ :

Recent work for Low GWP candidates, R32 and CO₂ are best examples for development of new POE lubricants to meet their miscibility and net viscosity needs. [10,11,12,13]. The discharge line temperature for R32 alone as a refrigerant was higher than that with R410A at equivalent compressor operating conditions. Compressor manufacturers to meet their reliability goals are still addressing this. Tran critical CO₂ applications operate at very high pressure and its effect on net viscosity is taken into account in improved lubricants.

With Propane and CO₂ refrigerants, and POE lubricant, solubility, miscibility and PVXT measurements (Daniel Plots) have been made and reported. [14]

9.1 Lubricants for Carbon Dioxide ,CO₂ (R744) [14]

POE lubricants showed good miscibility; however severe viscosity reduction possibility limits its uses in low temperature cascade systems.

PAG,PAO,MO, and AB are only partially soluble in CO₂. In Trans critical application, receivers,. Internal Heat Exchangers and compressor sump are affected.. However, the PAG type lubricant seems to give the best lubricity for trans critical applications based on the highest mixture lubricity. Also, high efficiency oil separators may make MO a viable lubricants in some cascade systems.

9.2 Lubricants for Propane,(R290) [14]

Miscibility, Solubility and Daniel Plots were determined for Five families of ISO 32 grade lubricants. They were compared to baseline POE with R134a in automotive air conditioning., the viscosity was compared at test condition (-6degC,Evaporating, 6 degree C Superheat, 10 degree C Suction Line HX and 20 deg C Compressor Heating). PAG was superior 50 cSt, better than POE (38 cost), MO (22 cost) and AB(20 cost). The baseline POE with 134a was 48 cSt). The details of the data on these candidates are provided in ref 14.

Summary

1. System Chemistry and Tribology play a vital role in Compressor Lubrication Selection, and Optimization in the Air Conditioning and Refrigeration Applications.
2. Studying contact surfaces using appropriate Surface Analysis Techniques and identifying the type and extent of wear mode is the first step.
3. Lubricant supply to where needed should be guaranteed in the inherent design.
4. Friction Co-Efficient Measurement and plotting Stribeck Curve is the next step.
5. Lubricant viscosity after refrigerant solubility should be taken into account. PVXT data (Daniel Plot) should be experimentally generated.
6. Lube additives, if any, should be thoroughly evaluated for adverse effects in the system.
7. Stribeck Curve helps designer optimize surface finish, lubricant viscosity and lubricity additive for boundary lubrication.
8. The selected final lubricant candidate should be validated in compressor life tests and system tests for Trouble Free Operation.

10.Future Trends and Needs

Changing Environmental Regulations.

Retrofits with new lubricants in existing equipment.

Refrigerants with poorer thermal stability.

Refrigerants with Higher Pressures
Refrigerant Blends with moderate to high glide
Compressor designs operating at higher speeds.
Compressors operating with High Discharge Line Temperature.
System designs requiring oil equalization between compressors.
Lubricants degradation at extreme contaminants level.
Removal of additives by filter driers.
Enhanced heat transfer tubing entrapping lubricants.
Oil Return to compressor sump.
Increased Oil Circulation rate outside the compressor.
Malfunction of expansion devices.
Modeling of interaction between Refrigerants and Lubricants.
Advanced Surface Analysis Tools.
Advanced Analytical Chemistry Tools (Separation and Identification)
Thesis in interdisciplinary sciences (Tribology and System
Chemistry) Training (Workshops, Tutorials, Seminars and
Symposiums)

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