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Opening up the lubricant toolbox

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Opening up the lubricant toolbox

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Abstract. Frequently, we fall back to concepts or ideas that we are comfortable with or have more understanding of. In these cases, we don't always utilize all the resources available to us in make advancement or just try something new. This is sometimes true when it comes to using or evaluating lubricants for various refrigerants or refrigerant related applications. Too often we try to fit what is currently being used in existing applications into new applications instead of expanding our thinking and overall understanding. Usually these efforts are not put forward because we are not taking advantage of all the resources available to us to make good technical decisions. This paper will focus on the various types of lubricant chemistries available for use in the refrigeration and air conditioning industry and markets. Why some lubricants are used, while others are not used and while some lubricants are impractical. Various tools, techniques and computer assisted programs will be outlined that are useful when evaluating lubricant and refrigerant interaction properties.

A few key examples of refrigerants particular to current lower global warming potential reduction efforts will be investigated and what systematic approach can be used to make sure we don't exclude potential lubricant candidates as viable options.

1. Introduction

Changes have occurred in the refrigeration and air conditioning industry which have resulted in significant efforts to identify new refrigerants which meet market acceptability. These changes have also required evaluation of new materials like lubricants. Reduction or optimization of engineering staff makes it essential to develop and utilize methods to make the time and cost of approvals more effective. For lubricant evaluation this requires the ability to run tests in both a timely manner, at a reasonable cost, but also representing acceptable results. For the refrigeration and air conditioning market, this usually means running tests that require special equipment while understanding skills in the art.

This paper will describe how a lubricant manufacturer goes about developing lubricants to meet the demand for refrigerants and given applications. Over the years, refrigerant changes to meet both environmental regulations and energy efficiency standards often puts a strain on identifying appropriate lubricants. Sometimes these changes have resulted in slight modifications to existing lubricant options while other changes have made lubricant chemistry selection more radical with some instances demanding new lubricant options. What hasn't changed is interaction properties that lubricants and refrigerants need to exhibit in a system in order to maintain acceptable operation.



Compatibility, stability, miscibility and working viscosity are a few terms that are used to evaluate lubricant and refrigerant properties. These evaluations result in understanding how properties will affect reliability and performance while still achieving a positive environmental impact.

Air conditioning and refrigeration compressor and system design engineers look for ways to make evaluations prior to implementing a full-blown evaluation program. Data that can be used to reduce or maybe eliminate certain tasks in the evaluation process are considered helpful in streamlining cost and making up for the lack of personnel and other needed resources.

2. What Defines Lubricant and Refrigerant Interaction

Refrigeration and air conditioning systems are a complex dynamic when considering the various interactions taking place within a system. Figure 1 illustrates a simple type of refrigeration system. In general, systems are going to be defined by a compressor, heat exchange coils and componentry for operation. Within the system you will find refrigerant, lubricant, chemicals and a variety of metallic, plastic and elastomeric materials all interacting in some form or another. Introduce temperature and pressure variations, time of operation along with the sheer number of lubricant and refrigerant combinations and you have a complexity that is hard to predict the outcome outside of running in the system for a long period of time with multiple combinations. This complex matrix and extended time parameter makes it beneficial to have predicting outcomes based on shorter time periods and evaluating events outside of operating in a system.

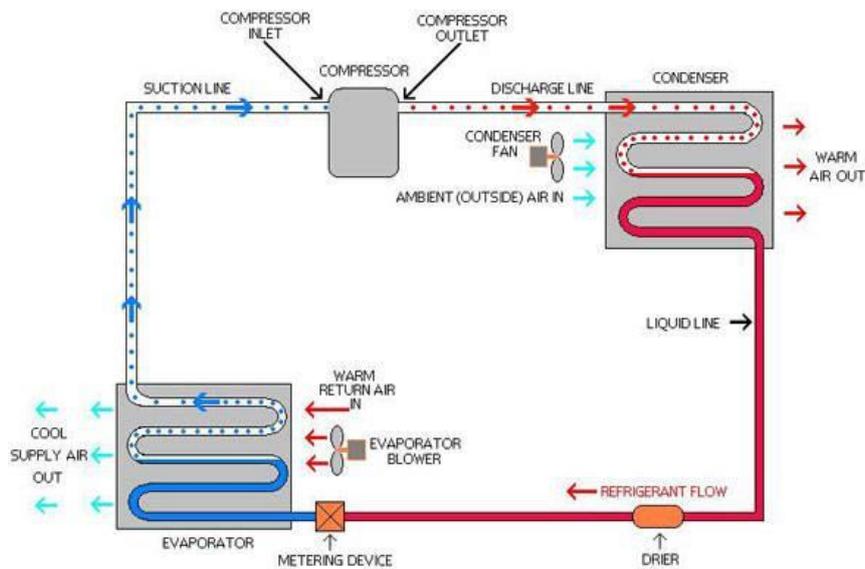


Figure 1: Illustrates a simple approach to a refrigeration cycle

3. Breaking Down System Interaction

If we start to breakdown specific areas within a system and what needs exist for evaluation, we can start to design what experiments are needed to generate valuable data. Referring to the refrigeration cycle diagram we can start to divide the system into different areas that have specific needs. Figure 2 shows four specific areas of the system that require different types of evaluation and requirements. We will breakdown the various regions of the refrigeration system and discuss what analysis is beneficial to making bench top evaluations helpful in the screening process.

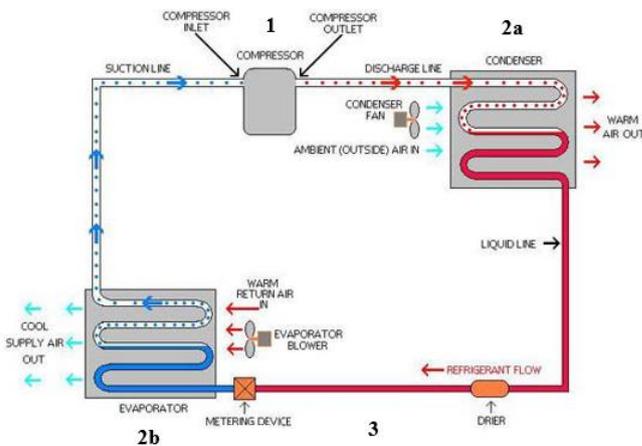


Figure 2: Specific Areas of Interest

3.1 Region 1 – Compressor

The compressor, number 1 in the diagram, is the most critical requirement regarding lubricant, refrigerant and material interaction understanding when making lubricant selections. The main functions of the lubricant are to lubricate, seal and remove heat and debris from the bearings, but this activity is complicated with the presence of refrigerant which dilutes the lubricant and adds pressure differentials that influence bearing loads. Additionally, only one lubricant is present to work on multiple bearing designs, various motions of operation and numerous material contact surfaces. Compressor engineers desire to know what is going to be the viscosity of the fluid that enters the bearing, so they can compute desired lubrication film thickness to overcome bearing load, surface finish and material design [1]. Proper selection of the lubricant chemistry and viscosity can benefit understanding concepts like friction loss analysis or bearing optimization to improve performance and increase reliability [2]. The earlier an engineer can predict the outcome, the more robust they can design the compressor in a timely manner to reduce testing cost and time.

Because the refrigerant can establish pressures during operation, with some being very high, it takes special equipment and techniques to be able to measure the viscosity of the working fluid combination of lubricant and refrigerant. For the refrigeration and air conditioning industry this is typically referred to as the working viscosity and over the years various techniques have been implemented to make this type of measurement. The importance of this information makes it essential to provide data that best represents an operating system, is accurate and can be generated in a timely manner. Shrieve utilizes a system which was designed and enhanced over the years by Shrieve Chemical Products Director of Research, Dr Chris Seeton, based on his thesis work at University of Illinois [3]. A schematic of this type of set-up is represented in Figure 3, which consists of a closed loop system mounted inside of a thermal chamber and has the capability of measuring simultaneously temperatures, pressure, viscosity and density. Various concentrations of lubricant and refrigerant are circulated while the temperature is slowly changed. Approximately 20,000 data points are collected over a 16-20-hour period per concentration. The internal volume of the loop is measured to correct for refrigerant vapor space to accurately know concentrations and each piece of instrumentation on the system is accurate to reasonable numbers to represent compressor operation. This type of set-up provides the most exact and best representation of data required for compressor engineers. Once gathered, a data analysis/regression operation is done to help reduce results to a manageable number and then curves for viscosity, pressure, density and solubility based on temperature are generated. Figure 4 is a representation of building a data set for a refrigerant and lubricant.

Various regions of the system will behave differently with lubricants, refrigerants and materials based on the condition. Lubricants can be a variety of chemistries both mineral based and synthetic based. Refrigerants are based on halon chemistry along with more “natural” based products. Materials range from metals that are pure components to alloys while plastic and elastomers typically are justified by the interaction of swell, tensile strength, embrittlement and temperature resistance.

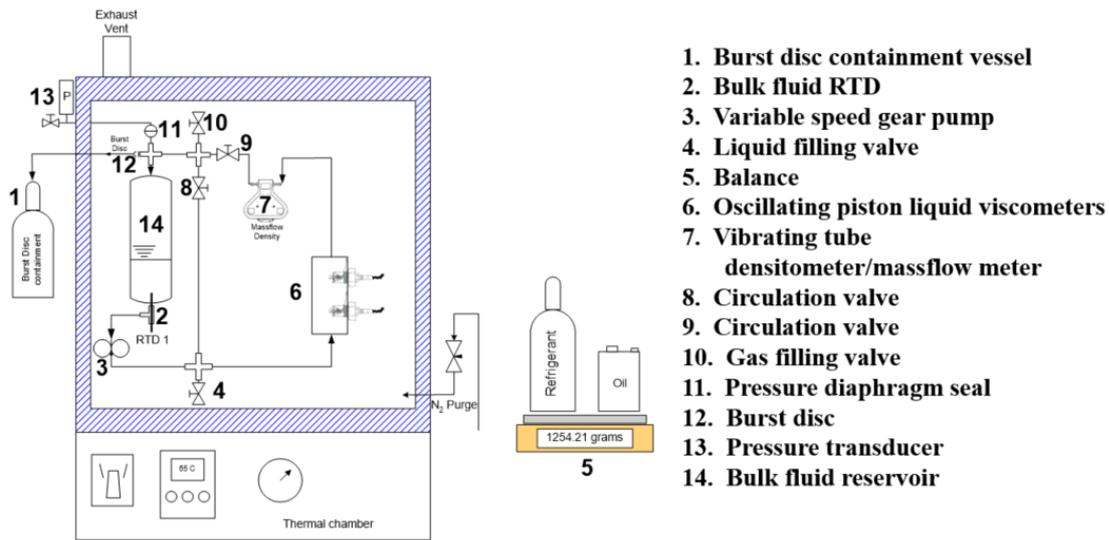


Figure 3: Schematic Design of Pressure-Viscosity-Temperature Test Equipment

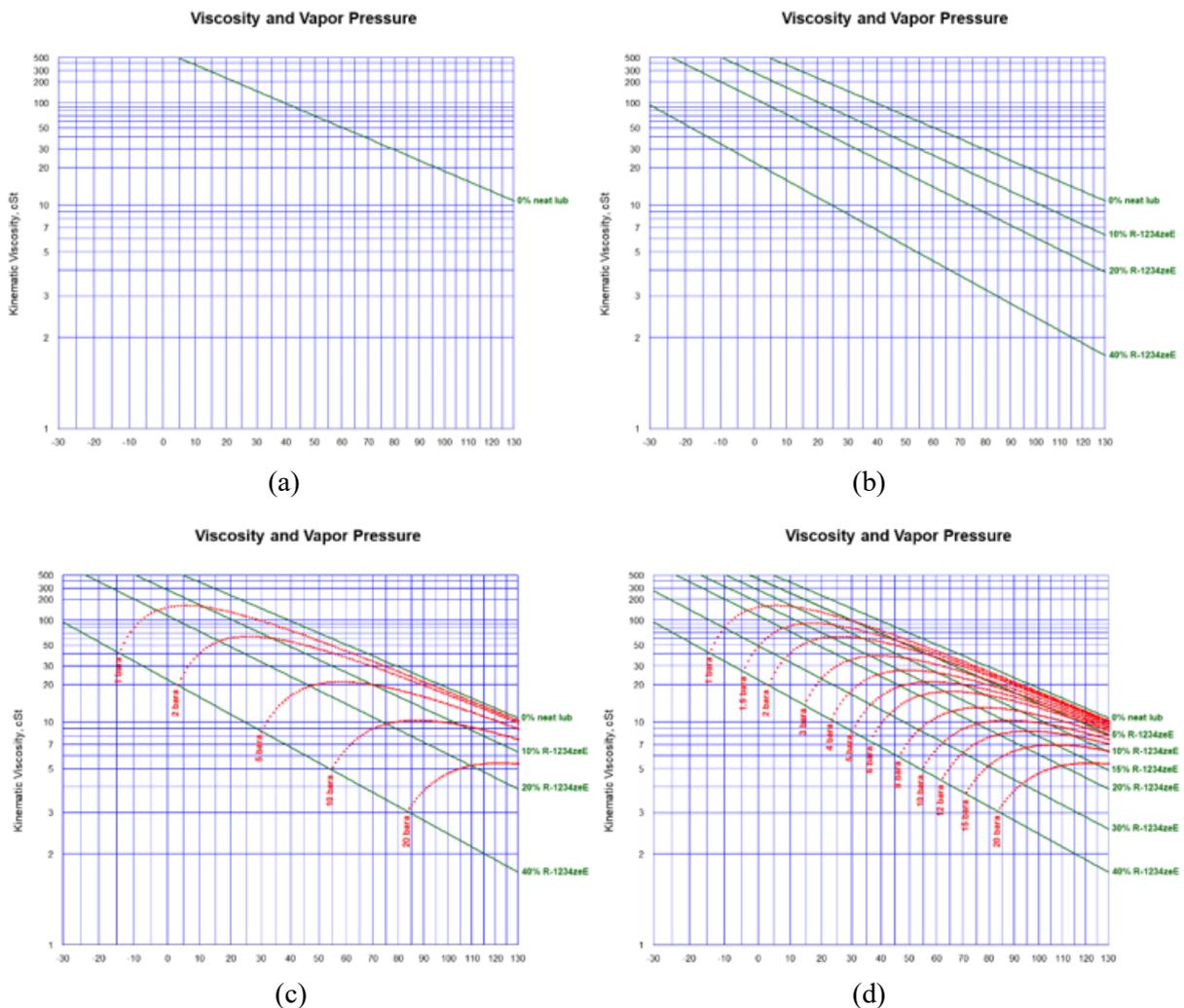


Figure 4: Building a Pressure-Viscosity-Temperature (Daniel Plot)

In (4a) the viscosity of the base lubricant “only” is measured and for accuracy should be compared to standard methods of viscosity measurements as a check. Next increasing levels of refrigerant dilution are separately measured, and the working viscosity is calculated at various concentrations as shown in (4b). Isobars, shown in (4c) can be added which represent pressure at dilution and then the Daniel Plot can be finished off as represented in (4d). It is important to understand as much as possible about interaction parameters of the mixture to make sure measurement data that could be representing an immiscible region is eliminated from the data set. If this raw data is incorporated into the finished data, then error will exist which could distort the results.

A data solver based on a 10 coefficient least squared regression and equations, as represented in Figure 5, can be provided with chart data for engineers to accurately determine the working viscosity, refrigerant dilution and density at any given temperature and pressure value within the bounds of the measured data. This information is used in various bearing and CFD programs to generate film thickness and other data essential to compressor bearing design which can aid in reliability and performance studies. Multiple viscosities of similar lubricant chemistries can be evaluated with refrigerants to build a matrix of results for the compressor engineer to make comparisons.

coeff #	Press	Density	Kin. Visc
a1	5.29335E+00	1.24277E+00	1.59868E+01
a2	-1.38746E+03	-8.94688E-04	-2.51632E+00
a3	1.90639E+04	2.14157E-07	0.00000E+00
a4	1.63050E+00	7.18163E-01	1.11141E+01
a5	-6.00971E+02	-2.47031E-03	-2.20766E+00
a6	7.83026E+04	2.77450E-06	0.00000E+00
a7	-2.33442E-02	-2.82521E-01	-6.80217E+00
a8	-9.37455E+01	2.51705E-03	9.66727E-01
a9	1.51596E+04	-5.59969E-06	0.00000E+00
rsq	0.999879	0.9999	0.9981

Temperature °C	Pressure bara
75	10
Dilution, %	20.1
Viscosity, cSt	9.7
Density, g/cm ³	0.993

$$\begin{aligned} \text{Log}(P) &= a_1 + \frac{a_2}{T} + \frac{a_3}{T^2} + \text{Log}(\omega) \left(a_4 + \frac{a_5}{T} + \frac{a_6}{T^2} \right) + \text{Log}^2(\omega) \left(a_7 + \frac{a_8}{T} + \frac{a_9}{T^2} \right) \\ \rho &= a_1 + a_2 T + a_3 T^2 + \omega \left(a_4 + a_5 T + a_6 T^2 \right) + \omega^2 \left(a_7 + a_8 T + a_9 T^2 \right) \\ \text{Log}_e \left(\text{Log}_e \left(\nu + 0.7 + e^{-\nu} K_0 (\nu + 1.244068) \right) \right) &= a_1 + a_2 \text{Log}_e(T) + a_3 \text{Log}_e^2(T) \\ &\quad + \omega \left(a_4 + a_5 \text{Log}_e(T) + a_6 \text{Log}_e^2(T) \right) \\ &\quad + \omega^2 \left(a_7 + a_8 \text{Log}_e(T) + a_9 \text{Log}_e^2(T) \right) \end{aligned}$$

Figure 5: Data and Equations for Calculating Dilution, Viscosity and Density

Within the compressor it is important to understand stability and compatibility parameters since the compressor will usually have the greatest variety of materials and encounter the highest temperatures. Lubricant and refrigerant interaction is usually studied via glass sealed tube testing and/or metal pressure vessel testing. Stability testing is based on ASHRAE Standard 97 which basically describes how to run the tests [4]. But even though this is a standard it still allows for some variation in test procedure, so it is critical to understand the best technique. Preparation of sealed glass tubes requires expertise to make certain the tube does not break under heating with refrigerant pressure, eliminate contamination and

make sure refrigerant is not present during the torch sealing process of the glass. The tubes can be sealed with any combination of lubricant, refrigerant, metals or any type of material associated with a refrigeration system as shown in Figure 6. By varying times and temperatures, one can begin to understand overall stability, reaction rates and kinetics; a typical rule that has been used in this type of testing is based on the Arrhenius equation where the reaction rate doubles for every 10 degree increase in temperature [5]. Testing is typically done with low amounts of moisture and no air unless doing some level of hydrolytic or oxidative stability study. Over the last few decades hydrofluorocarbon (HFC) refrigerants have dominated the market and demonstrate good thermal stability with usually no breakdown during the glass sealed tube stability tests. More recently refrigerants based on fluorinated olefin chemistry or iodine containing molecules are either on the market or being evaluated. These refrigerants can demonstrate varying levels of thermal instability and reactivity with air and moisture which leads to the need for more studies with sealed glass tubes. Refrigerant decomposition was a very common occurrence years ago when testing chlorinated refrigerants via glass sealed tube methods [6].

For testing materials like plastic and elastomers, larger samples or the need to go to higher pressures, it is best to evaluate in metal pressure vessels as described in the recent ASHRAE guideline GPC 38 [7]. This type of test is particularly valuable for looking at material used in hermetic motors and has been integrated into some agency type of testing such as UL984 [8]. Larger samples can be used and physical changes such as hardness, swell, tensile, elongation and other parameters can be tested with larger amounts of lubricant and refrigerant. Figure 6 illustrates a standard metal pressure vessel for this type of testing. If desired, pressures at the test temperature can be monitored and controlled to specific levels which is difficult to do in the glass sealed tube tests. Some fixtures can be set-up to perform extraction type of tests and glass liners can be used to provide a more inert surface compared to the metal walls.



Figure 6: Glass Sealed Tubes and Pressure Metal Vessel

3.2 Region 2 – Heat Exchangers

For the heat exchanger areas (2a, 2b), along with other components like receivers, it is vital to understand the miscibility relationship between the lubricant and refrigerant. Lubricant and refrigerant are deemed miscible if a liquid mixture of both maintain a single phase over a given concentration and temperature range. This is beneficial in the heat exchange areas because lubricant that gets pumped out of the compressor into the system needs to return to the compressor for lubrication purposes. Also, lubricant that remains in the heat exchanger can degrade system efficiency through heat transfer losses. Industry studies have been done that show the location of the lubricant as it migrates through the system and the amount of the lubricant in each location usually based on varying oil circulation rates. Since you typically need to visually see the changes in miscibility the best way to assess is in glass tubes, but some

refrigerant pressures can be excessive so metal cells with structurally enhanced glass windows can be used as shown in Figure 7. Since there are many refrigerants and several lubricant candidates for each refrigerant the methods need to be quick, accurate and the results understood by experts.

Several lubricant and refrigerant concentrations are exposed to a range of temperature to determine the point when single-phase changes to two phases or termed as “immiscible”. There are different methods from visual observation like graph paper behind the glass tubes or monitoring reduction level of light passing through the solution, each demonstrate the need for understanding of the technique. A newer standard which will be designated SPC 218 is currently being written as an ASHRAE standard on miscibility [9]. Sometimes this point of separation is called the critical solution temperature. Difficulty in determining an endpoint usually exist if the solution becomes hazy or cloudy prior in comparison to a distinct separation. After a separation point it is also important to record the appearance of the two phases like are the phases completely separated or does some of one component exist in the other component phase. Understanding which of the two phases, refrigerant or lubricant, is on top or bottom can help when designing some systems. Once the observations are made and the data

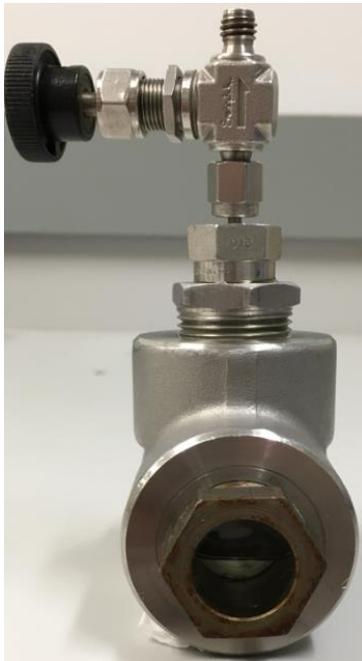


Figure 7: High Pressure Miscibility

collected the information can be presented in graphical form as shown in Figure 8. This information is easy for system designers to look at and compare to make decisions on the level of lubricant-refrigerant miscibility they require for a given application. Other factors such as oil circulation rate and system design will play a factor in lubricant selection for each refrigerant.

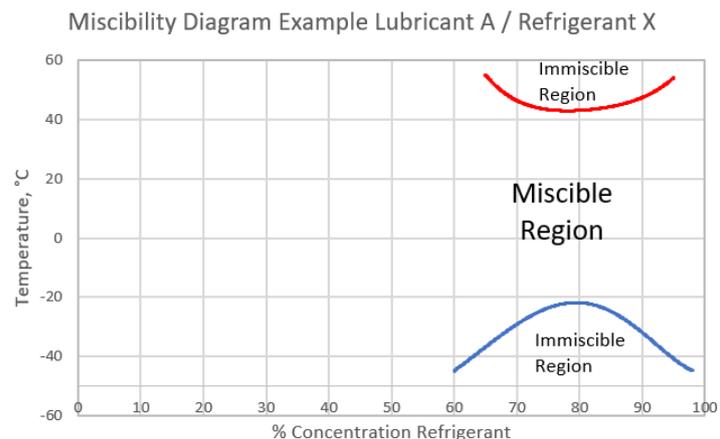


Figure 8: Lubricant-Refrigerant Miscibility Example

3.3 Region 3 – Expansion Devices and Contaminant Control

Expansion devices are sized to meet designed capacity and temperature requirements of the system. When effective size of the expansion device is altered, due to an unwanted deposit inside the opening or around the area hindering movement of mechanical devices, then system efficiency is changed. Over the last few decades this has been a concern due to the changes in refrigerant and lubricant chemistry. The dynamics of the expansion device with pressure drops and decreasing temperatures along with changing refrigerant to lubricant composition creates an opportunity for material, that is less soluble, to deposit out. It is helpful to perform testing on chemistries found in a refrigeration system to understand the potential compatibility of various combinations of lubricants, refrigerants and materials over a large temperature and pressure variation. Sealed glass tubes and pressure metal vessels can be used to evaluate compatibility of materials and chemicals used in the system to determine if extraction or interaction of chemicals can result in expansion device deposits. A newer ASHRAE Standard 172 was developed as a method to screen chemicals based on their solubility in HFC refrigerant and lubricant over a range of temperature which can be used to help determine acceptability in a working system [10].

To help control potential contaminants like moisture, acids and solid debris, that may enter or be generated within a system, components are installed to help mitigate the problems. These components contain desiccant type material that can help remove the undesirables but can also be an area for reactions to take place. It is important to treat the materials in these components as any other type of material within a system and make sure lubricant and refrigerant compatibility studies are done.

4. Lubricant-Refrigerant Interaction Example – Refrigerant R-1234ze(E)

Hydrofluoroolefin (HFO) based refrigerant R-1234ze(E) is a candidate to replace R-134a in some applications especially screw chillers. A challenge facing this refrigerant in application is that it is very soluble with most synthetic based lubricants, so trying to maintain the working viscosity that was seen with R-134a and POE lubricants is difficult. Screw compressors are typically designed to need larger amount of working viscosity going to the screws usually between 5 and 40 cSt depending on the design, to maintain proper lubrication and sealing. Too much refrigerant dilution into the lubricant can degrade working viscosity and is undesirable for the bearing and other aspects of system operation. Since these systems can be very large and costly, it is not always practical to screen lubricants in a system. To help screen lubricant candidates for acceptability, the PVT equipment is vital to understanding lubricant needs at numerous operating parameters. This information can then be shared with compressor design engineers to help reduce test cost and time.

To be able to evaluate different refrigerant chemistries that are entering the market, it is necessary to work with a lubricant supplier that not only has the equipment and technical expertise but also a variety of lubricant options to choose from and is innovative in designing new options. Lubricants for R-1234ze(E) requires this type of effort due to the interaction it has with lubricants and the type of systems it might operate in.

Table 1: Lubricants for R-1234ze(E)

Operating Parameters: R-134a Condition A 60°C/5.5 bar or Condition B 68°C/14 bar; R-1234ze Condition C 58°C/4 bar or Condition D 63°C/11 bar								
	R-134a				R-1234ze(E)			
	Condition A		Condition B		Condition C		Condition D	
	Vis	Dil	Vis	Dil	Vis	Dil	Vis	Dil
POE120 Baseline	22 cSt	9.0%	5.0 cSt	25.0%				
POE220 Baseline	28 cSt	9.7%	6.9 cSt	25.0%	25 cSt	11.3%	3.1 cSt	34.5%
POE370					40 cSt	10.0%	3.4 cSt	34.9%
PE46					12 cSt	11.7%	3.4 cSt	34.2%
PE68					20 cSt	10.9%	5.5 cSt	32.1%
PE100	28 cSt	8.2%	6.0 cSt	30.0%	32 cSt	10.4%	8.2 cSt	31.7%

Table 1 defines some system operating parameters, makes a comparison to traditional R-134a options, shows how traditional R-134a lubricants compare when used with R-1234ze(E) and introduces various lubricant options for R-1234ze(E). When R-1234ze(E) is used as a substitute for R-134a it is difficult to use the same lubricant, both the POE 120 and POE 220 are product viscosities currently used with R-134a in screw compressor operation while Conditions A-B and C-D are considered some examples of operational parameters for R-134a and R-1234ze(E) respectively with B and D being the most severe. As an example, when the POE 220 is used with R-1234ze(E) the solubility can increase which drastically reduces the working viscosity. Even raising to a higher viscosity POE 370 doesn't aid in increasing viscosity in one condition and might be too much of a viscosity increase in the other condition. For R-1234ze(E) lubricant options, it is best to look at other chemistries such as the polyethers listed as PE. The viscosities can be engineered to work well with R-1234ze(E) and as is the case with PE 100 can even be used for both R-1234ze(E) and R-134a to meet operational needs.

5. Lubricant-Refrigerant Interaction Example – Drop-in Retrofit Refrigerants

Several refrigerants have been inserted into the market, not as OE recommendations, but solely for retrofit situations when the production volume of the currently used refrigerant decreases or the cost increases. In this case, it is common to see refrigerants being used that are marketed as drop-in replacements. Mainly the retrofit refrigerant is trying to replace and maintain a system capacity and maybe energy efficiency but often the true interaction with the lubricant is overlooked. Such was the case with a very large system that was being retrofitted away from R-22 and the new refrigerant was dropped-in without doing anything with the existing lubricant in the system. The system was using a screw compressor and a high viscosity ester-based lubricant designed for R-22 use. After the fact, Shrieve was asked to evaluate the drop-in replacement refrigerant and lubricant combination because of some system operation differences that were being seen. The customer wanted to know if the current lubricant was suitable for the new refrigerant, and if not, to suggest an adequate replacement. Without seeing the system, laboratory tests were performed just based on miscibility studies that indicated a potential problem that might exist in the retrofitted system. The ester-based lubricant that was in the system, when operated with R-22 refrigerant, maintained a suitable miscibility over the operating range of the system. But when this lubricant was evaluated with retrofit refrigerant (an HFC blend), a very different miscibility profile was determined. Figure 9 below shows miscibility studies done in glass sealed tubes. Tubes A and B on the far left are current lubricant with new refrigerant at 10% (A) and 20% (B) lubricant concentration in refrigerant, evaluated at room temperature. The photo shows that the oil has separated from the refrigerant (immiscible), with the oil on top at both concentrations. Tubes C (10%) and D (20%) are the same oil but now in R-22 refrigerant and are miscible at room temperature. Sometimes immiscible oils in systems with refrigerant can be used if this is known and the system is designed for the situation. But what made this situation more unpredictable is illustrated in the right-hand picture of Figure 9, when the temperature was increased to 35°C the immiscible lubricant and refrigerant A & B inverted phases with the lubricant going to the bottom. This situation might occur at different regions of the system or at different times of the year based on temperature. This explained the undesirable issue that was being encountered and a new lubricant was recommended with improved miscibility to more match what was seen with R-22. Studies were also performed to determine how much of the existing oil could remain in the system when retrofitted with the new lubricant. In addition, the PVT equipment was used to compare working viscosity and solubility of the ester oil with R-22 to the new lubricant and new refrigerant which is outlined in Table 2.

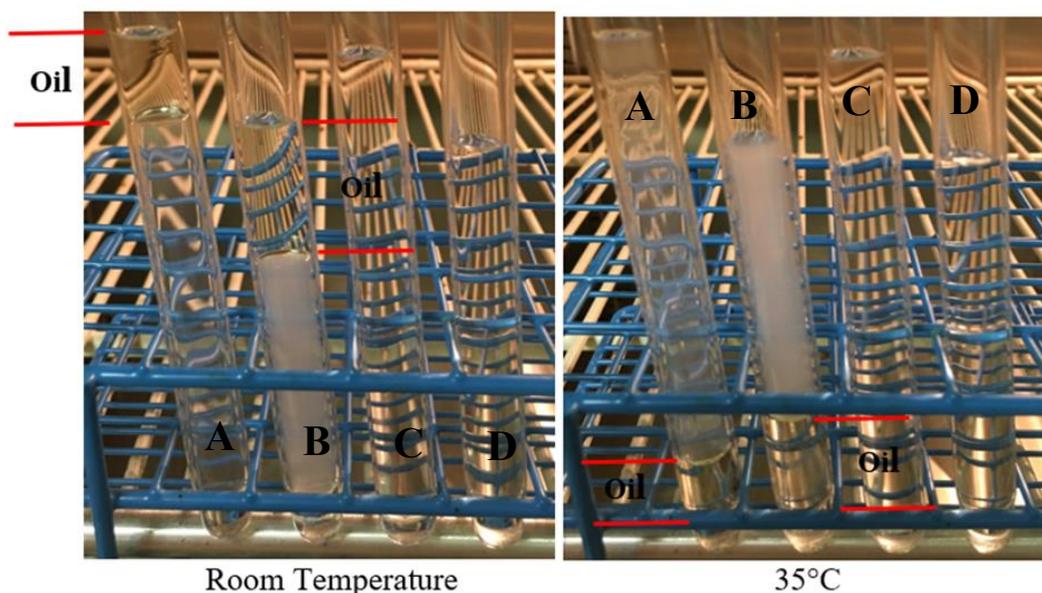


Figure 9: Miscibility Data for Lubricant Replacement Study

Table 2: PVT Data Comparison

Condition	Pressure (psig)	Discharge Temperature (°F)	Oil Cooler Exit Temperature (°F)	R-22 Ester (cSt) (%g/g)	HFC Refrigerant PE68 (cSt) (%g/g)
High Cond. Temp, Warm Oil (100°F)	200 (14.8 bara)	160 (71.1 °C)	100 (37.8 °C)	21 28%	32 14%

6. Conclusions

The refrigerant market is changing and will probably continue to change at a more aggressive rate over the next several years. It is important not only to find acceptable lubricant candidates to match existing performance, but also use this time of change to identify new lubricant options that may improve performance or reduce cost. Sometimes just using what was used in the past to replace the future is not always the right choice when investigating change. Making this work requires an organization that understands lubricant chemistries, the refrigerant properties and engineering of compressors and systems to make the proper fit [11]. To make a more than acceptable lubricant selection, in a timely manner, takes necessary tools to test and understand refrigerant and lubricant interaction.

This paper has described what is needed to keep up with the demand for refrigerant change in the industry and provides some examples of how these tools come into play when making a selection. Alternate lubricant chemistries have also been discussed that fit the qualification parameters for meeting the needs of refrigerants like R-1234ze(E) that create different challenges from the previous refrigerant chemistries it is substituting.

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