

Keeping Your Compressor Healthy: Developing the Right Lubricant Formulation is the Key

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Abstract. Selecting the correct compressor lubricant is crucial to the duration of the compressor and the refrigerant systems' useful life. However, developing an optimized lubricant for a refrigeration system requires a multitude of screenings and tests. The compatibility and stability of the lubricant with the refrigerant and compressor components needs to be examined at various accelerated conditions. The lubricant and refrigerant working viscosity must be determined at various refrigerant concentrations, temperatures and pressures as the diluted refrigerant in the lubricant has a significant effect on the viscosity. The correct lubricant formulation needs to be investigated for optimal performance. A compressor lubricant can provide many benefits to a refrigeration system such as bearing durability, sealing, and increased efficiency. Sometimes it is necessary to formulate the lubricant in order to optimize system performance. Specifically, this study investigated anti-wear properties of different oil additives to create a more robust refrigeration system. Many different additives and concentrations were considered and screened. Pending a successful screen test; these different additives' anti-wear properties were analyzed using bench top tribology tests. To reduce uncertainty and provide more in-situ results the different additives were operated in a refrigerant compressor on a gas-loop testing apparatus. Oil samples were taken periodically during the test duration for analysis. Lastly, upon test completion the compressors were dismantled and the parts were examined to determine the effectiveness of the anti-wear additives.

1. Introduction

Charging a refrigerant compressor with the incorrect or subpar lubricant can have devastating effects on the compressor and risks the contamination of the entire refrigeration system. This is why great emphasis is put on not only testing a compressor in a system but also selecting the optimal lubricant for different refrigerants, compressors, and systems. The significance of utilizing the appropriate lubricant is amplified by the fact refrigeration systems are expected to operate for many years without major repairs. Additionally, there is extreme limitation on the ability for the system to undergo regular lubricant changing intervals. The above factors are the motivation for formulating lubricants that improve refrigeration systems efficiency, working fluid purity, and reliability [1]. Specifically, this study aimed at beginning the process of discovering a new additive that when combined with the appropriate base lubricant would provide anti-wear characteristics to ensure compressor longevity.



However, there are many obstacles to overcome before a new additive can go into production. Firstly, an appropriate base fluid lubricant to be additized must be determined. Next, the compatibility of the formulation (lubricant + additive) with the working fluid (refrigerant) and system materials needs to undergo investigation. This investigation is very important since additive chemistry types used in refrigeration applications are limited due to the design and operation of a refrigeration system along with potential environmental, health and safety regulations that need to be met. Pending successful compatibility, the ability of the additive to actually provide anti-wear performance is examined by utilizing bench top tribology tests. Ultimately, the formulation is operated in an actual refrigeration compressor to provide in-situ results. Lastly, the compressor parts undergo a surface finish analysis to confirm the additive's effect or lack thereof. A design of experiment (DOE) is an effective way of evaluating numerous additive candidates.

2. Screen Tests

Generally, the first stage to develop a new lubricant or formulation is to perform screen testing. Screen tests produce timely results to assist in the elimination of unsuitable lubricants or additives. Additionally, most screen tests do not require a lot of resources. Screen testing performed prior to this study included miscibility, sealed tube stability, and bench top tribology. However, before newly developed additives are screened, the base lubricant should be determined. Base lubricant selection is based off of the refrigerant utilized, compressor design, and the system application. One of the most sophisticated methods for obtaining data to make a base fluid selection is to operate different base fluids in a pressure, viscosity, and temperature (PVT) apparatus.

2.1. Pressure, Viscosity, and Temperature (PVT) Apparatus

The PVT apparatus measures the temperature, pressure, density, and dynamic viscosity of the lubricant or lubricant/refrigerant combination [2]. Charging the system with a known mass of lubricant and refrigerant in addition with a vapor space correction computes the concentration of refrigerant to oil by mass. Ultimately, the PVT outputs essential data such as solubility and Daniel plots. An example of a Daniel plot can be seen in Figure 1.

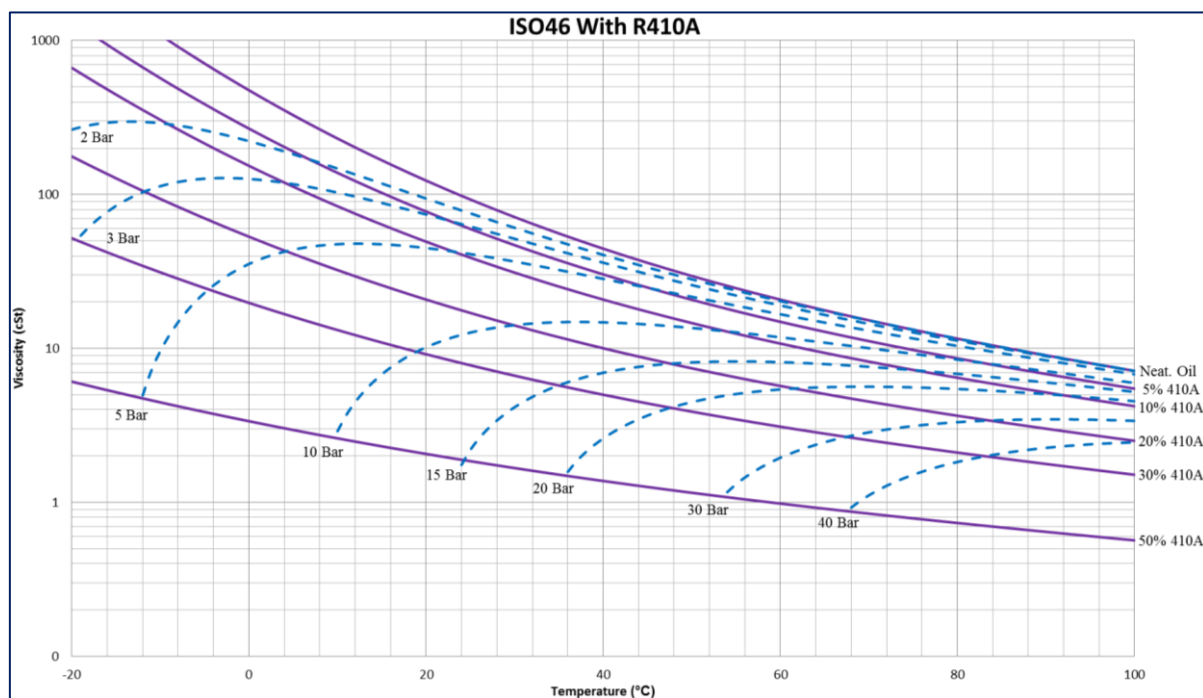


Figure 1. Daniel Plot

The Daniel plot is an exceptional example of the effect the refrigerant has on the lubricant's kinematic viscosity. The illustration clearly shows a drastic decrease in working viscosity as more refrigerant is dissolved into the lubricant. Essentially, without performing a PVT analysis on the base fluid the effectiveness of an anti-wear additive could translate into indiscernible results. The design of this experiment is to evaluate the additive and not the base fluid lubricating properties. For this reason the base fluid working viscosity needs to be such that it is not too low resulting in no additive being effective or too high where the base lubricant carries the load. Utilizing PVT analysis assists in selecting a base fluid with the optimal viscosity for the screening test.

2.2. Sealed Tube Stability and Miscibility

Lubricants with different additives and concentrations were measured for miscibility and evaluated for system stability. One method to perform stability tests is to seal a formulated lubricant and refrigerant with material catalysts (in this case aluminum, copper, and iron) in a glass tube [3]. A vacuum was pulled on the tube and then refrigerant was added. Once, the desired concentration of refrigerant was reached the glass tube was sealed shut with a torch. These samples were then heat aged at 175°C (347°F) for fourteen days. Subsequently, solutions were examined for changes in color, acid value, metal content in solution, and catalysts were examined for stains and tarnish. Stability tests assure that the formulations will be compatible with materials found in refrigeration systems.

Miscibility screening provides information regarding the ability of the lubricant and refrigerant to remain as a single phase over a range of operating conditions [4]. Conditions that allow for the change from single phase liquid to two phase liquid can have various detrimental effects on system performance. Miscibility testing focuses on the temperature at which the oil and refrigerant separate and a two phase condition exists. Miscibility can be evaluated over a wide temperature range and lubricant concentrations, for this particular test the focus was on lower temperature and concentration miscibility. Though the same base fluid was used for each additive response study, addition of certain additive chemistries can change the miscibility, requiring the need for this investigation. Results from miscibility testing can be seen in Table 1.

Table 1. Miscibility Results

Sample Set 1	Immiscible Temperature °C/(°F)	Sample Set 2	Immiscible Temperature °C/(°F)	Sample Set 3	Immiscible Temperature °C/(°F)
EXP-4957	-30 / (-22)	EXP-4969	-25 / (-13)	EXP-5031	-25 / (-13)
EXP-4958	-10 / (14)	EXP-4970	-25 / (-13)	EXP-5032	Immiscible
EXP-4960	-25 / (-13)	EXP-5020	-30 / (-22)	EXP-5033	0 / (32)
EXP-4963	-5 / (23)	EXP-5021	15 / (59)	Baseline	-30 / (-22)
EXP-4964	-30 / (22)	EXP-5024	-30 / (-22)	State-of-the-Art	-30 / (-22)
EXP-4966	-5 / (23)	EXP-5029	-10 / (14)		
EXP-4968	-10 / (14)	EXP-5030	-25 / (-13)		

The tests began at a temperature of 20°C (68°F) and then were placed in a cooling bath. The bath temperature was decreased by 5°C (9°F) intervals and the tube was inspected at each interval. The solution was immiscible below the corresponding temperature listed in Table 1. The importance of miscibility testing is to ensure the oil doesn't separate from the refrigerant in areas of the system that can have negative effects to system operation, efficiency and compressor lubrication. Miscibility and stability testing results are used for making final decisions on potential additive candidates. Succeeding successful miscibility and stability testing the additives actual anti-wear performance was screened by using a bench top tribology apparatus.

2.3. Bench Top Tribology

Bench top tribology tests are extremely useful for testing lubricants [5]. Tribology testing gives the ability to accelerate the wear between two or more surfaces. These surfaces are then inspected to determine the lubricants effectiveness. The bench top tribology test used was a four-ball machine. The four-ball machine operates by stacking four stainless steel spheres in a pyramidal shape with a lubricant film between them. A load is then applied to the top sphere while it spins and the three lower balls remain stationary. Concluding the operation of the four-ball machine, the scars on all of the spheres are measured and averaged. The average scar diameter and coefficient of friction of each proposed formulation is listed in Table 2. Please note that samples with poor miscibility are not included in the four-ball results as they were eliminated from the test matrix.

Table 2. Four-Ball Results

Sample Set 1	Average Scar Diameter (mm)	Coefficient of Friction	Sample Set 2	Average Scar Diameter (mm)	Coefficient of Friction
EXP-4957	0.231	0.042	EXP-5030	0.237	0.063
EXP-4964	0.24	0.057	EXP-5031	0.247	0.053
EXP-4969	0.261	0.053	Baseline	0.634	0.072
EXP-4970	0.264	0.059	State-of- the-Art	0.241	0.059
EXP-5020	0.473	0.092			
EXP-5024	0.286	0.055			

It is clear that according to the four-ball test some formulations are equal or better than the state-of-the-art anti-wear additive. Additionally, the worst performing sample was the baseline (un-additized base fluid). However, it must be noted that all of the results from the screening tests (miscibility, stability, tribology) need to be analyzed adjacent to each other. Essentially, if a formulation fails the stability or miscibility test; its' anti-wear performance is irrelevant to a refrigeration system.

3. Compressor Testing

As previously stated bench top tribology tests are a useful tool to simulate a wearing condition and help expedite the additive elimination process. However, most bench top tribology tests neglect significant variables. Specifically, the four-ball test ignores the effect of the refrigerant, pressure, and multiple catalytic materials. Therefore, to obtain real world results, the finalists in the additive matrix were tested in an actual refrigerant compressor for endurance testing [6].

3.1. Testing Rig

The rig utilized for compressor endurance testing was a gas-loop apparatus. A picture of the rig alongside of its' schematic can be seen in Figures 2a and 2b. The compressor endurance test rig consisted of a fan (F1) driven air-cooled tube and fin heat exchanger (HX), a receiver (REC), two metering valves (MV1 & MV2), solenoid valve (SV), fan (F2) cooled compressor with accumulator (COMP), two pressure transducers (P), and three thermocouples (T). The suction and discharge of the compressor had one thermocouple and pressure transducer each. The third thermocouple was placed on the shell of the compressor. When the shell temperature exceeded its' set point the lower fan (F2) would operate to maintain the desired temperature. The top fan was variable speed and was used to control the discharge pressure when running continuously. Both metering valves opening were manually adjusted to set the differential pressure.



Figure 2a. Picture of Testing Rig

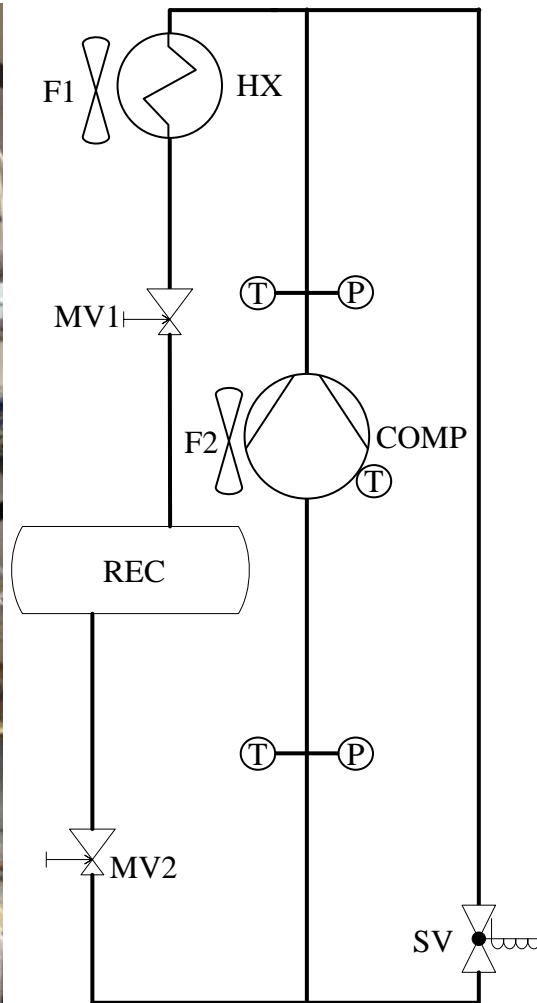


Figure 2b. Schematic of Testing Rig

The compressors utilized were a 2460W (8400 BTU/HR) hermetic rolling piston/vane rotary. The compressors were received dry of oil and a port was brazed into the lower side of the shell for oil charging and periodic sampling. The solenoid valve allowed the equalization of the high and low side. This allowed the pressures to rapidly equalize and increase the frequency at which the compressor could cycle on and off. The receiver provided additional volume for an intermediate pressure and the compressor was equipped with an accumulator to help prevent liquid refrigerant from entering the suction of the compressor.

3.2. Methodology

The endurance testing involved operating numerous rotary compressors with most of the compressors utilizing a different experimental anti-wear additive and R410A refrigerant. Each compressor underwent a relaxed break-in period and a severe condition period. The compressor operated continuously for twenty-four hours during the break-in period with the low side set to 6.9 bar (100 psig) and a high side of 27.6 bar (400 psig). The shell temperature of the compressor was set to not exceed 60°C (140°F) during the break-in. After the break-in procedure, the compressor was shut down so that an oil sample could be taken.

Next, the compressor was set to a higher load of 6.9 bar (100 psig) on the low side and 48.3 bar (700 psig) on the high side with a shell temperature of 90°C (194°F). During these severe conditions the compressor operated cyclically for 500 hours. The frequency was set for ten seconds of operating

and seven seconds of idling during the entirety of the severe condition testing. This resulted in the total number of cycles being roughly 100,000. In addition to counting the number of cycles; the suction, discharge, ambient, and shell conditions were recorded for the duration of the test. The data acquisition frequency was 2.5 seconds during the operation portion of the cycle.

4. Initial Results

The investigation of the compressor test results began with using inductively coupled plasma atomic emission spectroscopy (ICP-AES) instrumentation on all of the oil samples [7]. The ICP-AES operation involves injecting the oil sample into a high temperature plasma source which moves electrons in an atom to an excited state. When the electrons fall to a lower energy state (ground state) photons are emitted. Since most atoms will emit light at different wavelengths a detector is used to measure both the wavelength of the emission and the intensity. This enables the quantification in parts per million (ppm) of various metals species present in the oil from the endurance test. A supplemental investigation involved visually inspecting the compressor parts.

The compressors operated during the test were hermetically sealed. Therefore, the shell of the compressor had to be carefully cut so the internal working components could be inspected. Once, the shell was open the internal mechanism was dismantled to inspect the bearing surfaces.

4.1. Oil Draws

As previously mentioned, a small volume of oil was withdrawn from the compressor periodically throughout the test. These small samples were analyzed for dissolved metal content by ICP. A sampling of the ICP results for dissolved iron is outlined in Table 3.

Table 3. Oil Sample ICP Results

Sample	Element Content (ppm)	
	After 24 Hour Break-In	After 500 Hours
	Fe	Fe
EXP-4957	0	0
EXP-4964	0	1.7
EXP-4969	0	1.2
EXP-4970	0.1	0.5
EXP-5020	2.0	23.8
EXP-5024	19.5	205.8
EXP-5030	0	15.5
EXP-5031	6.6	228.3
Baseline	5.4	224.9
State-of-the-Art	0	0

Levels of dissolved metals in the lubricant, specifically iron, are a potential indication for the lack of proper lubrication in a compressor. When investigating rotary compressor wear performance, the measure of iron levels provides exceptional evidence of the lubricant formulations effectiveness. Other metals were measured but aren't listed as they may indicate compositional additive content or other non-lubrication related reactions.

4.2. Compressor Components

Upon dismantling the compressor, a subjective evaluation of the compressor components was performed by visually inspecting them and rating their condition. The inspection was broken down into six categories which included polish, wear, copper plating, residue, chemical staining, and scratches.

Polish describes a condition where traditional wear isn't present but, it is clear that the compressor operated. Wear describes the condition of parts showing signs of excess friction such as dark regions. Copper plating is very obvious due to the reddish-orange color of the parts. Residue describes debris or actual solids that were clinging to the parts. Chemical staining results from a reaction occurring inside the compressor during operation that tarnished the parts a different color. Lastly, a scratch was considered an easily identifiable groove or cavitation found on the part. Scratches aren't necessarily considered wear as it is typically the result of foreign debris getting lodged between two moving parts.

Table 4. Key for Table 5

Description	Polish	Wear	Copper Plating	Residue	Chemical Staining	Scratch
None	0	-	-	-	-	-
Light (Small)	1	4	A	L	X	E
Medium	2	5	B	M	Y	
Heavy (Large)	3	6	C	N	Z	F

Table 5. Visual Results of Compressor Parts

Oil Sample																	State- of-the- Art			
Part	EXP- 4957		EXP- 4963		EXP- 4966		EXP- 4970		EXP- 5020		EXP- 5024		EXP- 5030		EXP- 5031		Base line			
Roller	2	-	1	-	2	X	3	-	3	A	1	F	1	F	1	-	4	A	1	-
Vane	2	L	2	L	2	XL	2	-	3	-	2	-	2	F	1	-	4	-	1	-
Crankshaft	1	-	1	Y	2	X	2	-	1	A	1	XL	1	B	2	A	3	X	1	-
Outboard	2	-	1	Z	4	Z	2	-	2	A	1	AX	3	B	2	A	3	-	2	-
Main	1	-	2	Y	2	X	2	A	2	A	1	-	1	A	1	-	2	A	1	-

5. Validation

Since, a four-ball test neglected important variables, metals analysis data doesn't precisely measure wear, and visual inspection is subjective; due to this, methods to validate the above were performed. The validation tests consisted of surface finish analysis and Auger. Another advantage to conducting the validation tests was the ability to compare new and unused compressor parts to those found in the experimentation.

5.1. Surface Finish

The instruments used to quantify the surface finish performed Stylus Profilometry and Optical Profilometry. Both methods measure the indentations in the part due to wear [8]. The Stylus method provides a 2-dimensional representation of wear whereas; the Optical method utilizes a color gradient to illustrate depth in a 3-dimensional wear profile. Figure 3 shows pictures of the compressor's vane tips, two after the 500 hour endurance test and one of a new vane tip.

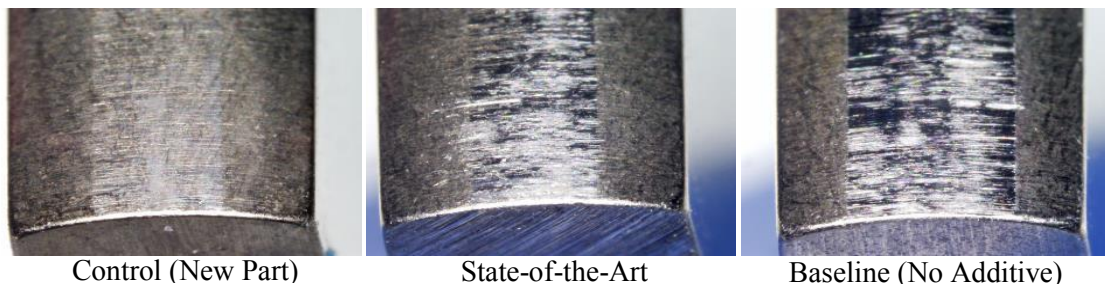


Figure 3: Photographs of Vane Tip from Compressors Parts

5.1.1. Stylus Profilometry. Figure 4 shows the surface finish results of the vane tip surface from the baseline and state-of-the-art. The compressor tested without an anti-wear additive shows a significant surface finish change (increased surface roughness) compared to the state-of-the-art additive formulated lubricant compressor test. The state-of-the-art indicates only slight changes to surface finish when compared to the new part.

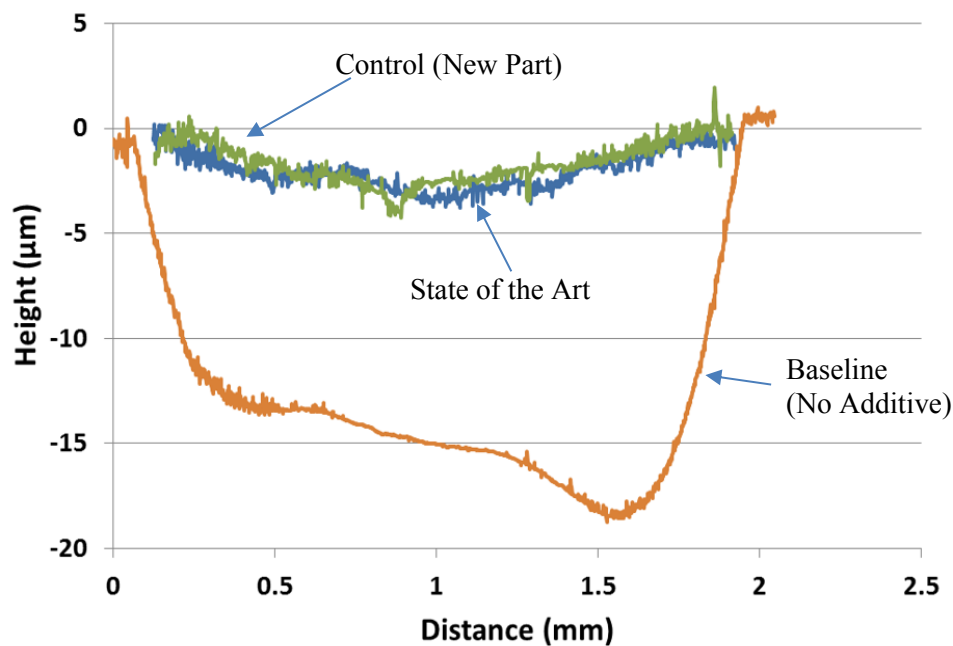
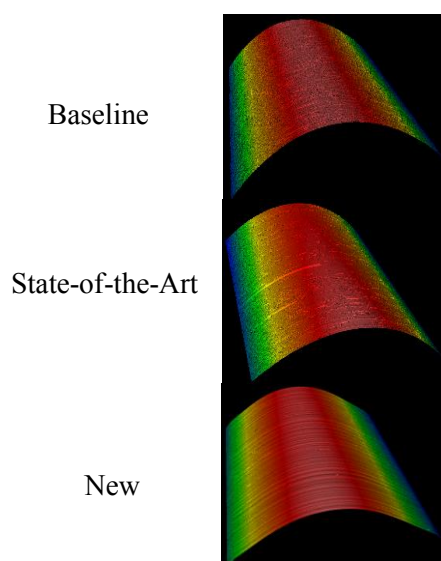
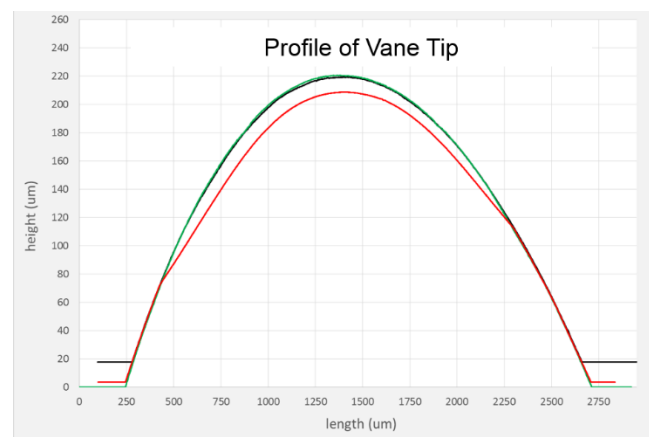


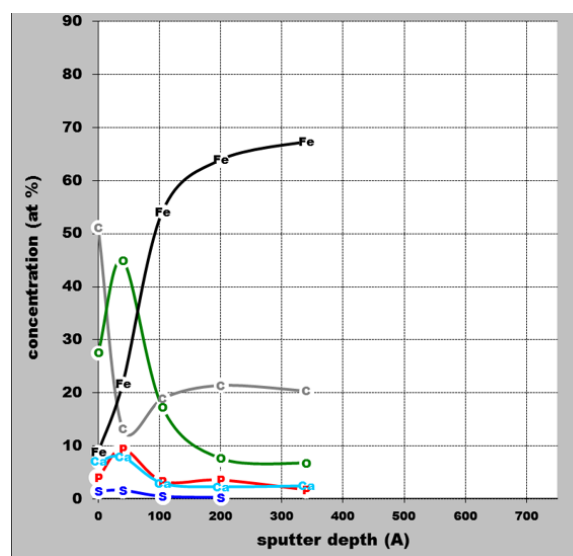
Figure 4: Surface Finish Measurements of Compressor Parts - Vane Tip

5.1.2. Optical Profilometry. Optical Profilometry is another way to evaluate the surface of a bearing. It is easy to see the surface roughness difference between the three vane tip surfaces in Figure 5a. Figure 5b shows a calculation of the surface profile curvature differences of the vane tip. The lower curve indicates a more worn surface of the baseline sample while, the similar profiles between the new compressor part and the state-of-the-art compressor test illustrate little to no surface change. These results correspond well with the stylus profilometry results and both results show the leading and trailing edges of the wear pattern.

**Figure 5a.** Optical Measurements**Figure 5b.** Surface Profile Calculations

5.2. Auger

When differentiating the effectiveness of additives, it is useful to understand how the additive interacts with the bearing surface. Most anti-wear additives function or activate when there is failure of the base fluid to provide the appropriate bearing film thickness. Auger analysis looks at the surface of a material at a micro level (to a depth of approximately 5 nanometers) and each formulated lubricant is composed of elements that can be detected via Auger. However, this type of analysis does have some limitation. An Auger bearing surface analysis example is shown below in Figure 6. Specifically, these results were obtained from performing Auger chemical analysis on the vane tip from the state-of-the-art compressor test.

**Figure 6:** Auger Chemical Analysis of Vane Tip Surface

Examination of the Auger results above show at no depth into the surface metal; the primary elements present are carbon, oxygen, and some phosphorus. These elements are most likely from the formulated

lubricant as well as, a combination of residual lubricant and reactive chemistry of the additives on the surface. When the analysis moved deeper into the surface the concentration of the lubricant elements decreased and bearing surface became more prevalent as indicated by the increase in iron. This phenomenon gives the notion that the additive response to the surface was not significant. This could be a function of initial additive level or additive surface activeness at these conditions. Evaluation of other bearing surfaces or tests with different additives might show a different additive response via this method.

6. Conclusion

Changes in the HVAC&R industry have always driven the need to find solutions that maintain reliable and energy efficient products. Today these changes continue not only in regards to refrigerant but also other aspects of the chemical industry. System chemistry and lubrication have always been critical parameters that need to be investigated and bench top qualification is helpful to screen products.

This paper demonstrated methods to evaluate various anti-wear additives designed to replace or be substitutes for current state-of-the-art chemicals. Lubricant additive formulation criterion is not limited to compressor performance alone. Today restrictions reside in chemical registration and environmental acceptance that can limit additive options and concentrations. Methods such as miscibility, stability, wear testing and compressor testing were used to screen the acceptability of various additive candidates. Visual observation along with more sophisticated methods of evaluating the effect of additive response on the compressor bearing surface during operation are the qualifying steps to approving a formulated lubricant acceptable for OEM system and field trial testing.

The beginning stages of evaluation showed some additive chemistries were too reactive or incompatible for effective use in HVAC&R applications. Compressor testing and bearing surface finish evaluation are still in the early stages of investigation but some candidates appear to have the potential to be acceptable replacements or prospective anti-wear additives to provide performance improvements. Additionally, work is ongoing to identify the appropriate anti-wear candidates that not only meet performance requirements but also conforms to chemical sustainability.

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