Effect of R600a on tribological behavior of sintered steel under starved lubrication

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ARTICLE INFO

Available online 21 December 2009 Keywords: Starved Lubricated Hydrocarbon

ABSTRACT

This paper describes the impact of the isobutane refrigerant on the wear performance of tribopairs at hermetic compressor bearings. The tribological behavior of 100Cr6 steel pin is investigated under starved lubrication condition in air and R600a environments when running against sintered steel which was treated with and without steam. EDS and SEM are carried out on pin and plate samples after wear tests. The results indicate that wear durability is lower for the tests with R600a than those with air. The adverse effect of R600a on wear rate is linked to the change in the viscosity and foaming characteristics of the oil in the presence of R600a as well as the lack of oxides.

1. Introduction

As energy costs increase rapidly, mechanical losses in refrigerator compressors attract renewed attention. Various surface treatments and oil-refrigerant compositions have been proposed to decrease friction and wear in closed type (hermetic) compressors [1–3]. On the other hand, research on the stratospheric ozone layer demonstrated the detrimental effects of conventional refrigerants containing halogens. Discharge or leakage of refrigerants containing chlorine, bromine, and other halogens affects the stratospheric ozone equilibrium [4], and their use has been restricted by Montreal and Kyoto protocols [5,6].

A conventional closed-type compressor uses CFC (chlorofluorocarbon) like R12, or HCFC (hydrofluorochlorocarbon) like R22. Typically these refrigerants work well with mineral oils to achieve desirable wear and friction levels. None chlorine substitute refrigerants mean that favorable lubrication properties of R12 or R22 can not be utilized. As conventional refrigerants phased out, isobutane (R600a) emerged as the main alternative in refrigeration industry. Hydrocarbons (HCs) such as R600a are viable substitutes as they possess favorable refrigerants properties. However, their compatibility and performance with compressor oils are being investigated.

Transition of refrigerants occurred in two phases. First, CFC-12 and HCFC-22 evolved to HFC-134a, and then HFCs were replaced with HCs (R600a). Although there are some research studies on

HFCs, published literature on HC refrigerants remain very limited. This work aims to provide information on friction and wear performance of common compressor bearing materials under R600a atmosphere with common mineral oil.

Solzak and Polycarpou [7] have studied the tribological effects of connecting rod-wrist pin interface with HFC refrigerants. Their experiments with unlubricated and uncoated steel surfaces indicated high friction and wear suggesting the need for protective films. Tribological behavior of some hermetic compressor parts in R134a environment has been studied by a number of researchers [8–10]. These studies show an increase in surface temperatures resulting in the decomposition of thin lubricant films between contacting surfaces. The best wear performance was obtained with R134a with poly-ol-ester (POE) synthetic lubricants due to the release of the fluorides during sliding and decreasing frictional heating.

Alsaad and Hammad [11], Jung et al. [12], indicated that mixture of propane (R290)/butane (R600) and propane/isobutane (R600a) could be successfully adopted for the replacement of CFC-12/HFC-134a. Wongwises et al. [13,14] studied the application of hydrocarbon mixtures R290, R600 and R600a to replace HFC-134a in domestic refrigerators while maintaining low energy consumption. Garland et al. [15] has studied the tribological behavior of some hermetic compressor parts in R134a, R12, and R600a environments. The results indicated a superior coefficient of performance (COP) for R600a over R134a and R12, yet the long term wear and durability of equipment using this refrigerant needs further investigation. Zhelezny et al. [16] studied thermo-dynamic properties of R600a as a function of isobutane/Azmol concentrations. Garland and Hadfield [17] investigated the impact

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of hydrocarbon refrigerants indicating that R600a mixture with mineral oil appeared to be an appropriate long-term candidate to replace R134a.

Although better COP values are achieved with HC refrigerants, wear life related issues need to be resolved since limited literature is available. Possible problem areas include motor/crankshaft journals; crank pin/connecting rod bearings, piston/cylinder sliding interface and the inlet/exhaust flapper valves [18].

Most sliding elements are usually fabricated from sintered iron in order to improve lubricant retention. Steam treatment is also implemented to improve scuffing resistance, prevent seizure, and prolong the life of the critical components. Sintered iron against 100Cr6 is one of the most common tribopairs used in hermetic compressors. This study aims to aid compressor designers in achieving extended life goals by shedding light on friction and wear performance of 100Cr6/sintered iron pairs under R600a atmosphere. With renewed attention to use less and less oil, friction and wear performance under starved lubrication and dry conditions are also presented.

2. Experimental details

The sintered disc material was prepared from the iron powder of 5–100 μ m grade size at a constant compaction pressure of 475 MPa, containing (wt%) 0.30 C, 0.0043 S, 2.44 Cu, 0.21 Si, 0.54 Mn, and the remaining being Fe at a density of 6.8 g/cm³. Sintering process was conducted in a mildly reducing atmosphere of 75% N₂+25% H₂ at a constant temperature of 1120 °C for 25–30 min. Then samples were cooled at 1.0 °C/s to room temperature in a H₂ atmosphere with a low dew point. As-sintered samples had a bulk hardness around 85 HRF. The surface roughness (Ra) of 0.50 μ m was measured. Steam treatment involved 2 h of pre-heat process at 100 °C prior to steam oxidation for 1 h at 600 °C, and following 2 h of cool-down process in the furnace. Steam treated samples had a bulk hardness around 102 HRF.

A standard pin-on-disc test rig was used. A 100Cr6 steel pin (1250 HV), 7.89 mm in diameter and of a 5 mm in length, was rubbed sideways against a rotating sinter disc. Prior to each test, samples were cleaned in an ultrasonic cleaner for 15 min in acetone, followed by 15 min cleaning in ethanol. Dry sliding tests were conducted in an atmosphere with 60-70% relative humidity and at a temperature around 23 °C. For starved oil lubrication tests, mineral oil (We 7125 compressor oil), with a viscosity of 7cSt at 40 °C, was misted on the sliding surface for 1 s at 30 psi oil pressure through a fully controlled nozzle at the beginning of the each wear test. The amount of oil used at each test was measured to be 100 mg. No other oil was introduced throughout the test. Applied loads of 40 N and 50 N, as well as the speeds of 0.26 m/s and 0.8 m/s were chosen for these tests. New pin and disc were used for each test and the track diameter was kept constant for each sliding speed so as to eliminate this as a further variable. All of the disc specimens investigated in this study were kept in desiccators before and after their friction/wear tests.

The R600a gas pressure and composition inside the tribometer was monitored with a flow regulator. A large isolated Plexiglas cage was used to ensure atmosphere control to observe frictional behavior in isobutane atmosphere. Being heavier than air, R600a refrigerant was introduced from a lower point while excess atmosphere is bled through a higher exhaust to ensure that the entire test system is submerged in R600a atmosphere. To facilitate uninterrupted R600a exposure, refrigerant is continuously fed to the system.

The amount of wear was determined by appropriate measure of the weight of both specimens before and after each test (Table 1). Initial weight of pins and disc were measured after Table 1

The test conditions of pin-on-disk tribometer tests.

Parameters	Conditions
Applied load (N) Velocity (m s ⁻¹) Rotational speed of substrate (rpm) P.V. (MPa m s ⁻¹) Wear track (mm) Environment Temperature (°C) Humidity (%RH)	50 0.8 350 8 21.90 Air, R-600a 23-25 55-60

cleaning in acetone and ethanol followed by drying operation using an electronic weighing balance with 0.1 mg accuracy. The wear rates were obtained by dividing the wear volume by the load and the total sliding distance. Wear tests were conducted at normal loads of 50 N. A fresh abrasive surface was used in every test. The surface microstructures of the wear tracks of each specimen and its paired pin were investigated using JEOL JSM 7000F scanning electron microscope (SEM) with energydispersive X-ray spectroscopy (EDS).

3. Results and discussion

In order to facilitate easier comparison of various cases, wear tests at identical conditions were conducted in both R600a and air environment. First, friction and wear performance of both pairs under dry conditions were tested [19]. The weight loss measurements were taken for applied loads of 40N and 50N. Fig. 1 illustrates weight loss against the test time at a constant sliding speed of 0.26 m/s. It is observed that the load increase changes the wear regime, and wear rate was more than doubled with 25% load increase. However, steam treatment had a favorable effect decreasing the wear rates by four-folds as compared to untreated sinter material. The lower wear rate for steam treated sinter sample was due to sealing of pores and formation of oxide layer during steam treatment, which in turn forms a smoother sliding surface. As shown in Fig. 2, accompanied by an excessive noise and vibration during testing, the coefficient of friction fluctuated more for the untreated sinter sample. This is due to the accumulation of laminar oxidized wear particles and smearing on track as seen in Fig. 3.

When dry tests were repeated in R600a environment, it has been observed that wear rate increases when compared with that in air (Fig. 4). The oxidation of iron contributed significantly to the reduction of wear rate for samples tested in air. The hard oxides form a protective layer, and increase wear life. However, under R600a environment, EDS analysis showed that the oxidation of iron was obstructed (Fig. 5). The results clarify that introduction of R600a degrades wear performance of sintered surfaces (Fig. 6).

As starved lubrication tests took much longer, test speed had to be raised to 0.8 m/s to achieve longer sliding distances in a shorter test period. Wear performance is established by comparing the sliding distance before the sudden increase and fluctuation of the friction curve. When plotted against the sliding distance versus COF, the transition in friction coefficient is noticeable in Fig. 5 for both air and R600a environments. Just as observed in dry test conditions, introduction of R600a during starved lubrication tests resulted in noticeable reduction in wear performance (wear durability). Adverse effect of R600a on wear is thought to be due to change in viscosity and foaming characteristics of the oil [20,21].

It is clear that the micro structural features of the sintered material greatly affect the properties of the oil absorbed layer,



Fig. 1. Weight loss under dry sliding at 40 N and 50 N, at RT and 0.26 m/s: (a) Sinter; (b) ST-Sinter.



Fig. 2. Fluctuation in coefficient of friction under dry sliding at 50 N at RT and 0.26 m/s: (a) Sinter; (b) ST-Sinter.





Fig. 3. SEM micrograph of the wear tracks: (a) ST-Sinter; (b) Sinter.



Fig. 4. Weight loss under dry sliding at 50 N, RT and 0.8 m/s for in air and R600a.

which in turn influence the wear durability. The observed higher wear durability for untreated sintered steel is attributed to higher porosity levels which resulted in higher oil absorption of pores providing a smoother sliding surface by supplying oil over extended time period. For the steam treated sintered steel this distance was shorter since the oil absorption gets lower due to



Fig. 5. EDS analysis results for sinter iron samples after wear tests in (a) air; (b) R600a.

sealing of the pores during heat treatment process. The adverse effect of R600a on wear regime was noticeable for both untreated and steam treated sintered steel, showing 50% decrease for untreated case, and more than 60% decrease for the steam treated case. The wear rate results in Table 2 point out that 100Cr6 steel have longer life than sintered steel. This is due to the hardness of the 100Cr6 pins, which is greater than that of the sintered steel.

4. Conclusions

Low cost and ozone-friendly hydrocarbons like isobutane are replacing other conventional refrigerants. The results of the current study indicate that introduction of R600a refrigerant in to the compressor bearings will have adverse effects on friction and wear performance at critically loaded interfaces. Adverse effect of R600a environment is notable for both dry and starved lubricating conditions. Especially for starved lubrication case, the wear life for both untreated and steam treated sintered steel was almost reduced in half in the presence of R600a as compared to that of in air. The decrease in wear resistance of all samples under R600a is thought to be due to change in viscosity and foaming characteristics of the oil. Furthermore, EDS analyses of untreated steels indicate that the oxidation under R600a was blocked, causing an increase in weight loss of untreated sintered iron. Overall, these results raise the question as to how effective the starved lubrication by itself can be in achieving ambitious targets for controlling the wear rate in ambient of R600a.



Fig. 6. Transition in friction coefficient under starved lubrication in air and R600a.

Table 2

The wear rate and weight loss of steam treated sintered steel (ST), and no steam treated sintered steel (NT) under air and isobutane (R600a) conditions

Samples	Air		R600a	
	Wear rate $(mm^3 N^{-1} m^{-1})$	Weight loss (g)	Wear rate $(mm^3 N^{-1} m^{-1})$	Weight loss (g)
ST Sintered NT Sintered 100Cr6 (ST) 100Cr6 (NT)	$\begin{array}{l} 1.35 \times 10^{-5} \\ 0.76 \times 10^{-5} \\ 4.17 \times 10^{-8} \\ 1.46 \times 10^{-8} \end{array}$	0.24 0.17 0.0009 0.0004	$\begin{array}{l} 4.71 \times 10^{-5} \\ 4.52 \times 10^{-5} \\ 2.50 \times 10^{-8} \\ 4.07 \times 10^{-8} \end{array}$	0.30 0.50 0.0002 0.0006

Acknowledgments

This paper presents part of the work carried out under the project (106M310) supported by The Scientific and Technological Research Council of Turkey, TUBITAK.

References

- [1] Honma H, Closed-type compressors, Japan, U.S. Patents 5,531,574, 1996.
- [2] Hart et al., Bushingless piston and connecting rod assembly and method of manufacture, U.S. Patents 6,557,457, 2003.
- [3] Endo Y, Satoh E, et al. Displacement type compressor and method of forming coating film, Japan, U.S. Patents 6,079,963, 2000.
- [4] Calm JM. Emissions and environmental impacts from air-conditioning and refrigeration systems. International Journal of Refrigeration 2002;25: 293–305.
- [5] United Nations Environmental Programme, Montreal protocol on substances that deplete the ozone layer, Final Act, New York: United Nations; 1987.
- [6] Global Environmental Change Report. A brief analysis of the Kyoto Protocol., vol. IX, No. 24, 1997.
- [7] Solzak AT, Polycarpou AA. Tribology of WC/C coatings for use in oil-less piston-type compressor surface and coating technology. Surface and Coating Technology 2006;201:4260–5.
- [8] Safari S, Hadfield M. Wear behaviour of the piston/gudgeon pin in a hermetic compressor with replacement CFC refrigerants. Wear 1998;219:8–15.
 [9] Sheiretov T, Hyung Y, Cris C. Scuffing under dry sliding conditions—part I:
- [9] Sheiretov T, Hyung Y, Cris C. Scutting under dry sliding conditions—part 1: experimental studies. Tribology Transactions 1998;41(4):435–46.
- [10] Nicholaos GD, Andreas AP, Thomas FC. Tribological studies on scuffing due to the influence of carbon dioxide used as a refrigerant in compressors. Tribology Transactions 2005;48:336–42.

- [11] Sheiretov T, Hyung Y, Cris C. Scuffing under dry sliding conditions—part I: experimental studies. Tribology Transactions 1998;41(4):435–46.
- [12] Jung D, Kim CB, Song K, Park B. Testing of propane/isobutane mixture in domestic refrigerators. International Journal of Refrigeration 2000 517–27.
- [13] Wongwises S, Chimres N. Experimental study of hydrocarbon mixtures to replace HFC-134a in a domestic refrigerator. Energy Conversion and Management 2005;46:85–100.
- [14] Wongwises S, Kamboon A, Orachon B. Experimental investigation of hydrocarbon mixtures to replace HFC-134a in an automotive air conditioning system. Energy Conversion and Management 2006;47:1644–59.
- [15] Garland NP, Hadfield M. Environmental implications of hydrocarbon refrigerants applied to the hermetic compressors. Material and Design 2005;26:578-86.
- [16] Zhelezny PV, Vitaly P. An experimental investigation and modelling of the thermodynamic properties of isobutane compressor oil solutions: some aspects of experimental methodology. International Journal of Refrigeration 2007;30:433–45.
- [17] Garland NP, Hadfield M. Tribological analysis of hydrocarbon refrigerants applied to the hermetic compressor. Tribology International 2005;38: 732–9.
- [18] Na BC, Chun KJ, Han DC. A tribological study of refrigeration oils under HFC-134a environment. Tribology International 1997;30(9):707–16.
- [19] Sariibrahimoglu K, Kizil H, Aksit MF, Efeoglu I, Birol FS. A study on wear rates of 100Cr6 steel running against sintered steel surfaces under dry and starved lubrication. In: Proceedings of Conf. of Metallurgists, COM 2008, Winnipeg, Canada; 2008. pp. 71–75.
- [20] Goswami DY, Shah DO, Jotshi CK, Bhagwat SS, Leung MK, Gregory AS. Foaming characteristics of HFC refrigerant. ASHRAE Journal 1997;39(6) 39-44.
- [21] Fukuta M, Yanagisawa T, Omura M, Ogi Y. Mixing and separation characteristics of isobutene with refrigeration oil. International Journal of Refrigeration 2005;28:997–1005.