1996

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SCROLL COMPRESSOR PERFORMANCE WITH OIL INJECTION/SEPARATION

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ABSTRACT

Leakage in scroll compressors is a dynamic process affected by several factors including: machining tolerances, thermal effects, operating instabilities, wrap deflections, oil circulation, oil distribution, refrigerant/oil solubility, etc. Previous investigations attempting to characterize the leakage processes inside the scroll compressor pump assembly have yielded little information into the nature of the mechanisms involved. Most analytical models treat leakage in the scroll compressor as a Fanno flow process and do not include the effects of oil; while most experimental efforts involve measuring steady-state leakage flow rates through fixed clearances. Limited knowledge is available regarding the effects of oil on the leakage characteristics of scroll compressors. For these reasons, tests were conducted to determine the effects of oil circulation on the performance of an operating low-side scroll compressor. Due to the adverse effects of high system oil circulation, efforts were also made to develop and test an oil separator and return system internal to the compressor.

Various amounts of oil were injected into the compression pockets of a three ton scroll compressor in an attempt to: 1) characterize the oil film behavior on the scroll tips, flanks, and thrust surface, 2) monitor the leakage processes across the scroll tips and flanks using high-speed pressure transducers, and 3) determine how the oil is distributed in the scrolls. The compressor performance, noise, and compression process characteristics were recorded during testing at both steady-state and transient operating conditions. The test results indicate that at low-pressure ratio conditions, leakage losses are governed by thermal effects. At mid-pressure ratio conditions, leakage losses are minimum and are related to the machining tolerances and local deformations, while at high-pressure ratio conditions, leakage is increased because of minute separations of the scrolls as a result of significant back-flow during the discharge process. Overall, indications are that an optimum level of oil circulation exists that results in a significant increase in operating efficiency and decrease in radiated noise (both shown to be a strong function of operating pressure ratio).

INTRODUCTION

Leakage within the scroll compressor has a significant effect on performance. Although the clearances are small, significant leakage can occur resulting in a substantial decrease in capacity and increase in power consumption. Knowledge of the governing mechanisms involved allows for accurate modeling of the leakage processes and the ability to improve the overall performance of the compressor.

The leakage processes within scroll compressors are very complex and have yet to be clearly defined and understood. Most analytical models treat leakage as a Fanno flow process while others assume the leakage paths are fully liquid (oil with dissolved refrigerant). Even if the true nature of the leakage flow is known, a larger problem would be to calculate the appropriate local clearances. Along with machining tolerances, thermal effects, and operating instabilities, wrap deflections due to pressure loads would have to be defined; each of which will affect the local leakage path clearance. It is clear that a comprehensive leakage model would be very complex, having to include several factors that affect both the local gap clearance and leakage process. Most of the previous experimental efforts involve measuring steady-state leakage flow rates through fixed clearances, revealing little information about the actual processes in an operating compressor. For these reasons, a primary objective of this investigation was to learn as much as possible about the factors that govern the leakage processes in an actual operating compressor.

This paper contains discussions of the leakage processes occurring within scroll compressors; the test equipment and test procedures used during this investigation; as well as representative test results showing the effects of oil injection on compressor performance, noise, and the governing leakage mechanisms.
EXPERIMENTAL APPARATUS

Instrumentation

The focus of this investigation was to learn as much as possible about the leakage processes in an actual operating scroll compressor with oil present. High-speed pressure transducers were installed in a laboratory test compressor in an attempt to 1) characterize the oil film behavior on the scroll tips, flanks, and thrust surface, 2) monitor the leakage processes across the scroll tips and flanks, and 3) determine how the oil is distributed in the scrolls. Compressor performance, noise, and compression process characteristics were recorded during testing at both steady-state and transient operating conditions while the internal oil circulation was varied.

The test compressor was instrumented with 11 high-speed pressure transducers, 6 to monitor the compression process and 5 to monitor leakage processes. The 6 compression process transducers were used to generate pressure vs. crank angle and pressure vs. volume plots by tracking a fluid element from start of suction (soc) to end of discharge (eod). Figure 1 shows the installation locations for the pressure transducers. Leakage pressure transducer no. 1 was installed in the tip of the fixed scroll wrap near mid-compression, transducer no. 2 was installed to monitor the interface between the fixed and orbiting scroll baseplates (thrust surface), transducers no. 3 and no. 4 were installed in the base of the fixed scroll to monitor orbiting scroll tip leakage events and also to provide pressure boundary conditions for transducer no. 5 which was located in the side wall of the fixed scroll for monitoring flank leakage.

![Diagram of fixed scroll with pressure transducer locations](LocationDiagram.png)

**Figure 1: Fixed Scroll Showing Locations for Pressure Transducers. (Bottom View)**

Test Compressor

Figure 2 shows a schematic diagram of the leakage test apparatus. A small positive displacement pump was used to inject oil directly into the compression process. The injection port was located in the floor of the fixed scroll at a centered location approximately 30 degrees inside the suction port (see Figure 1). The oil flow rate was controlled using a by-pass loop and metering valve and was monitored using a digital micro-flow meter. The injected oil was removed from the discharge flow using an oil separator to ensure accurate performance measurements. Since the injected oil was taken directly from the oil sump, an auxiliary oil supply container was connected to the system to prevent the oil charge in the sump from falling below a safe level. All of the instrumentation was interfaced with a central data acquisition system.
RESULTS

For a given operating condition, compressor efficiency is directly proportional to mass flow rate and inversely proportional to compressor power. Internal leakage within the scroll elements can adversely affect both. A reduction in mass flow due to leakage from the first part of compression back to suction reduces the ideal mass flow for constant suction conditions. This reduction can be characterized by defining the volumetric efficiency of the compressor. The volumetric efficiency with respect to the suction flange is calculated from:

$$
\eta_{vol} = \frac{\dot{m}}{\dot{V}_{d} \rho_{suc} N} = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}}
$$

where,

$$
\dot{m} = \text{mass flow} \ [lbm/sec] \\
\dot{V}_{d} = \text{displacement volume} \ [in^3] \\
\rho_{suc} = \text{suction flange gas density} \ [lbm/in^3] \\
N = \text{compressor speed} \ [rad/sec]
$$

The denominator in equation (1) is the ideal mass flow rate for a positive displacement compressor. The volumetric efficiency deviates from unity due to losses associated with leakage and temperature rise. In addition, internal leakage increases the polytropic exponent and indicated work for the compression process resulting in an overall increase in power consumption. These issues further affect the compressor heat transfer characteristics which ultimately affect motor efficiency, internal suction superheat, etc.

Controlled amounts of oil were injected into the compression pockets of an operating low-side scroll compressor while the compressor performance, noise, compression process, and internal leakage characteristics were monitored. Table 1 summarizes performance results for one of the operating conditions tested. The data are normalized with respect to baseline values.
Table 1: Test Results at 50/150/20/0.

<table>
<thead>
<tr>
<th>Oil Circulation</th>
<th>Power</th>
<th>Capacity</th>
<th>Indicated Work</th>
<th>Polytropic Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>3.0</td>
<td>0.991</td>
<td>1.022</td>
<td>1.000</td>
<td>0.974</td>
</tr>
<tr>
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<td>1.025</td>
<td>0.990</td>
<td>0.977</td>
</tr>
<tr>
<td>11.0</td>
<td>0.982</td>
<td>1.028</td>
<td>0.982</td>
<td>0.967</td>
</tr>
<tr>
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<td>0.983</td>
<td>1.021</td>
<td>0.987</td>
<td>0.962</td>
</tr>
<tr>
<td>21.0</td>
<td>0.983</td>
<td>1.019</td>
<td>0.975</td>
<td>0.956</td>
</tr>
</tbody>
</table>

The general trends in the data for all operating conditions were as follows:

1. Capacity tended to increase with oil circulation reaching a maximum value when the reduction in effective pocket volume due to the oil became dominant over any improvements in capacity due to reduced leakage losses. Since suction conditions and therefore inlet gas density remained constant (measured internal suction superheat values did not change with oil injection), the increase in capacity was a direct result of decreased internal leakage rates. The improvements in measured capacity were reflected in calculated values for volumetric efficiency.

2. Overall, reductions in leakage due to liquid oil injection decreased the indicated work and polytropic exponent for the compression process resulting in a lower gas pressure at each point in the compression process and lower compressor operating power. In addition, oil injection was shown to reduce the effective polytropic exponent below isentropic values early in the compression process due to the thermal capacity of the oil.

3. Sound intensity and radiated sound power data were recorded as a function of oil circulation at several operating conditions to determine the effects of various amounts of oil on the compressor noise characteristics. Sound intensity data are used to spot general trends but is not very accurate compared to a complete radiated sound power measurement. Measured reductions in noise for the operating conditions tested are not presented but ranged between 2 and 3 dB for both measurement techniques.

The plot in Figure 3 is obtained when the measured capacity data are curve–fitted and plotted versus compressor operating pressure ratio and oil circulation. The shape of the plot can be explained by analyzing the data generated from the leakage

![Figure 3: Characteristic Plot of the Effects of Oil Circulation on Capacity.](image-url)
pressure transducers mounted in the fixed scroll. While the magnitude of the leakage rates inside the scroll pump is difficult to measure, information could be obtained about the nature of the leakage process by monitoring the pressure history of the leakage event. At pressure ratios below the design pressure ratio, thermal expansion effects become a significant contributor to the overall internal leakage rate. Since the scroll wrap tips are cut back slightly to allow for thermal expansion at high pressure ratio operating conditions, increased leakage occurs at low pressure ratio operating conditions due to much lower operating temperatures. Figure 4 contains pressure traces from a transducer monitoring the latter portion of the compression process (and a portion of the discharge process) as well as from the transducer mounted in the tip of the fixed scroll. These data are for a low–pressure ratio operating condition. The dynamic nature of the pressure trace from the tip transducer suggests a fair amount of leakage is occurring across the wrap tips. It can also be seen that the pressure pulsations in the signal follow the pressure pulsations that occur during the discharge process. At this operating condition, the wraps do not grow as much as they do at operating conditions with higher discharge temperatures resulting in larger clearances between the wrap tips and adjacent scroll floor and increased leakage losses. This allows a direct path for the tip transducer to react to the discharge pressure pulsations. Figure 5 shows the same signals for a mid–pressure ratio operating condition. The dynamics of the tip leakage transducer trace are significantly reduced as the wraps grow due to increased operating temperatures and the leakage passages are subsequently reduced. Leakage losses for mid–pressure operating conditions are mainly associated with machining tolerances and local deformations. Figure 6 shows the pressure signals for a high–pressure ratio operating condition. The increase in pressure that occurs in the tip transducer trace near 270 degrees was at first believed to be a result of the sudden increase in pressure within the scroll pockets that occurs when the discharge port opens to line pressure (following start of discharge). After further investigation, it was discovered that the tip transducer was reacting to a momentary separation of the scroll elements as a result of significant back-flow caused by the difference in line and pocket pressures. This pressure differential is enough to instantaneously separate the scroll elements slightly and effectively increase the mating clearances resulting in fairly substantial leakage losses. The addition of oil is shown to significantly reduce these losses as seen in Figure 7. Here, the tip transducer trace remains at nearly constant pressure throughout the cycle. No high–pressure oil films were shown to develop on the wrap tips following oil injection. Similar results were shown at all pressure ratios following oil injection. As stated earlier, capacity tended to increase with oil quantity reaching a maximum value when the reduction in scroll compression pocket volume due to the oil became dominant over any improvements in capacity due to reduced leakage losses. Additional oil beyond this point results in a decrease in capacity as shown in Figure 3 for all pressure ratios.

Finally, efforts were initiated to develop and test an oil separator and return system internal to the compressor as a means of realizing the beneficial effects of increased oil quantity within the compression process without incurring penalties associated with increased system oil circulation. A small amount of system oil circulation does no harm; however, too much oil in such components as the condenser, refrigerant flow controls, evaporator, and filters interferes with their operation. For high system oil circulation (generally > 1%), the oil must be separated from the discharge flow and returned to the compressor. In commercial systems, oil separators are designed to remove the oil from the hot compressed vapor after the vapor leaves the compressor. Coalescers and/or centrifugal separators are the preferred types. These devices, however, are generally large, costly, and can have significant pressure losses. In order to take full advantage of the compressor improvements as a result of oil injection, a passive internal oil separation and return system having minimal pressure loss was designed and tested. Preliminary results appear to be promising, however further development is required.

CONCLUSIONS

Test results from this investigation indicate that for an operating low–side scroll compressor, an optimum level of oil circulation exists that results in a significant increase in operating efficiency and decrease in radiated noise. This optimum value occurs where the reduction in pocket volume due to any additional oil becomes dominant over improvements in capacity due to reduced leakage losses. In addition, results indicate that at low–pressure ratio conditions, leakage losses are governed by thermal effects. At mid–pressure ratio conditions, leakage losses are minimum and are related to the machining tolerances and local deformations, while at high–pressure ratio conditions, leakage is increased because of minute separations of the scrolls as a result of significant back–flow during the discharge process. Oil injection also resulted in a significant reduction in compressor average radiated sound intensity.

In order to take advantage of the measured performance improvements, most of the injected oil must be removed prior to entering the system due to the adverse effects of high system oil circulation on heat exchanger surfaces, etc. Accordingly, efforts were initiated to develop and test an oil separator and return system internal to the compressor. Initial results appear promising, however, more development is necessary to optimize key design parameters.
Figure 4: Baseline Pressure Traces for Low-Pressure Ratio Operating Condition.

Figure 5: Baseline Pressure Traces for Mid-Pressure Ratio Operating Condition.

Figure 6: Baseline Pressure Traces for High-Pressure Ratio Operating Condition.

Figure 7: Pressure Traces for High-Pressure Ratio Operating Condition w/ Oil Injection.