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THE STATE OF COMPRESSOR LUBRICATION AS MEASURED BY CONTACT RESISTANCE DURING TWO TRANSIENT TESTS

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ABSTRACT

Understanding the state of lubrication in refrigeration compressors is fundamental for identifying causes of compressor failure. This article will discuss a practical method for measuring the contact resistance between the shoe and swashplate sliding contacts of a mobile air conditioning swashplate compressor. The contact resistance between the shoe and swashplate can be used to indicate the degree of metal-to-metal contact between the sliding surfaces in the compressor.

The results of measurements made on the compressor with oil return shut off and during slugging start up events are presented. The results demonstrated that the contact resistance method is a practical research and development technique and it shows surprising behavior during oil shut off tests. In addition, results of dynamic pressure measurements taken within the compressor swashplate cavity are presented. The latter results show promise for this technique as a diagnostic tool for production compressors.

INTRODUCTION

The state of lubrication in swashplate compressors during failure is not well understood. With oil film breakdown, compressor failures usually occur at either the shoe/swashplate interface, the piston bridge, or the piston ring. Understanding oil film breakdown is critical to predicting possible failure conditions that occur in the compressor.

Two promising methods for early failure conditions have been developed. The more direct method is the measurement of electrical contact resistance at the shoe/swashplate interface. Previous work by Yoon and Cusano [1999] on a pin-on-disk machine has demonstrated that there is a significant drop in contact resistance when oil film breakdown occurs. A less direct, but less intrusive, method is the measurement of the dynamic fluid pressure in the swashplate cavity. Both methods can be used during steady state as well as transient loop conditions.

The results in this paper are part of ongoing research involved in the study of oil circulation in a swashplate compressor loop using PAG lubricant and R134a. The methods and some results for steady state conditions have been presented in Drozdek et al. [2000]. This paper focuses on two transient conditions: oil shut off and slugging of liquid refrigerant during start up. Future work will investigate dry start conditions and potential production system diagnostics using a dynamic pressure transducer.

EXPERIMENTAL APPARATUS

Loop Description

The experiments were performed on a test stand designed to accurately simulate driving conditions. To do this, the speed of the motors controlling the evaporator air loop, the condenser air loop, and the compressor are controlled. Loop instrumentation is such that all refrigeration performance criteria can be calculated as described in Weston et al. [1996]. The current system contains components from a 1994 production vehicle air conditioning system. This system typically includes a fixed orifice expansion device, and a suction line accumulator. For these experiments, the suction line accumulator was replaced with an oil separation device to control the amount of oil

returning to the compressor. The compressor is an off the shelf current model. The swashplate is made of 390 Al coated with tin and the shoes are made of 52100 steel.

The liquid return line, as shown in Figure 1, includes a mass flow meter, a concentration sensor, and a needle valve to control oil return to the compressor. It was necessary to add this oil flow control section in the suction line to the compressor to obtain accurate control of oil return to the compressor. Changes in oil return rate to the compressor could be immediately detected with this instrumentation. The concentration sensor correlates refractive index to concentration of oil and refrigerant mixtures, with the capability of measuring the full range of mixtures present with PAG oil and R-134a. These techniques are described in more detail in Drozdek et al. [2000], Newell [1996] and Wandell et al. [1998].

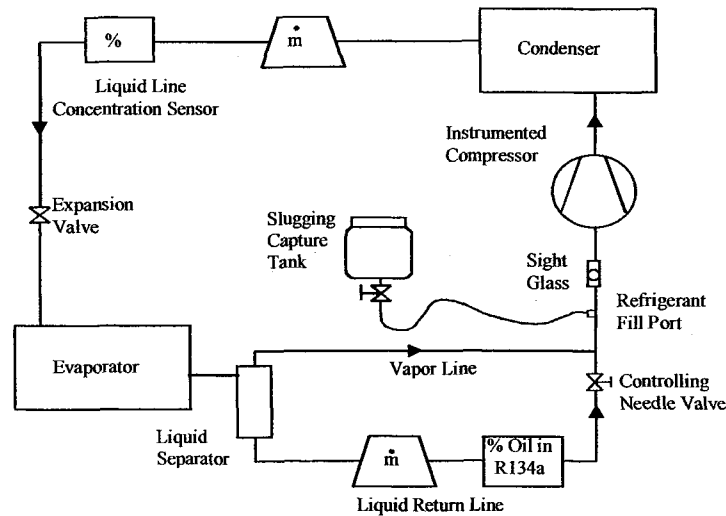


Figure 1. Simplified loop schematic

Compressor Instrumentation

The primary measurement of oil film breakdown in the compressor was contact resistance. This method directly measures the resistance across the critical shoe/swashplate interface. The method maintains electrical contact to the piston and swashplate through slip ring brushes, as described in Figure 2. The path of the current loop begins at the brush assembly to the piston, then continues through the shoes and across the shoe/swashplate interface. The loop is completed by passing through the swashplate, shaft, and the slip ring. This method has been more thoroughly described in Drozdek et al. [2000]. To provide more accurate data, a voltage divider circuit was constructed with a 50Ω resistor in series with the contact resistance across the shoe and swashplate interface. This method assumes zero resistance through the sliding contact interfaces. These interfaces are the sliding brush on the piston, the piston and shoe, and the slip ring. Based on measured resistances, these assumptions are reasonable.

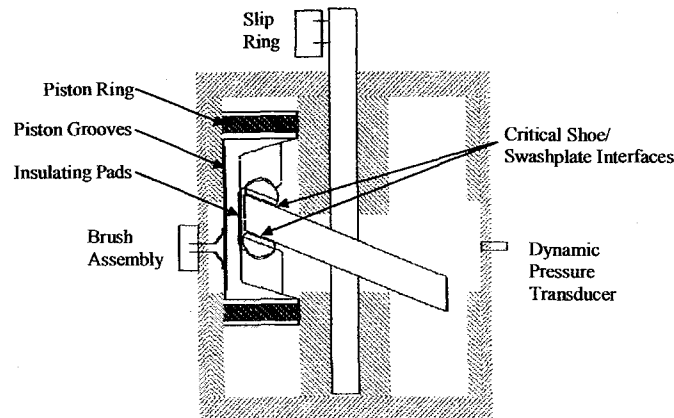


Figure 2. Compressor instrumentation schematic

A dynamic pressure transducer was also installed in the swashplate cavity of the compressor to detect sound pressure. The approximate location of this sensor is shown in Figure 2. Since this method is less intrusive and less expensive than the contact resistance measurements, it could be more easily applied as a diagnostic tool for production vehicles. The transducer has a bandwidth of 125 kHz. Measured dynamic pressure signals have a maximum frequency content of approximately 10 kHz.

Data Acquisition

Loop instrumentation data were sampled throughout the tests with a relay multiplexer data logging system and PC. In addition to the contact resistance and dynamic pressure sensors, a position sensor output was necessary to correlate contact resistance and dynamic pressure to swashplate position. Data from all three devices were collected simultaneously at a sampling rate of 50 kilosamples per second on a separate data acquisition unit. Approximately 10 seconds of data were taken for each set. These sets were taken at regularly spaced intervals to observe trends during the tests performed.

TEST DESCRIPTION

The purpose of the oil return loop was to determine the lower limit of oil circulation for steady oil return rates. The lowest level measurable was approximately 2 g/min. The minimum measurable oil return rate is sufficient to provide good lubrication. The results of these tests are described fully in Drozdek et al. [2000]. Results for transient oil conditions caused by oil shut off and refrigerant slugging during start up are discussed here.

For all tests described here, the compressor was run at an idling speed of 800 rpm. The steady oil return rate was controlled at 9.1 g/min. When the oil separator was operated, high superheat conditions (>20 °F) were maintained at the evaporator exit to ensure no liquid refrigerant was trapped in the liquid separator.

The oil shut off test was performed to investigate near zero oil return conditions during otherwise steady operation. The test began by operating the loop under steady conditions for several hours with the oil return rate remaining constant. Next, the oil return flow rate to the compressor was shut off by closing the controlling needle valve, as seen in Figure 1. Visual changes in the oil flow could be observed in the sight glass in the suction line to the compressor. This sight glass was located after the oil recombines with the vapor flow from the separator. Approximately 5 minutes after the oil was shut off, it was observed in this sight glass that no visible oil was returned to the compressor.

Refrigerant migration can lead to slugging of the compressor during start up conditions. This occurs when liquid refrigerant migrates to the suction line of the compressor while the loop is not operating. Initially, the liquid refrigerant will carry the oil out of the compressor. Without sufficient oil in the compressor, severe damage can occur until oil return to the compressor is established. Similar start up conditions were simulated in the test loop. The refrigerant fill port, located in the suction line of the compressor before the sight glass, as seen in Figure 1, was used to simulate slugging. Before the slugging test, steady oil return and operating conditions were established throughout the loop. At this point the loop was shut down. Next, the capture tank was submerged in an ice bath to condense the liquid refrigerant in the loop and the valve to this tank is opened. After the liquid has condensed in the capture tank and the capture tank valve was closed, the slugging test was ready to start. The capture tank was hung upside-down, as seen in Figure 1, so the liquid refrigerant in the tank could be quickly pulled into the compressor during start up to simulate condensed liquid refrigerant in the suction line. Once the compressor was started, the valve to the capture tank was opened, and liquid refrigerant flowed into the compressor. The effects of the slugging event were present within the compressor until nominal oil flow conditions were established in the suction line to the compressor.

TEST RESULTS

Oil Shut Off to Failure

Data collected from two compressors tested during oil shut off tests are shown in Figures 3(a-c). The first compressor (compressor #1) was operated for short lengths of time with the oil return shut off to avoid compressor failure. The second (compressor #2) was run with the oil return shut off until failure occurred. The length of time

the second compressor operated without oil return was twenty hours, and this time was spread over three days of operation. During failure, levels of contact resistance dropped from values near 10Ω to values between 0.01Ω and 0.1Ω . These low levels of contact resistance correspond to boundary level lubrication during failure.

The data presented show trends in contact resistance as the sampled data sets were taken. A more detailed analysis of the structure of the contact resistance data collected can be found in Drozdek et al. [2000]. To compare each set of contact resistance measurements, a threshold resistance analysis was performed. In this analysis, arbitrary threshold levels of contact resistance were established at 1000Ω , 100Ω , 50Ω , 10Ω , and 1Ω . For each threshold level, the number of samples below the threshold was counted for the data set. The data sets included approximately 10 cycles to get an accurate average. This value was then divided by the total number of samples in the data set to determine percent time below the threshold level. The resulting percentage of time the contact resistance is below the threshold level will be referred to as the threshold resistance level.

Compressor #1 data, shown in Figures 3(a), are the results of the run-in of the compressor, and include the beginning of an oil shut off test. This test was the first time this compressor had been used, and therefore, any initial smoothing of surfaces that would be the result of the run-in of the compressor are present in the trends of the graph. Initially, the upper threshold resistance levels (50, 100, 1000) are high; this corresponds to long amounts of time within the data set that the contact resistance was below these levels of contact resistance. After 100 minutes, the threshold resistance levels drop and reach a steady value. As mentioned, these trends may be attributed to the initially smoothing of the swashplate surface. However, a more detailed analysis of compressor run-in is necessary to fully understand the data. After 245 minutes of steady oil circulation to the compressor, the oil return was shut off and the separator slowly collected the residual oil in the loop. As expected, most of the threshold resistance levels increased. This trend corresponds to lower values of resistance as the oil return was shut off. However, as time progressed, the resistances increased, i.e. threshold resistance levels began decreasing. An unusual result was that the 10Ω threshold resistance level fell near zero once the oil return was shut off. This indicates the contact resistance did not go below 10Ω as often once the oil was shut off. A possible explanation for these trends involves changes in oil viscosity during oil shut off and will be given later.

The second test performed continued using compressor #1, and the results are shown in Figure 3(b). The threshold resistance levels during the initial steady oil return are similar to those seen in the first test after steady levels had been reached, as seen in Figure 3(a). The start up of the second test does not show run-in trends of the swashplate surface as described by the trends of the first start up test data. After 125 minutes, when the system had achieved steady state, and the oil return was shut off. Once the oil return was shut off, all but the lowest threshold resistance levels climbed. However, after less than 30 minutes, the values began to drop. After 60 minutes without oil return the threshold resistance levels were back to where they began, and continued to decrease. Instead of continuing until failure, the oil return was re-established after 100 minutes with the oil return shut off and threshold resistance levels returned to the same levels as before the oil was shut off. This trend did not seem to agree with intuition, since it was expected that once oil return is turned on, the film thickness across the sliding interface should increase not decrease as the trends show.

A possible explanation for the trends observed during oil shut off has been developed. The trends during oil shut off may be attributed to changes in the oil viscosity on the swashplate. During steady oil circulation, a constant supply of low temperature oil from the evaporator cools the oil mixture on the swashplate surface. This oil returning to the compressor through the oil return line was measured to be approximately 20% refrigerant by mass. This liquid refrigerant in the oil assists in cooling the oil on the swashplate as it mixes with the oil already present on the swashplate. When the oil return is shut off, the cooling of the swashplate by the oil-refrigerant mixture ceases and the oil on the swashplate surface heats up. The heating of the oil would evaporate the refrigerant out of the oil. Two competing effects change the viscosity of the oil-refrigerant mixture on the swashplate surface: heating of the oil decreases the viscosity and driving the refrigerant out of the oil increases the viscosity. Unfortunately, neither swashplate oil temperature nor concentration data were available to quantify these effects. However, data on temperature and refrigerant mixture effects on oil viscosity are available in 1998 ASHRAE Refrigeration Handbook. While this data does not include PAG oil, in general, these data show that for temperature ranges near oil temperatures of $200\text{ }^\circ\text{F}$, changes in refrigerant mixture dominate the change in viscosity. Therefore, it is suspected that during oil shut off, the net result of increasing the temperature of the oil on the swashplate is to increase the

viscosity of this oil. This would cause the oil film thickness to increase, and hence, the contact resistance would increase. Therefore, the threshold resistance levels would decrease.

The final oil shut down test was performed on a second compressor (compressor #2) and included shutting off the oil return to the compressor until failure occurred. The failure occurred twenty hours after the oil was shut off. The data from this test prior to failure and during failure are shown in Figure 3(c). The general resistance threshold trends are similar to those shown in Figure 3(b). This time after about 130 minutes, the threshold levels increased. This corresponds to a decreasing contact resistance across the interface as metal-to-metal contact increased. The threshold resistance levels of interest are those at 1Ω and 10Ω , since they are more likely indicators of lubrication breakdown. After 220 minutes of running, the compressor was shut down, because the drive motor for the compressor began to overheat. After 2 hours of allowing the motor to cool, the compressor was turned on again and the threshold resistance values began climbing again until failure occurred.

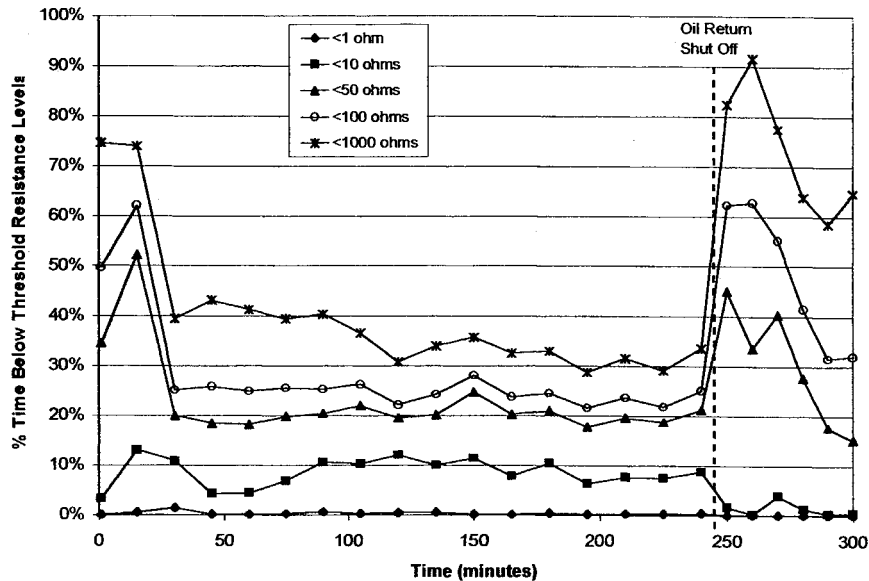


Figure 3(a). Threshold contact resistance during run-in and oil shut off for compressor #1

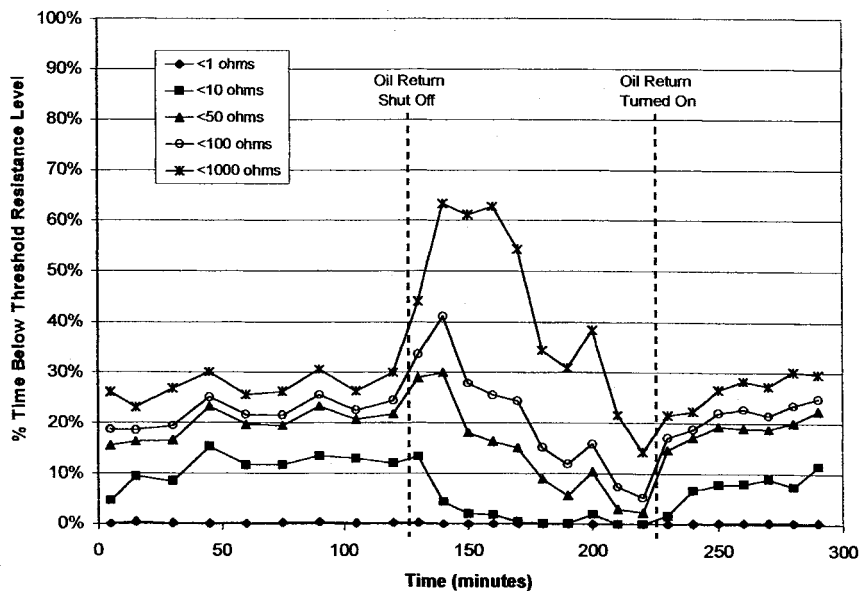


Figure 3(b). Threshold contact resistance of second oil shut off and oil turned on for compressor #1

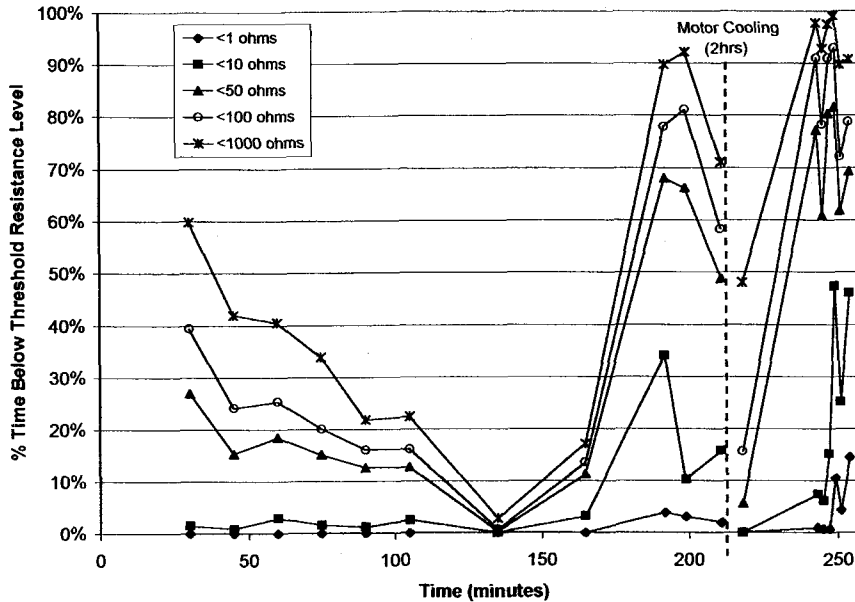


Figure 3(c). Threshold contact resistance during failure of compressor #2

Slugging During Start Up

The slugging tests were performed to measure changes in the contact resistance and dynamic pressure within the compressor cavity during start up conditions of a compressor when liquid slugging is present. During the slugging event, drastic changes in both contact resistance and dynamic pressure were observed. The threshold contact resistance summary and history of pressure microphone signals are shown in Figures 4 and 5, respectively. The physical phenomenon that occur include the initial flow of liquid refrigerant into the compressor that removes oil from the compressor, followed by a delay in oil return until nominal oil return conditions are established.

The threshold resistance levels during slugging start up, as seen in Figure 4, initially rise due to the removal of oil from the surface of the swashplate by the liquid refrigerant. This is followed by a time delay until steady oil return to the compressor is established. Once oil returns to the compressor after approximately 20 minutes, threshold resistance levels return to levels observed during steady oil circulation. The long time delay before steady conditions are reached may be associated with the capture tank technique used in simulated liquid slugging. Therefore, slugging start up conditions in normal automotive systems may be significantly shorter in duration.

The pressure microphone data also show differences in the signal as slugging occurs. Figure 5 shows the pressure microphone signal (A) after 25 seconds, as well as the signals after 85 seconds (B), after 5 minutes (C), and after 20 minutes (D). The signal in Figure 5(A), occurring 25 seconds after the start of slugging, is similar in structure to signals recorded before the slugging test. This signal structure then disappears as the liquid refrigerant floods the compressor cavity, as seen in Figure 5(B). Once the liquid refrigerant has passed through, there is a delay before oil return is re-established. The signal structure in Figure 5(C) is similar to pressure microphone signals recorded when the oil return to the compressor is shut off, as described in Drozdek et al. [2000]. After oil return is established to the compressor, the pressure microphone signal returns to its original shape, as seen in Figure 5(D).

Currently there exists a hypothesis for the signal structure seen in Figure 5(C). Since the “spikes” only occur when there is no oil returning to the compressor, it is believed droplets of oil in the swashplate cavity may cause attenuation of a signal that is always present.

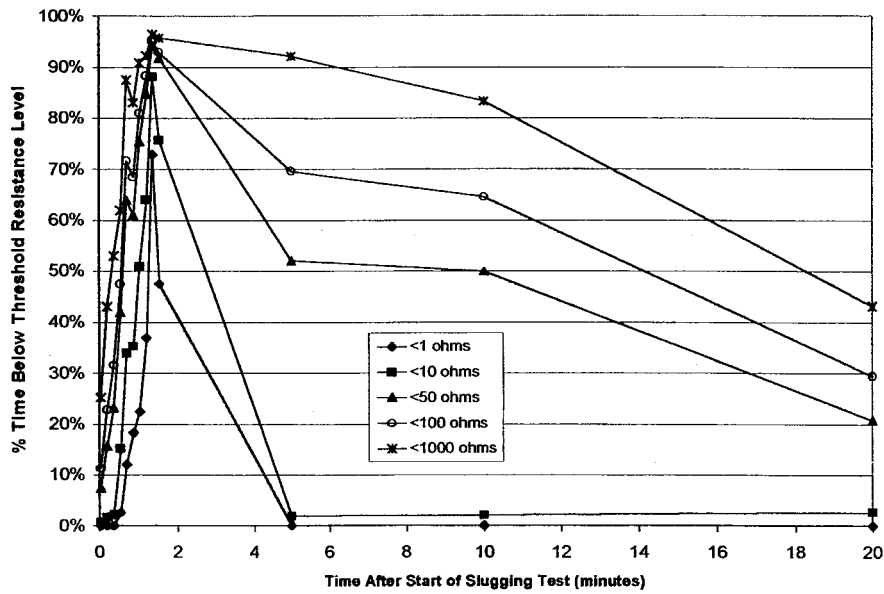


Figure 4. Threshold resistance levels during slugging start up test

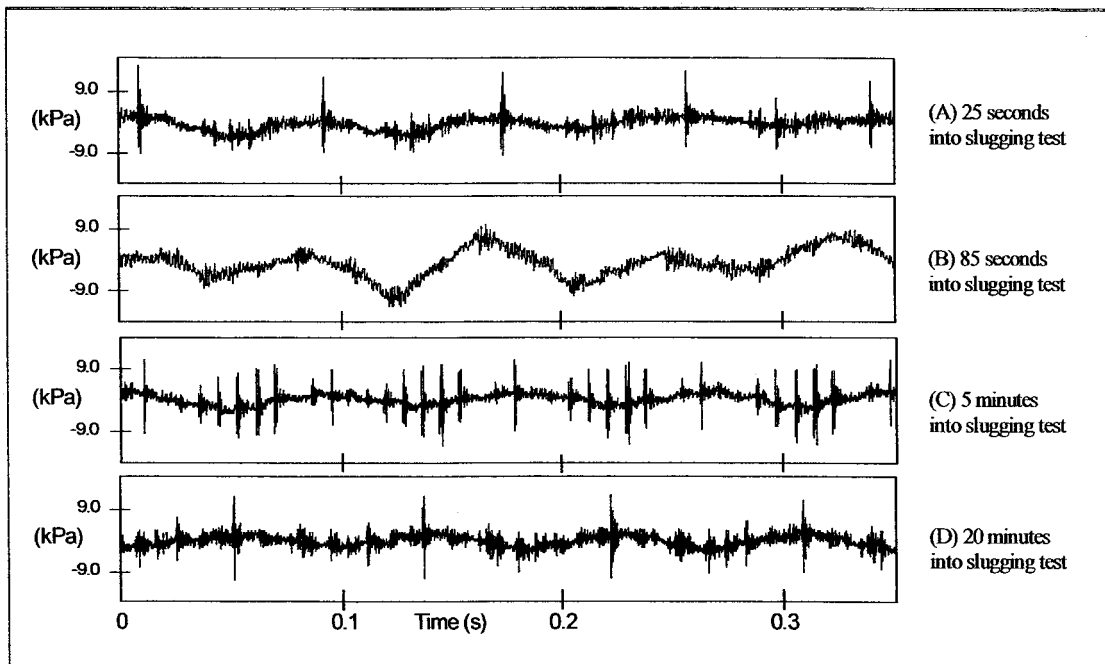


Figure 5. History of pressure microphone signals during slugging start up test

CONCLUSIONS AND FUTURE WORK

Measurement of contact resistance across the shoe/washplate interface during two transients tests have been performed. These measurements have provided insight into the possible regimes of lubrication during these transient conditions. In addition, the dynamic pressure microphone produces signals that agree with previous oil shut off test data as found in Drozdek et al. [2000]. The presence of evenly spaced acoustic events when oil is not

returning to the compressor can be seen during the slugging start up event and when oil shut off occurs. The data presented here show that the lubrication conditions can significantly worsen immediately after slugging.

Future work will focus on the use of the dynamic pressure data as a possible diagnostic tool for swashplate air conditioning compressors. Preliminary analysis of the pressure signal using wavelet decomposition shows promise for such an application. The contact resistance measurements will continue to be used on a dry-start test to examine contact resistance trends during startup conditions when no oil is present in the compressor.

Work presented here will be published as a complete technical report at the Air Conditioning & Refrigeration Center at the University of Illinois by Chappell and Drozdek in July, 2000.

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REFERENCES

- Drozdek, J., J. Chappell, C. Cusano, P. Hrnjak, N. Miller, T. Newell, 2000: "Methods for Detection of Lubrication Failure Applied to a Swashplate Compressor." SAE Technical Paper 2000-01-0974
- Newell, T. A., 1996: "In Situ Refractometry for Concentration Measurements in Refrigeration Systems." HVAC&R Research. Vol. 2, No. 3, pp. 247-256.
- Wandell, E., W. E. Dunn, N. R. Miller, and T. A. Newell, 1998: "Conditions That Limit Oil Circulation in a Mobile Air Conditioning System." SAE Technical Paper 98PC-21.
- Weston, P. G., W. E. Dunn, and N. R. Miller, 1996: "Design and Construction of Mobile Air Conditioning Test Facility for Transient Studies." Department of Mechanical and Industrial Engineering University of Illinois at Urbana-Champaign, ACRC TR-128.
- Yoon, H.K., and C. Cusano, 1999: "Scuffing Under Starved Lubrication Conditions." Department of Mechanical and Industrial Engineering University of Illinois at Urbana-Champaign, ACRC TR-147
- 1998 ASHRAE Refrigeration, SI Edition, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Atlanta, GA., 1998