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ABSTRACT

The refrigeration and air-conditioning industries are going through rapid changes because of environmental concerns and emerging regulations. Environmentally friendly refrigerants that cause no damage to the ozone layer or global climate are leading candidates for possible replacement of chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants. Extensive research and development efforts have been devoted to carbon dioxide (R-744) due to its favourable thermodynamic and heat transfer properties. The selection of a lubricant for the CO_2 compressor could have a major impact on the reliability and performance of the system. The importance of this issue is further highlighted by the exceptional solvency of CO_2, it's high operating pressure and the acidic nature of CO_2 in the presence of moisture. In this work, laboratory bench tests, compressor tests and field trials were conducted to investigate the performance of various lubricant chemistries with CO_2. The data presented shows that compressor/system manufacturers and lubricant suppliers are making progresses with CO_2 systems that give dependable and efficient performance.

INTRODUCTION

The 1987 Montreal Protocol addressed the important environmental issue of ozone depletion. This led to the phase out of ozone depleting CFC and HCFC refrigerants and the introduction of HFC refrigerants with zero ozone depletion potential (ODP). However, HFCs do have a global warming potential (GWP) and are included in the basket of gases targeted by the 1997 Kyoto Protocol that deals with the issue of global warming. As a result of this, alternative refrigerants with zero ODP and negligible or no global warming impact are receiving attention from manufacturers of refrigeration equipment. One phase of this research and development has focused on carbon dioxide.

CO_2 is generally considered to be non-toxic, is non-flammable, has zero ODP and has net zero GWP when obtained from an industrial waste or by-product source. CO_2 is an attractive candidate refrigerant because of a number of its physical properties as well as its low cost compared to HCFCs and HFCs. Key physical properties include excellent heat transfer characteristics and high volumetric capacity. Compressors utilizing CO_2 as a refrigerant are smaller than those operating with more commonly used refrigerants. Similarly, pipe-work and heat exchangers are also smaller and subsequently less costly (1). The primary drawback to the use of CO_2 is the high operating pressure required in trans-critical systems. Drees et.al. (2) suggested that the high operating pressure and polarity of CO_2 make lubrication of CO_2 compressors difficult.

Supercritical CO_2 is an excellent solvent. This is exemplified by its use in supercritical fluid chromatography (SFC). This solvency may cause excessive lubricant dilution, producing a working lubricant without sufficient viscosity to perform effectively (3,4). Even at sub-critical conditions certain lubricants can be diluted beyond usefulness. This can lead to additional problems such as high oil carry-over and foaming. This solubility effect can significantly reduce the efficiency and reliability of the system if the lubricant is not chosen properly.

This paper discusses the advantages and disadvantages of the types of lubricant available for CO_2 systems. Potential applications include trans-critical operations as well as CO_2/NH_3 cascade systems. The most suitable candidates have been evaluated in compressor tests to compare the performance of different lubricant chemistries. The results of the compressor tests including oil and compressor parts analysis are provided and discussed.

LUBRICANTS

The base lubricant chemistries used in the compressor or system tests included polyalphaolefin (PAO), polyol ester (POE), polyalkylene glycol (PAG) and alkyl naphthalene (AN). These synthetic lubricants were chosen because of their attractive properties such as stability, wide operating temperature range and low volatility.

PAOs are completely saturated synthetic hydrocarbons that enjoy wide acceptance in stringent industrial applications due to their desirable properties. These properties include a wide operating temperature range, chemical inertness, high viscosity index, hydrolytic stability, shear stability, compatibility with mineral oil, low toxicity and good additive response (5). PAO lubricants have been used in low temperature ammonia applications where they have demonstrated superior performance over mineral oils in terms of minimal impact on heat transfer, overall high system efficiency and low system operating temperatures (6).

POEs have wide market acceptance with HFC refrigerants. Applications include appliance, refrigeration and air-conditioning. Ester chemistry allows the use of numerous alcohols and acids that can be combined to tailor make esters with desired properties (7). As a result, POE-based refrigeration lubricants with structures designed to control miscibility and solubility and other properties have been developed.

PAGs are polymers of alkylene glycols. The chemical structure of PAGs can also be varied to give desired miscibility and solubility with the HFC refrigerants. This is often achieved by varying the ratios of ethylene oxide and propylene oxide in the synthesis process (8). Currently, PAGs are the lubricant of choice in most R-134a automobile A/C systems.

ANs are prepared via the alkylation of naphthalene with alpha-olefins. The combination of long chain alkyl groups and an aromatic framework provides improved solvency and stability compared to mineral oils. The hydrocarbon structure results in less affinity for water compared to POEs or PAGs (9). As with other lubricant chemistries, the miscibility of ANs with CO_2 decreases as viscosity (molecular weight) increases. A remedy to preserve the desired miscibility is blending ANs and PAGs. Table 1 summarizes the advantages and disadvantages of the various lubricant chemistries when used with CO_2 (1,2,3,4,11).

Table 1.
Advantages and Disadvantages of Various Lubricant Chemistries with CO_2 Refrigerant

	Advantages	Disadvantages
PAO	Experiences with CO_2 compression Compatible with CO_2 and NH_3	Immiscible Oil return concern Heat transfer concern
AN	Compatible with CO_2 and NH_3 Partial miscibility with CO_2 Limited solubility with CO_2	Limited experience
POE	Very miscible with CO_2 Flexible chemistry	Hydrolysis potential High dilution Incompatible with NH_3
PAG	Compatible with CO_2 and NH_3 Flexible chemistry Controlled solubility with CO_2	Oil return issues
AN/PAG	Compatible with CO_2 and NH_3 Partial miscibility with CO_2 Limited solubility with CO_2	Limited experience

RESULTS AND DISCUSSION

Effect of Lubricant Chemistry on a Trans-Critical Heat Pump System

Lubricants have a significant impact on the performance/efficiency of AC or refrigeration systems. Lubricant chemistry, density, miscibility and solubility with refrigerants are factors that impact system performance. The performance of a refrigeration system is important for compressor OEMs as it indicates the level of energy efficiency and quality of engineering. It can be argued, however, that performance is an even more important issue for CO_2 systems since under-performance would undermine the driving environmental purpose of replacing existing refrigerants with CO_2.

A series of tests to compare the performance of different lubricant chemistries was conducted using an 11 KW stationary heat pump system. The three lubricants evaluated had the same viscosity (ISO VG 68), but their working viscosities were significantly different (3). Important properties of the lubricants are presented in Table 2. Since relatively little oil return experience is available for operating CO_2 systems, an oil separator was built into the test stand to insure lubricant return to the compressor. A brief description of the test configuration and conditions is listed in Table 3. During the test, the system was charged with various amounts of CO_2 and the discharge pressure was adjusted to determine the maximum system performance. Results showed all three types of lubricants afforded peak performance at about the same refrigerant charge. All three lubricants also gave the same level of performance, COP = 2.78.

Table 2.
Test Lubricants Properties

Lubricant	EXP-1927	EXP-1928	EXP-1926
Chemistry	PAO	POE	AN/PAG blend
Miscibility with CO_2	Immiscible	Miscible	Partially miscible
Viscosity 40^{o}C (cSt) 100^{o}C	66 9.9	64 8.9	67 10.3
Viscosity Index	130	114	139
Total Acid No. (TAN)	<0.1	<0.1	<0.1
Metal	None	None	None

Table 3.
Performance Test Configurations and Conditions

Heat Exchanger	**Surface Area (cm^3)**	**Air Inlet Temperature(^{o}C)**	**Air Flow Rate (m^3/hr)**	**Relative Humidity(%)**
Gas Cooler	30	35	2930	40
Evaporator	24	25	2150	50

The three lubricants tested cover a wide range of chemical structures, density and miscibility/solubility with CO_2. It appears that the properties and/or operating characteristics of CO_2 have neutralized some of the effect of the lubricants properties under the test conditions. This finding is in contrast to experience gained with HFC/POE or HFC/PAG systems and is worthy of further investigation.

Lubricant Performance in a Sub-Critical CO_2 Screw Compressor

The use of CO_2 as the refrigerant in the low-pressure side of CO_2 / NH_3 cascade systems is an application that is attracting significant interest. These cascade systems are beginning to be viewed as an alternative to low temperature R-22 refrigeration systems. The CO_2 cycle in these systems is entirely sub-critical, with compressor discharge pressures typically up to about 4 MPa.

One preferred design consideration for cascade systems is that the lubricants in both the high and low sides are compatible with each other and with both refrigerants. This design will prevent unnecessary operational risks or high maintenance costs should the wrong lubricant be charged during servicing. POEs are known to chemically react with ammonia and form solids (6). Therefore, the consequence of accidentally charging a POE to an NH_3 system could be very costly. The best solution appears to be a single lubricant that can be applied to both sides.

Both PAOs and ANs are chemically compatible with NH_3 and CO_2. These lubricants were chosen for evaluation in a CO_2 / NH_3 cascade test facility consisting of a screw compressor operating on the CO_2 (low) stage and a different model screw compressor on the NH_3 (high) stage. The CO_2 compressor was rated to 4 MPa maximum discharge pressure. The CO_2 was condensed in a cascade condenser at –5°C before being expanded and returned to the compressor at –50°C. The three lubricants evaluated in this test rig were: an ISO VG 68 PAO, an ISO VG 68 AN and an ISO VG 32 AN. Results showed that all three lubricants properly lubricated the compressor. One observed difference between the ISO 32 and ISO 68 ANs was the improved sealing of the rotors provided by the higher viscosity product. As the CO_2 was simply expanded through a valve rather than in an evaporator this test rig did not adequately evaluate lubricant return characteristics.

Lubricant Performance in a Trans-Critical CO_2 Reciprocating Compressor

The reciprocating trans-critical CO_2 compressor used in this study has a maximum operating pressure of 15 MPa on the discharge side. The high solubility of lubricants at the high crankcase pressures in these compressors can result in significantly reduced viscosity and possible foaming problems (10). Additional considerations regarding lubricant selection include: high mechanical stresses generated, lubricant resistance to chemical attack by carbonic acid and lubricant carry-over and circulation. AN was chosen as the lubricant meeting most of the desirable characteristics (11). The partial miscibility of ANs with CO_2 should prevent excess dilution while providing sufficient oil return. ANs are also stable in a CO_2 atmosphere.

A 4000 hr life test was conducted with an ISO VG 68 AN in a trans-critical, single stage reciprocating compressor. This experiment provided long-term durability data. The compressor was operated at a suction pressure of 3 MPa and temperature of 10°C. The discharge pressure was controlled at 11 MPa. The test stand was observed regularly and operated smoothly throughout the entire test. The oil level remained steady in the sight glass and the oil differential pressure was stable at 0.32 MPa. Both of these observations indicate a steady oil flow rate in the test system. The compressor was dismantled for inspection after completion of the test. All parts were in good condition and had original dimensions/tolerances.

The good result obtained from the life test prompted more reciprocating compressor tests using different designs/models. A lubricant sample was taken from another compressor after 934 hours of operation. Analytical results from this sample are shown in Table 4. The data in Table 4 clearly indicates the physical properties of the lubricant remained unchanged. There are no detectable metals in the lubricant indicating wear is not a concern. The slightly higher acid number of the test lubricant has been verified not to result from lubricant or additive degradation.

Table 4
Lubricant Physical Properties Before and After Testing

	Original AN 68	**In-house Test 934 hours**	**Field Trial 1000 hr**
Viscosity at 40°C	64.14 cSt	65.11 cSt	65.25 cSt
Viscosity at 100°C	8.70 cSt	8.60 cSt	8.76 cSt
Viscosity Index	108	103	107
Water Content	16 ppm	58 ppm	80 ppm
Total Acid Number	0.156 mgKOH/g	0.632 mgKOH/g	0.256 mgKOH/g
Density	0.887 g/mL	0.892 g/mL	0.889 g/mL
Metals	P = 785 ppm	P = 723 ppm	P = 780 ppm

The successful bench tests with the AN lubricant lead to further evaluation in a field trial. The project selected for the trial was an air conditioning system with a typical evaporating temperature of 2°C. At the time of writing this system had operated successfully for over 1,000 hours. A lubricant sample was evaluated after approximately 1,000 operating hours and the results of this analysis are also shown in Table 4. This sample shows no evidence of any degradation. The field trial is continuing.

CONCLUSIONS

A variety of lubricant chemistries have been evaluated in different CO_2 systems and compressor test stands. The results show that various lubricant chemistries and/or formulations can successfully lubricate CO_2 compressors. System needs must be considered when making a lubricant choice. Factors impacting lubricant return to the compressor, lubricant dilution and lubricant compatibility with system components should all be considered. Bench tests have provided insight into the selection process and have led to ongoing field trials. The results from these field trials will further define the necessary lubricant parameters.

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