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ULTRA HIGH PRESSURE TRIBOMETER FOR TESTING CO₂ REFRIGERANT AT REALISTIC COMPRESSOR CONDITIONS AND THE ROLE OF CO₂ IN THE TRIBOLOGICAL BEHAVIOR OF COMPRESSOR SURFACES

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ABSTRACT

In recent years, the environmental necessity to replace HFC refrigerants with natural refrigerants like carbon dioxide (CO₂) in refrigeration and air-conditioning applications has led to the development of an Ultra High Pressure Tribometer (UHPT) specifically customized for testing in CO₂ environment at pressures comparable to those found in compressors up to 13.8 MPa (2000 psi). It was found that at three different pressures of CO₂ refrigerant under unlubricated conditions the experimental results were similar. However, under boundary-lubricated conditions, the highest pressure had a slightly more positive effect on friction than in the case of the lower pressures. Furthermore, the role of oxygen and in particular CO₂ in the tribological performance of compressor surfaces was examined. It was found that the presence of oxygen is beneficial and that the use of CO₂ promotes a different wear mechanism than in the case of pure O₂ while it is superior to other environments.

1. INTRODUCTION

In recent years, the interest of the refrigeration industry in CO₂ to be used as a refrigerant has increased due to the fact that it is an environmentally friendly, non-flammable, nontoxic and economical solution to the harmful hydrofluorocarbon refrigerants (HFCs) widely used today in many applications (Domanski, 1998, Lorentzen, 1995). Even though CO₂ has long been a proven refrigerant from a thermodynamic standpoint and has been used in the past for refrigeration applications, the high operating pressures limited its use in refrigeration systems. The operating pressures with CO₂ are an order of magnitude higher in comparison with conventional refrigerants. However, advances in compressor designs have eliminated concerns regarding design criteria and safety due to the different thermodynamic properties of CO₂ and the different range of pressures required for the CO₂ refrigeration cycle for typical applications in refrigeration (Lorentzen, 1995, Hagita, et al., 2002).

Tribology plays a crucial role in the progress of work related to CO₂ as a refrigerant. In recent years, comparative studies of refrigerants and their tribological performance have been performed (Lee et al., 2005, Demas and Polycarpou, 2005). These studies focused in comparisons of different loading techniques and environmental conditions under CO₂ environment and the effects these testing conditions have on wear of the interacting surfaces. Even though these works provided helpful insight in regards to the behavior of CO₂ they focused in investigations at relatively low pressures up to approximately 3.1 MPa due to equipment restrictions. In order to investigate the tribological behavior of CO₂ during compression, testing at pressures up to 13.8 MPa are required, even though the thermodynamic operating conditions for a compressor operating with CO₂ may vary among different manufacturers. Furthermore, the role of CO₂ has not been studied from a tribological perspective but it is important to know the implications of its use.

In this work, we introduce a unique machine that has been custom designed and manufactured to allow testing under CO₂ refrigerant environment at pressures comparable to those found inside compressors. The Ultra High Pressure Tribometer (UHPT) was used to investigate the tribological behavior of contact surfaces under different testing conditions and a wide range of environmental pressures while it made possible the study of the effects of CO₂. This machine is capable of simulating both extreme conditions, when the compressor runs without lubricant, as well as ideal conditions, under which the contact interface is submerged in lubricant in pressures up to 13.8 MPa.
2. DESCRIPTION OF THE UHPT

The UHPT was specifically manufactured for CO₂ testing and was developed to conduct controlled tribological experiments using realistic compressor components under different environmental conditions. A photograph of the UHPT is shown in Figure 1.

![Ultra High Pressure Tribometer (UHPT)](image)

Figure 1: Photograph of the Ultra High Pressure Tribometer (UHPT)

The UHPT is a servo-hydraulic machine with two major components. The upper part contains the pressure chamber, test samples, actuator interfaces and load frame. The lower part of the machine contains the hydraulic power supply and the electrical and control systems.

The UHPT uses a lower stationary sample in contact with an upper rotating sample as shown in Figure 2. There are two important parts that make the tribo-contact possible. The first part is a base holder, which serves as the mounting surface for the lower specimen holder. A hole-pattern permits the holder to be securely mounted to a force transducer module. The lower specimen holder is self-aligning to ensure that the contact between the pin and the disk remains flat during testing. The second part is an upper holder that serves as the mounting surface for the disk sample. This part is attached onto a rotating spindle controlled by an AC servo control motor.

Another important part of the tribological interface is a removable quartz sleeve that serves as the lubricant reservoir during testing. The sleeve, when used, is sealed at the bottom by an O-ring that surrounds the cup and permits the cup to be filled with a lubricant, completely submerging the contact to be tested. An infrared camera that fits through a sight port that is machined in the wall on the backside of the pressure chamber allows for viewing of the contact during testing.

In order to allow for pressurized environment, the test must take place within a pressure chamber. The chamber of the UHPT is rated for 13.8 MPa operating pressure and consists of two parts separated by an O-ring seal that come together to form the pressure housing as shown in Figures 2. The environmental chamber temperature can be controlled from 0°C to 100°C by means of a recirculating cooling/heating unit.

Inside the pressure chamber a miniature thermocouple is used to measure near-contact temperature by inserting it into a small drilled hole underneath the pin specimen, and an electrical contact resistance (ECR) measurement can provide indirect information about the regime of lubrication, the formation of protective surface films and the extent
of metal-to-metal contact. Specifically, if the samples are fully separated (by air or lubricant), the contact resistance is infinite. On the other hand, if the asperities experience significant contact, the contact resistance should theoretically be zero. For the specific electrical contact resistance (ECR) circuit used in the UHPT, an ECR value of $10^{-2}$ ohms indicates that a significant number of asperities are contacting, while $10^2$ ohms indicates that fewer asperities are contacting. These numbers are empirical and only relevant to the instrumentation and sensors in our laboratory. Details of these features are shown in Figure 2.

![Figure 2: Close-up photograph of the pressure chamber](image)

The force transducer used in the UHPT is outfitted with an array of strain gages, which are used to measure frictional forces ($F_x$, $F_y$) and normal load force ($F_z$), as well as moments $M_x$, $M_y$, and $M_z$. The strain gages are connected to a data acquisition card, and computer software is used for recording the data during testing. The capacity of the load cell in the normal direction is 4448.2 N and in the friction direction is 2224.1 N. The force transducer is attached onto a 25.4 mm diameter shaft that moves along the vertical direction via hydraulic actuation.

There are two main components that make up the control system, an interface board and a control box. All sensors located throughout the machine pass through the interface board. The sensors include potentiometers for position control, stain gages for force measurement and temperature and pressure measurements. The control box is an Ethernet enabled digital PID controller that was specifically developed for the UHPT. It has 8 independent PID control channels, 6 strain gage bridge input channels, and 9 high level analog input channels which may be software selected to provide feedback for the PID control loops. The control instrument interconnects with a PC through a BNC Ethernet cable. The Ethernet connection provides both data and control interface. For the specific tribological research in our laboratory, the UHPT main features are computer control of the axial load and the rotational velocity of the specimen.

The software of the machine provides both operating and programming controls. Operating controls consist of simple single button controls to start, stop, pause and home the machine’s actuators. Manual controls are provided to jog and position the actuators for setup and test sample loading. Once the samples have been loaded, the start control can be used to initiate a specified test.

### 3. EXPERIMENTAL PROCEDURE

The pin-on-disc contact geometric configuration was used for the experiments in this study. The types of tests performed were series of unlubricated and boundary lubricated experiments. For the unlubricated experiments, only CO$_2$ refrigerant was used, while for the boundary lubricated experiments, CO$_2$ refrigerant and PAG (ISO VG 46) lubricant were used. Both types of tests were performed at pressures ranging from 1.4 MPa to 6.9 MPa of CO$_2$. 

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refrigerant. The results at the lower range of pressures for the experiments performed on the cast iron were
compared with experimental data previously obtained using an existing High Pressure Tribometer (HPT) (Demas
and Polycarpou, 2005) suitable for testing under refrigerant environments (Yoon et al., 2002, Cavatorta and Cusano,
2000).

The contacting surfaces for the unlubricated experiments were performed using gray cast iron pins on gray cast iron
disks, while the tests performed under boundary lubricated conditions were performed using 52100 steel pins in
contact with Al390-T6 disks. The materials tested were actual samples used in compressors. The first material
interface is found in scroll compressors while the latter in swash plate automotive compressors. The samples were
 machined to fit the holders of the UHPT and were placed in sealed containers to prevent contamination. Before
initiating a test, the samples were pre-screened both optically and using a contact profilometer, to ensure they have
minimal surface damage from scratches. Also, the root mean square surface roughness of all samples was measured
with a contact profilometer using 1 mm long scans and was found to be 0.3-0.6 \( \mu \)m for the cast iron pins and disks,
while the roughness of the Al390-T6 disks was 0.5-0.8 \( \mu \)m and the roughness of the 52100 steel pins was 20 nm.
Subsequently, the samples were immersed in a pool of acetone and ultrasonically cleaned, then rinsed with alcohol
and dried using warm air. After tribological testing, the samples were again ultrasonically cleaned and used for
wear quantification, surface topography measurements and further analysis.

In order to demonstrate the capability of the UHPT various experiments with different loading conditions were
performed. The first set of experiments was under dry conditions in the presence of CO2 refrigerant only. This set
of experiments was performed at pressures ranging from 1.4 MPa to 6.9 MPa of CO2 refrigerant. It should be noted
that pressures up to 13.8 MPa are possible using special CO2 canisters in order to supply them to the UHPT. The
load applied between the contact interfaces was 44.5 N and the rotational speed of the disk was 1030 rev/min which
for the geometrical configuration of this work corresponds to a linear speed of 2.4 m/s, while the test duration was
set for 10 minutes for all environments. This set of experiments was performed using a constant load for which the
friction coefficient was determined.

A different series of experiments under boundary lubrication conditions were performed at 1.4 MPa to 6.9 MPa of
CO2 refrigerant. In this case, the interface was separated with a small amount of oil applied at the pin before testing.
The load applied between the contact interfaces in this case was 222 N and the rotational speed of the disk was 1030
rev/min while the test duration was set for 5 minutes. This set of experiments was also performed using a constant
load for which the friction coefficient was determined.

Finally, the last series of experiments was performed in the presence of atmospheric air, N2, O2, and CO2. The
chamber pressure was set to 0.69 MPa for all gases under gas phase conditions while air was at atmospheric
conditions. No lubricant was used for any of these tests. Furthermore tests in R134a refrigerant at 0.17 MPa were
performed. All tests were conducted at ambient laboratory conditions of 21-22 °C and 40-50 % RH. The normal
load applied between the contact interfaces was 44.5 N.

4. EXPERIMENTAL RESULTS AND DISCUSSION

A series of experiments under non-lubricated conditions was performed at pressures of 1.4 MPa, 4.1 MPa and 6.9
MPa. Figure 3 (a) shows a representative photograph of one of the disk specimens tested at 1.4 MPa, while Figure 3
(b) shows the corresponding long profilometric wear measurement of the disk specimen after testing. The scan
started and finished outside the wear track as shown in Figure 3 (a). It is seen that the wear is relatively mild due to
the low normal load applied between the surfaces. The profilometric scan was 7 mm long and the wear depth was
approximately 0.6 \( \mu \)m. The wear depth of the rest of the disk specimens was very similar, i.e. always less than 1 \( \mu \)m
deep. However, it should be noted that higher loads than 44.5 N result in severe wear and the test has to be stopped
within seconds after initiation. Furthermore, the results are better under CO2 refrigerant environment in comparison
to results performed under the same loading conditions in air at atmospheric pressure at the same temperature, which
resulted in severe wear. This is in agreement with previous work (Demas and Polycarpou, 2005).

Figure 4 (a), (b) and (c) shows a series of tests under boundary lubrication conditions at pressures of 1.4 MPa, 4.1
MPa and 6.9 MPa, respectively. A small amount of lubricant of approximately 20 mg was applied onto to the pin
before testing. The friction coefficient was relatively constant for all cases. Three tests at each pressure were
performed and the results were very similar, thus, only representative results are shown. In the case of 1.4 MPa the friction coefficient had a mean value of 0.086 with a standard deviation of 0.009. The coefficient of friction in the case of 4.1 MPa was very similar as in the case of 1.4 MPa, taking a mean value of 0.084 with a standard deviation of 0.011. However, at the higher pressure of 6.9 MPa the friction coefficient was lower than in the previous two cases taking a mean value of 0.059 with a standard deviation of 0.009. Due to the presence of lubricant there is only very mild wear for all cases. The ECR measurement confirms that in all cases the interface was under the same lubrication regime. A photograph of the disk after testing is shown in Figure 5 (a). The profilometric scan was 12 mm long. From the profilometric measurement shown in Figure 5 (b) that corresponds to the disk specimen tested under the pressure of 4.1 MPa it can be seen that mild burnishing of the topmost asperities occurred. The profilometric measurements under 1.4 MPa and 6.9 MPa were very similar with the measurement under 4.1 MPa. In all cases the burnishing depth was approximately 0.35 μm.

Figure 3: (a) Photograph, and (b) profilometric measurement of disk specimen after testing in CO₂ refrigerant at 1.4 MPa (200 psi) under dry conditions and 22°C using the UHPT (Cast iron/Cast iron)

Figure 4: Comparison of experimental results in CO₂ refrigerant under boundary lubricated conditions at 22°C using the UHPT (Al390-T6/Steel 52100) and pressures: (a) 1.4MPa (200 psi), (b) 4.1 MPa (600 psi), and (c) 6.9 MPa (1000 psi)
Finally, the friction and wear performance of gray cast iron samples under different environmental conditions was examined first in N\textsubscript{2} environment, where the pin wore out completely at approximately 2 minutes, so the test was stopped prematurely. In atmospheric air conditions, the results were slightly less severe. In this case the test lasted for the whole duration of 10 minutes. In R134a environment the wear was significantly less than in the case of N\textsubscript{2} and air environments. Under O\textsubscript{2} environment, there was rapid oxidation and visible iron oxide “rust” debris, however there was less severe wear overall compared to the case of N\textsubscript{2}, air and R134a. When CO\textsubscript{2} was used the results were considerably different than all of the other environments. There was no measurable wear, but mild burnishing of the topmost asperities. This is a significant finding, as in past CO\textsubscript{2}-related research under lubricated conditions it was reported that the tribological performance of CO\textsubscript{2} refrigerant was about the same as conventional refrigerants. However, in this work (under unlubricated conditions), CO\textsubscript{2} clearly performs superior than any of the other cases considered.

Subsequently, the wear tracks of the disks tested in the different environments were examined using an optical microscope. Representative images for each case are shown in Figure 6, with Figure 6(a) showing a virgin sample before testing.

Figure 6: Optical micrographs of (a) virgin sample and (b)-(f) inside the wear track of the disks tested using: (b) N\textsubscript{2}, (c) Air, (d) R134a (e) O\textsubscript{2} (f) CO\textsubscript{2} (sliding direction shown by thick hollow arrow)
It can be seen that machining marks on the virgin disk surface are dominant, while the machining marks are no longer present in the images of Figure 6(b)-(d) due to the fact that the wear due to tribological testing was sufficiently severe to remove them. Machining marks are slightly visible in the image of Figure 6(e), which corresponds to the disk sample tested in O2 environment, while they are prevalent in the case of the disk sample tested in CO2 environment as seen in Figure 6(f). Furthermore, in the latter case, smooth areas between the machining marks can be observed, compared to the virgin sample (figure 6(a)). This surface “polishing” effect was generated by mild wear process or burnishing.

Figure 7: Surface profiles of the wear track of disks tested in
(a) N2, (b) Air, (c) R134a (d) O2 and (e) CO2

From Figure 7, it can be clearly seen that the most severe wear occurred in the presence of N2 environment, with a wear depth of approximately 25 μm (figure 7(a)). In the case when air was used the wear was also significant, with an average wear depth of 11 μm, shown in Figure 7(b). Note that in the case of the atmospheric air environment, as well as in the case of R134a shown in Figure 7(c) (average wear depth is 5 μm), the wear track is significantly rough, indicating a different wear mechanism, and that the wear depth calculation is based on the average wear depth. In figure 7(d) the wear depth was determined to be approximately 5 μm, which corresponds to the case of the disk tested in O2. Furthermore, the roughness inside the wear track is an order of magnitude smaller than in the case of R134a, indicating that the wear mechanisms between the two cases were different. It has been suggested that the “smoothing” in the wear track is attributed to the formation of a surface coating consisting of graphite in the metal structure and iron oxide, rather than wearing off the topmost asperities. This coating may cover valleys and surface irregularities and produce a smooth surface. Finally, only mild burnishing occurred in the case of CO2. In this case, asperity tops are worn off to provide flat contact regions as seen in Figure 7(e). Specifically, due to this burnishing phenomenon, the skewness value decreased from a value of –1.03 to –1.85 when compared the virgin with the CO2 tested surface. X-ray photoelectron spectroscopy (XPS) was utilized to detect the different chemical states resulting from compound formation on the tribologically tested surfaces. It was found that CO2 leads to better tribological
performance of the interface due to the formation of carbonates on the surface, which reduces friction and prevent wear.

5. CONCLUSIONS

A custom designed Ultra High Pressure Tribometer (UHPT) has been introduced in order to investigate the tribological behavior of contact surfaces under different testing conditions in carbon dioxide (CO₂) refrigerant environment at environmental chamber pressures comparable to those found inside compressors, i.e. up to 13.8 MPa. Two different series of experiments were performed in this work. These were unlubricated and boundary lubricated with PAG oil both under the presence of CO₂ refrigerant over a range of pressures between 1.4 MPa and 6.9 MPa. It was found that under the unlubricated conditions the experimental results at different pressures were similar as was also confirmed by profilometric techniques. Under boundary-lubricated conditions, there was no significant wear but only burnishing. The burnishing was quantified by profilometric techniques. Furthermore, the results appear very similar at pressures up to 4.1 MPa. However, the higher pressure seems to have a slightly positive effect on friction as indicated by the friction coefficient values reported being lower than in the case of the lower pressures. Furthermore, series of experiments was performed in environments of air, nitrogen (N₂), oxygen (O₂) and carbon dioxide (CO₂). While it was found that the presence of oxygen is beneficial, CO₂ has a more positive effect on the surfaces than in the case of pure O₂ suggesting that the use of CO₂ promotes a different wear mechanism.

The tests in this work demonstrate that testing at very high chamber pressures similar to the pressures inside an air-conditioning compressor is possible. This is a very important step in tribological testing in the presence of CO₂ that has not been undertaken before and will provide insight on the tribological behavior of CO₂ at very high pressures. Furthermore, the findings in this work support the tribological advantage of CO₂ refrigerant compared to conventional HFC refrigerants, especially in the absence of lubrication, as it clearly demonstrates lubricity capabilities.

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