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ABSTRACT

Rolling piston rotary compressors are widely used in room air conditioners. The development of a lubricant for machines using hydrofluorocarbon (HFC) refrigerants has been difficult. Lubricity problems are often seen at the critical vane-roller contact. Wear in this area can shorten compressor life and result in decreased operating efficiency. Working fluids for these applications must have both sufficient working viscosity and antiwear performance. This paper describes our effort to develop a polyol ester (POE) lubricant suitable for use in rotary vane compressors of current design/materials. Viscosity, additive effect, stability and deposit forming tendency were evaluated. Bench test data as well as actual compressor test results are reported. A properly formulated POE was found that gives equal or better wear performance compared to R-22/mineral oil.

INTRODUCTION

Rolling piston rotary compressors are mostly used in room air conditioners and in refrigerators. These compressors have compact size, high efficiency, low noise levels and proven reliability. Currently, R-22 is used in air conditioner applications while R-134a is replacing R-12 in household refrigerator applications. The lubricants used with R-22 and R-12 refrigerants generally are mineral oil (MO) and alkylbenzene (AB).

Environmental concerns have resulted in the phase-out of CFCs (chlorofluorocarbons) and the production of HCFCs (hydrochlorofluorocarbons) will be phased-out in the US in the year 2020. The more environmentally friendly HFCs (hydrofluorocarbons) have been developed to replace CFCs and HCFCs. The most likely candidates to replace R-22 in rotary applications are R-407C and R-410A. R-407C is thermodynamically more similar to R-22, however rotary OEMs are favoring of R-410A due to equivalent or improved efficiency compared to R-22. Lubricants such as MO and AB have poor miscibility with HFCs, therefore, polyol esters and other miscible lubricants have been extensively evaluated in the HFC compressors.

The main components in a rotary compressor are shaft, rolling piston, roller, vane, cylinder and two flange plates. Critical areas in terms of lubrication are shown in Figure 1 and include the vane-roller contact and the journal bearings. The lubrication requirements for a long-lasting journal bearing life are in the hydrodynamic (HL) or elastohydrodynamic (EHL) regimes. Lubricant viscosity sufficient to provide adequate fluid film thickness is essential to provide these conditions. The effect of refrigerant dilution on the effective viscosity of the lubricant must be considered. Experimental data show that refrigerant dilution can vastly reduce the working viscosity of a lubricant (1).

The lubrication conditions in the vane-roller contact still are not fully understood. Analyses show the elastic/Hertzian contact pressure, which depends on material and operating conditions, can be as high as 200 MPa. This high contact pressure would normally create a boundary lubrication (BL) condition. Ozu and Itami studied the vane-roller contact using an electrical resistance method (2). Their findings show the contact operates in HL and BL conditions and that metallic contact can not be avoided. Similarly, Fukuda and Hayano evaluated the effect of viscosity on contact conditions (3). They found a higher viscosity lubricant can reduce electrical signal intensity, suggesting less metallic contact. A theoretical approach is to look at the motion at the interface between the vane and roller. This motion is sliding with reversal (4). That is, the roller slides in both directions, with respect to the vane, in one compression cycle. The relative speed becomes zero when the sliding direction changes. At the zero-speed moment, there is no oil film at the interface and metal-to-metal contact (BL) occurs. Therefore, both experimental results and theoretical analyses indicate that BL is at least one of the primary operating modes at the vane-roller interface. This most severe condition has to be taken into consideration when formulating a rotary compressor lubricant.

Almost immediate seizure will occur if full fluid film does not exist at the journal bearings of a rotary compressor. Since the lubrication requirements for journal bearings are more or less understood, this study focuses on the wear at the vane-roller interface. Although wear at the vane-roller interface will not result in immediate failure of the machine, it will have serious adverse effects on the system. First, the vane separates the high pressure refrigerant from the low pressure side during compression. Wear or rough surfaces at the interface can result in leakage past the vane and reduced efficiency. Secondly, capillary tubes are commonly used as thermal expansion devices in rotary systems. These thin tubes can be plugged with contaminants, including wear debris. Wear debris can also be sucked into journal bearings causing catastrophic failure. Thirdly, the vane-roller interface temperature will escalate by frictional heating if lubricant performs poorly under BL. Sufficiently high temperatures can degrade the lubricant and form deposits at the vane tip. Over time some of these deposits could circulate with the refrigerant/lubricant into the capillary tube and cause blockage.

The protection needed for BL at the vane-roller contact and the lack of lubricity of HFC refrigerants compared to CFCs and HCFCs have made the development of a successful rotary compressor lubricant challenging. System redesign, including coating of the vane tip, is feasible (4) but expensive. Most OEMs prefer using current construction materials with minimal design changes to accommodate the properties of the new refrigerants and lubricants. Just as important as lubrication and cost is the performance/efficiency issue. Lubricant has a major impact on the performance of a system (5, 6). The tradeoff between frictional loss at the journal bearings and better sealing at the vane-roller contact suggests that a high viscosity lubricant is worth investigation. In this work, efforts were made to develop a POE lubricant that provides superior protection and performance in a rotary compressor system. Additive packages were first evaluated with bench wear testers. Formulated lubricants of different viscosity were compressor tested at high load/high compression ratio conditions with different HFC refrigerants. The critical vane and roller surfaces were inspected by a profilometer for accurate comparisons. Finally, calorimeter tests were conducted to investigate the effect of viscosity on performance.

EXPERIMENTAL

Bench test: Two types of wear testers, a Falex pin-and-vee block machine and a four-ball wear tester, were used to investigate the effectiveness of antiwear formulations under the BL condition. Falex conditions chosen for this study were step-loading-to-failure with and without refrigerant (R-407C) bubbling through the lubricant. The failure load at the end of a test is reported. Four-ball tests were conducted at 40-kg loading with a run time of 60 minutes (ASTM D4172). The average wear scar diameter on the three bottom balls is reported for the lubricant. Steel-steel contacts were used in both Falex and four-ball tests since the material is similar to the roller and vane used in compressors.

Compressor test: Compressor tests were conducted at different loads and compression ratios not only because refrigerants have different thermodynamic properties, but also because compressor OEMs have set specific requirements for their designs. Table 1 lists the compressor test conditions used by two OEMs.

Table 1. Compressor Tests Operating Conditions

Refrigerant	Condition	Company A	Company B
R-407C	Discharge pressure (MPa)	2.7	3.4
	Suction pressure (MPa)	0.6	0.8
	Duration (hour)	4000	200
R-134a	Discharge pressure (MPa)	1.8	--
	Suction pressure (MPa)	0.3	--
	Duration (hour)	4000	--
R-410A	Discharge pressure (MPa)	4.2	--
	Suction pressure (MPa)	1.2	--
	Duration (hour)	4000	--

Profilometer: The stylus of a profilometer microscopically follows the contour of a specimen's surfaces and provides a detailed map on the dimension and roughness. This information enables visual and/or quantitative comparisons between parts from new and tested compressors as well as from compressors lubricated by different formulations. Figure 2 shows surface profiles of a vane and a roller from a new compressor. Although vane tip and roller surface were polished during manufacturing, they are not flat when magnified 4,000 times in the vertical direction. To illustrate the usefulness of the profilometer, surface profiles of vanes and rollers from a pass-life-tested R-22/MO compressor and those from a failed one are presented in Figure 3. The difference can easily be observed. Whereas the parts from the "pass" compressor show increased surface roughness, significant wear and major surface profile changes were observed on the parts from the failed compressor.

RESULTS AND DISCUSSION

Wear Test: An antiwear formulation is generally needed if BL is one of the primary operating modes in a mechanical contact. These types of formulations function by chemical reaction of the antiwear agent with the metal surface to form protective films. Falex and four-ball testing can provide guidance to predict BL performance. Results of wear tests on the preferred formulation are presented in Table 2. Both four-ball and Falex show the additized EXP-1280 has better antiwear characteristics than the base oil. In the four-ball wear test, a significant reduction on wear scar diameters was observed at constant loading and in the Falex test the EXP-1280 showed higher load-carrying capability in both air and R-407C environments. Although contact conditions in bench wear tests generally are not complicated enough to correlate with actual compressor tests, the wear test data indicate the chosen antiwear package provide superior protection for a steel-steel contact.

Table 2 Four-Ball and Falex Wear Tests Results

	Ester Base Lubricant	EXP-1280 (Ester Base Lubricant + Antiwear Package)
Four-ball, ASTM D4172, (mm)	0.96	0.66
Falex, in air, (N)	2200	4000
Falex, bubbled w/R-407C, (N)	3500	4400

Compressor Test: One advantage of a low viscosity lubricant is lower frictional drag at the bearings. An ISO VG 32 ester-based lubricant with the antiwear package, EXP-1106, was first tested in R-407C compressors at the conditions specified by Company A (Table 1). These compressors used the same materials of construction as the mass-produced R-22 systems. All compressors were able to complete the 4,000-hour life testing with polishing wear at the bearings. However, significant wear, similar to the failed compressor profiles shown in Figure 3, was observed on the vane-roller contact. The vane nose curvature was also flattened. The severe wear may have been the result of refrigerant dilution which reduced the working viscosity of the lubricant to an unacceptable level. Consequently, BL might have dominated the vane-roller interface and excessive metal-metal contacts had occurred. A higher viscosity lubricant was subsequently evaluated to increase the proportion of HL or EHL at the interface during compression cycles.

EXP-1280, ISO VG 68, was tested under the same conditions as EXP-1106. The compressors had stable operating conditions throughout the 4,000-hour test period. System tear-down showed that copper plating was not observable and there were insignificant deposits in the capillary tubes. The used lubricant was clean and had physical/chemical properties close to the original fluid. No wear metals were detectable. All compressor bearings were in good shape. There was slight polishing on the bearing surfaces most likely caused by the run-in process. The critical vane-roller contacts were checked by the profilometer. A typical result is shown in Figure 4. Although both vane and roller surfaces were roughened slightly, they were in better conditions than the parts from the R-22 compressors tested at similar severity. Satisfactory results were also obtained with R-410A and R-134a compressor tests at conditions listed in Table 1. The roughness and surface profiles of the vanes and rollers from the R-410A compressor were similar to those of the R-407C despite a significantly higher loading. This suggests that this basestock/formulation can be used with any of the three HFCs compressors without modification of the materials of construction.

The impact of an even higher lubricant viscosity was also evaluated. EXP-1448 (KV @ 40° C = 82 cSt) was tested side by side with EXP-1280 and R-407C at conditions specified by Company B (Table 1). All compressors showed stable operating conditions throughout the test period. Surface profiles of the vane and roller after tests are shown in Figure 5. Both EXP-1280 and EXP-1448 were effective; the roughness of the contact surfaces had changed little. Also, the difference between the two lubricants in terms of system cleanliness and wear protection are minimal. There appeared to be no significant benefit to using even higher viscosity lubricants.

Performance Test: The impact of a lubricant on the system performance is just as important as its wear protection capability. Since both EXP-1280 and EXP-1448 are capable of lubricating HFC rotary compressors, they were evaluated with a calorimeter using R-407C at standard ASHRAE test conditions. The compressor capacity, power and EER and oil circulation rate were determined and are shown in Table 3. These data suggest, within the accuracy of the calorimeter, there is essentially no difference in compressor performances between the ISO VG 68 and the higher viscosity lubricant. The EER rating of 10.9 for the EXP-1280 compressor compares favorably with the 10.5 specified for the R-22/MO and R-22/AB systems. One notable difference shown in Table 3 is the oil circulation rate. Based on the parameters measured, however, the increased oil circulation with EXP-1280 is not detrimental to the system performance.

Table 3. Compressor Calorimeter Tests Results

	EXP-1280	EXP-1448
Capacity (Btu/hr)	9483	9445
Power (watts)	872	874
EER	10.9	10.8
Oil Circulating Rate (cc/min)	9.8	6.0

CONCLUSION

The lubrication and performance issues in HFC rotary compressors have been studied. An ISO VG 68 ester-based lubricant , EXP-1280, was developed which demonstrated lubrication capability equal to or better than the R-22/MO systems with the same materials of construction. The lubricant did not produce capillary tube blocking deposits or copper plating after long test periods at high loading conditions with R-407C, R-134a or R-410A refrigerants. The calorimeter test showed the performance of R-407C/EXP-1280 compares favorably to the R-22/MO and R-22/AB systems. The use of higher viscosity lubricants shows no performance advantages.

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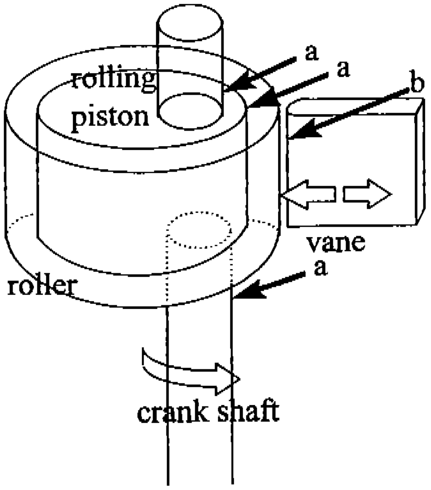

a: journal bearing

b: vane-roller contact

Figure 1. Critical lubrication areas in rotary compressors

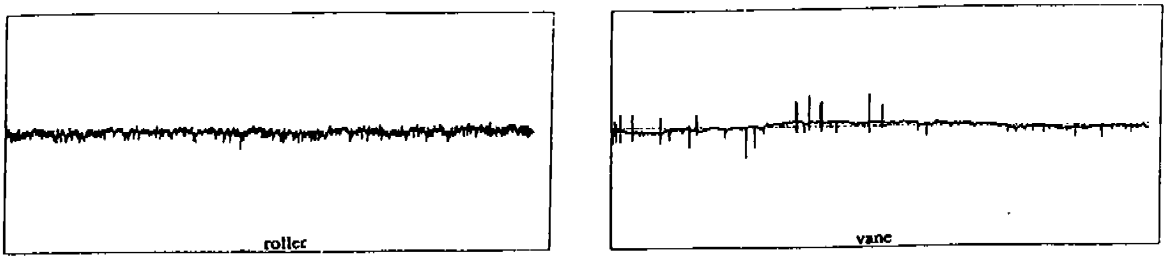

Figure 2. Surface profiles of a new roller and vane

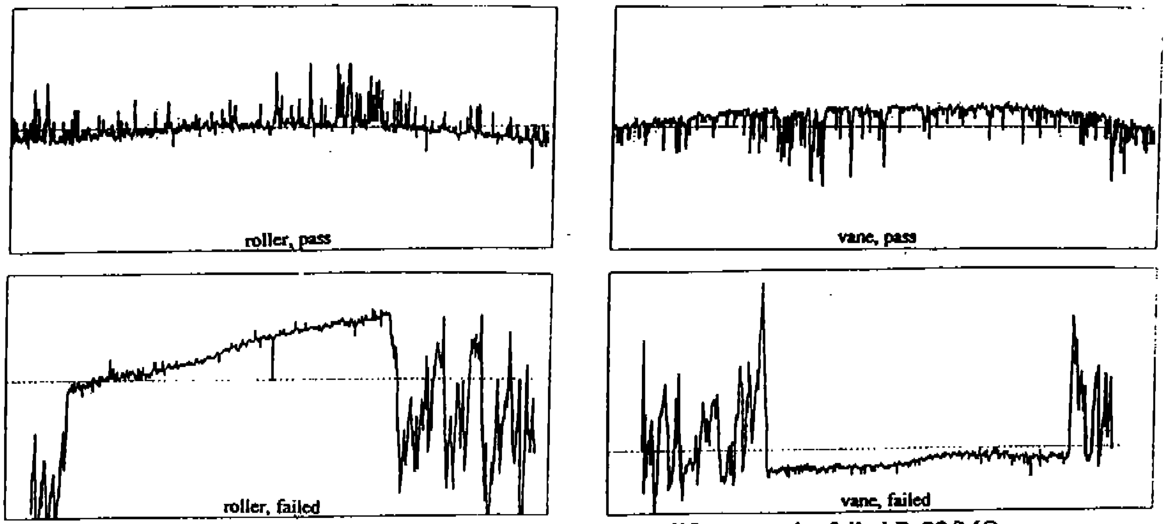

Figure 3. Surface profiles of rollers and vanes from a pass-life-test and a failed R-22/MO compressors

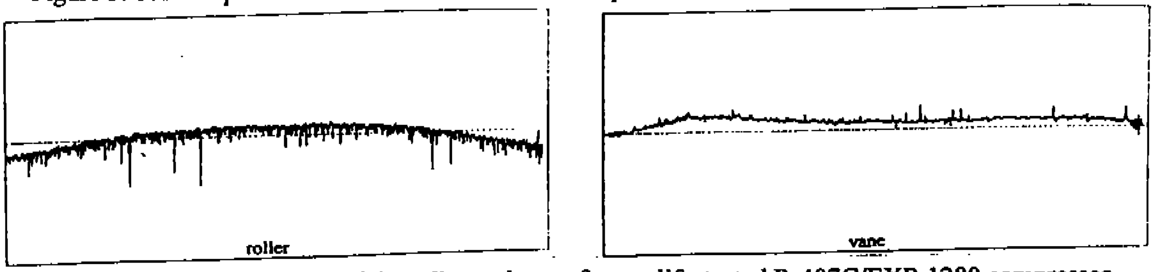

Figure 4. Surface profiles of the roller and vane from a life-tested R-407C/EXP-1280 compressor

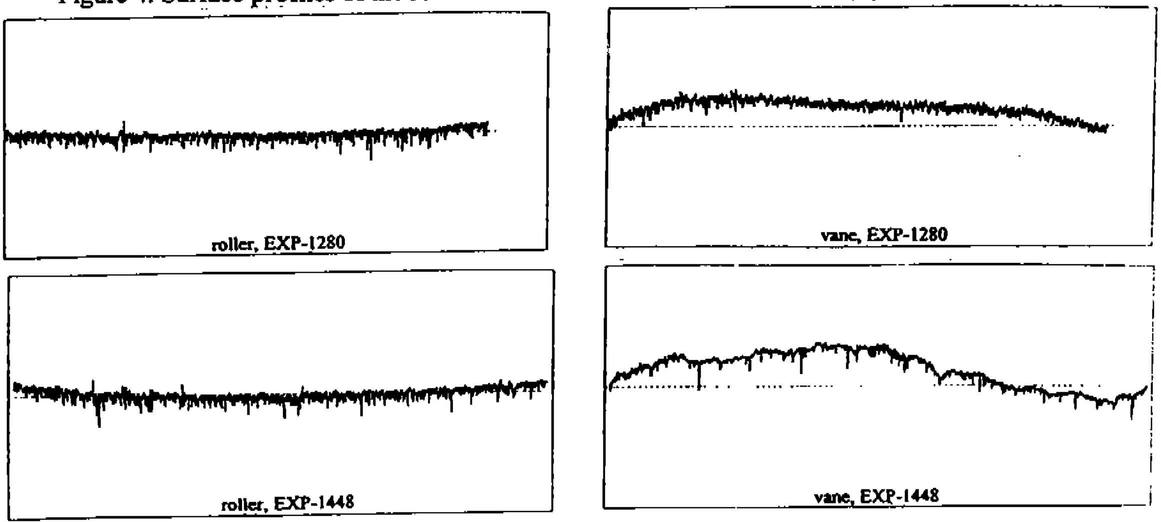

Figure 5. Comparison of surface profiles of vanes and rollers from EXP-1280 and EXP-1448 compressors