2014

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Effect of Lubricant-Refrigerant Mixture Properties on Compressor Efficiencies

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ABSTRACT

Lubricants are utilized on compressors to lower friction thus increasing efficiency while decreasing wear and increase longevity. While pure lubricant properties are commonly cited in literature due to more readily available property data, far more meaningful results are obtained when lubricant-refrigerant mixture properties are utilized. The most critical of these properties are the vapor-liquid equilibrium data, which relates temperatures, pressures, and concentrations, to other intensive properties such as density and viscosity.

To determine the impact of fundamental refrigerant-lubricant mixture properties on compressor performance, a series of lubricants having known mixture properties where utilized in a semi-hermetic transcritical carbon dioxide compressor. This compressor was installed in a calorimeter which allowed compressor electrical power consumption to be accurately measured. Likewise, refrigerant temperatures, pressures, and mass flows were measured. As this calorimeter utilized the full refrigeration cycle with both a gas-cooler and evaporator, it was possible to accurately determine the oil circulation ratio (OCR) via the sample based method given by ASHRAE Standard 41.4. The compressor was operated at a series of suction and discharge pressures and temperatures which were near the edge of the operating envelop.

Combining the property information with experimental data from the calorimeter experiments allow for analysis of the impact of refrigerant-lubricant mixture properties on compressor efficiencies. Due to the relatively small changes in performance, it was necessary to properly account for the presence of lubricant in the definitions of isentropic and volumetric efficiencies. After accounting for these properties, multivariate least square curve fitting was utilized to understand the relative impact of mixture properties and OCR on compressor efficiency. The analysis is furthered to show the impact of compressor efficiency on system performance for the purpose of pointing towards selecting lubricants to minimize energy consumption.

1. INTRODUCTION

Most of the focus on understanding how lubricant affects refrigeration systems has been directed at the effect of oil circulation ratio on efficiency on system performance. Lottin et al. (2003) modeled system performance R410A laboratory system but showed no meaningful effect on isentropic efficiency until oil circulation ratios were greater than 2.5%. Their models showed an approximately linear relationship of each percent of lubricant caused a percent decrease in system coefficient of performance (COP). DeAngelis and Hrniak (2005) showed that use of higher viscosity lubricants resulted in higher compressor power in a bottle cooler utilizing R744. They showed that lower
viscosity lubricants increased isentropic efficiency while the use of oil separators to return lubricant to the intermediate pressure increased the efficiency when high viscosity lubricants were used. However, it is unclear how they defined isentropic efficiency. Other researchers have focused at understanding how lubricants effect heat exchanger performance or heat transfer coefficients. Pehlivanoglu et al. (2010) and Kim et al. (2010) showed that generally increasing oil content decreased heat transfer coefficients in evaporators with the exception of a few results at high qualities and heat fluxes where lubricant helps to wet the tube walls.

However, few papers were found in the open literature which focused specifically on the effect that different lubricants have on the efficiency of the same compressor. This is especially true for comparisons between lubricants of the same nominal viscosity, but having different solubility, viscosity indices, or densities. Furthermore, it is important that the refrigerant-lubricant mixture properties be well characterized so that the effects may be more widely generalized.

2. ISENTROPIC EFFICIENCY

Isentropy efficiency, or compressor efficiency, is the metric commonly used to give an understanding of how close to ideality a compressor is able to utilize the power that it is supplied. For a thermodynamic cycle, ideality is a Carnot cycle. In the Carnot cycle, ideal compression is isentropic, meaning inlet and outlet entropies are equal. Heat rejection in the Carnot cycle occurs at a fixed temperature. Because most refrigerants condense during the heat rejection portion of the cycle, pressure is utilized as a surrogate for temperature in determining where the compression process could have stopped. This may make sense because for a certain condensing temperature, a minimum pressure must be obtained. These concepts lead directly to Equation 1 is the definition of compressor efficiency given by ASHRAE Standard 23.1 and AHRI Standard 571. In these definitions, \( \dot{m} \) is called the refrigerant mass flow rate, however in practice it is the mass flow of refrigerant and lubricant as the flow may contain up to 2% oil by mass. Likewise, enthalpy is defined based only on the properties of the refrigerant and do not include the contributions from the lubricant.

\[
\eta = \frac{\dot{m}(h_3 - h_2)}{W}
\]

The role of lubricant on compressor efficiency is a focus on the paper. As it is expected that relatively minor changes in lubricant properties may have minimal impact on isentropic efficiency, additional attention was given to the role of lubricant with regards to the calculation of isentropic efficiency. Lubricant could be seen to affect two different variables in the definition of isentropic efficiency: mass flow and enthalpy. The oil circulation ratio (OCR) is a quantity used to relate the total flow rate to that of oil as given by Equation 2. For all practical purposes, refrigerant and oil comprise the entirety of the flow in most refrigeration systems, therefore oil and refrigerant mass flow rates can easily be calculated from the total flow rate and the OCR.

\[
OCR = \frac{\dot{m}_{oil}}{\dot{m}}
\]

While there is no thermodynamic reason for wanting hot, high pressure lubricant, the pressure based definition of isentropic efficiency given by the ASHRAE and AHRI standards could be extended. Using Maxwell relations, Equation 3 can be derived. For a lubricant, specific volumes of pure lubricant are consistent to within 10% throughout the compression process. If an average specific volume is utilized, and pressure gain of the compression process is measured, the outlet enthalpy for isentropic compression of lubricant can be easily calculated.

\[
\nu = \left( \frac{\partial h}{\partial P} \right)_s
\]

Therefore, a slightly more complex definition for isentropic or compressor efficiency can be given by Equation 4. It will be shown later in the paper, that utilizing this definition gives more consistent results for comparing the same compressor but with different lubricants. Of course, even more complex definitions, which incorporate mixture properties, could also be defined.

\[
\eta = \frac{\dot{m}(1 - OCR)(h_{3,ref} - h_{2,ref}) + \dot{m}(OCR)\nu_{oil}(P_1 - P_2)}{W}
\]
3. EXPERIMENTAL FACILITY AND CONDITIONS

To determine the effect of oil, a transcritical carbon dioxide compressor, Bock HGX2/70-4, was chosen. Based on the compressor manufacturer’s published operating envelope, the 4 different conditions shown in Table 1 were selected. The first condition in the table was near the center of the operating envelope while all other points were at the high pressure or temperature limits of the compressor. The extreme high pressures or temperature limits were chosen with the view that they should induce the largest pressure forces and therefore more heavily tax the lubricant.

<table>
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<tr>
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While many parameters were measured, those critical for determining efficiency were suction temperature and pressure, discharge temperature and pressure, mass flow rate, oil circulation ratio, and compressor power. The published accuracy of the instrumentation, as well as the average absolute difference of repeated tests can be seen in Table 2. It should be seen that controls make it possible to repeat tests to nearly the accuracy limits of the instrumentation.

<table>
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<tr>
<th>Parameter</th>
<th>Instrument accuracy</th>
<th>Average absolute difference</th>
<th>Units</th>
<th>Relative average absolute difference [%]</th>
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<td>Isentropic efficiency</td>
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<td></td>
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<td>g/s</td>
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<td>Superheat</td>
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Six different polyolester (POE) lubricants were utilized in this study. Of these lubricants three were nominally ISO 68, two were ISO 85, and one was ISO 55. For lubricants of the same nominal viscosity, the main differences were typically related to viscosity index and solubility. Traditional POE lubricants of high viscosity typically have lower solubility and higher viscosity index than low viscosity POE lubricants. Recently developed, advanced POE lubricants typically have a higher viscosity index, and therefore their viscosity changes less with temperature, and solubility characteristics can be decoupled from viscosity. Besides varying lubricants, some tests were conducted with higher or lower oil levels in an attempt to understand how oil charge, and to some extent OCR, affect efficiency. For each lubricant, the manufacturer has characterized the effect of temperature and pressure on viscosity, solubility, and density using polynomial fits presented in Seeton and Hrnjak (2009).

4. EXPERIMENTAL RESULTS

Each experimental condition was repeated three times in order to decrease random error, thus increasing the precision of the results. The mean of the repeated experiments can be found in Table 3. Because of the 100 data points per experiment and 3 repetitions of each experiment, each number in the table represents an average of 300 data points.
Based upon these results, isentropic efficiencies can be calculated based upon both Equations 1 and 4 in conjunction with thermodynamic property data of pure refrigerant and pure lubricant. The efficiencies calculated based on the data in Table 1 using both equations can be seen in Figure 1. In all cases, calculating efficiency according to Equation 1 was greater than the efficiency calculated using Equation 4. This should not be surprising as the denominator is identical, but there is less flow of refrigerant for which the isenthalpic enthalpy change is far greater.

One feature to note is that while there is a nearly linear relationship between the results calculated from both equations, there are several data points which deviate substantially from the least square curve fit. It is this deviation which proved troublesome in getting sufficiently accurate polynomial fits of efficiency to resolve the effect of the lubricant using the standard definition for compressor efficiency, Equation 1, because the deviation from the least square fit is on the order of the effect that the lubricant has on efficiency.

Table 3. Mean experimental results

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A least squared polynomial curve fit was utilized to understand the role of different parameters on compressor efficiency. While the properties of the effect of the refrigerant on isentropic efficiency can be calculated based on solely on pressure ratio and suction pressure for the limited data set used in this experiment, the lubricant must be accounted for by looking into various relevant liquid mixture properties. Because lubricant in the compressor is mostly located in the low pressure oil sump, liquid mixture properties were calculated at the suction temperature and pressure. Those properties which were viewed to possibly affect efficiency, and for which data was available, were density, viscosity, and solubility. For each of these lubricant-refrigerant mixture properties, a polynomial having powers of -1, 1, and 2 was used initially to gage the dependency of each parameter and to identify which terms and powers were relevant.

After this initial analysis, the polynomial fit was reduced to only those powers which produced a measurable effect. In this case, the parameters related to the lubricant were only the directly proportional terms relating to oil circulation ratio, and refrigerant concentration in the liquid and the second order polynomial relating to viscosity. While not meaningful, the second degree term for viscosity was retained as this functional form is suggested by lubricity curves. The density was not found to have any measurable effect on isentropic efficiency. Equation 5, gives the final form of the parametric curve fit. The values for the oil related terms are also given. It is expected that the values of the coefficients will be different for other compressors and refrigerants, and terms such as superheat may also be important due to its effect on refrigerant density. The results of the parametric fit can be in Figure 2. As can be seen, the model was able to match nearly all measured results to within 1%, which is approximately 3 times the repeatability of isentropic efficiency measurements.

\[
\eta = C_1 + C_2P_2 + C_3P_2^2 + C_4\frac{P_3}{P_2} + C_5\left(\frac{P_3}{P_2}\right)^2 + C_6\nu_2 + C_7\nu_2^2 + C_8\text{OCR} + C_9x_2
\]

\[
C_6=-0.0079
\]
\[
C_7=0.0025
\]
\[
C_8=-1.7982
\]
\[
C_9=0.3186
\]
5. DISCUSSION

To show the effect of the various lubricant property terms, efficiency will be graphically compared with respect to nominal conditions. For this nominal condition, the suction pressure will be set at 34.05 bars (0°C saturation), discharge pressure at 95 bars, and suction superheat of 10K. This corresponds to the first test condition. Also, relatively typical lubricant physical properties from the testing were chosen: mixture kinematic viscosity of 4cSt, oil circulation ratios of 2.5%, and R744 concentration in the lubricant of 30%. From these nominal conditions, comparisons can be made to understand the importance of each term. The effect of viscosity, oil circulation ratio, and refrigerant concentration can be seen in Figures 3, 4, and 5, respectively. In these graphs, values greater than zero represent that the efficiency of the compressor would be higher than for the nominal properties defined earlier in this paragraph, and values lower than zero indicate lower efficiencies.

Figure 4 shows that an increasing the viscosity of the lubricant rich mixture introduced to the compressor results in a nearly linear decrease in isentropic efficiency. Some of the compressor power gets used by friction within the compressor. By looking into a Stribeck curve, it can be seen that once in the hydrodynamic lubrication regime then increasing viscosities result in increasing friction. This increased friction therefore decreases the portion of the compressor power going towards compressing the refrigerant, thus resulting in decreased efficiency. Based on the Stribeck curve, it would be expected that there is a certain viscosity lower than those used in this experiment, that provides minimal friction. At this ideal viscosity, the lubricant provides sufficient lift from the bearing surfaces without having high viscous work. One item to note is that the viscosities used in the calculation were based on properties in the compressor suction. Due to the suction fluid being used to cool the compressor’s hermetic motor, some additional refrigerant will be driven from solution. This will have the effect of increasing viscosity from those values shown.

Figure 5 shows that increasing the oil circulation ratio decreases the compressor efficiency. From the coefficients shown in the previous section it can be seen that each percent increase in OCR leads to an approximately 1.75% decrease in efficiency. The decreased efficiency of the compressor efficiency can be seen by studying Equation 4. Since the isentropic enthalpy change of the refrigerant is far greater than that for the oil portion, increasing oil circulation ratios leads to a smaller numerator, thus to a lower efficiency. The effect on efficiency is more than 1 to 1 with respect to OCR precisely because of these enthalpy differences. The lower efficiency is of course still

Figure 2. Comparison between modeled and measured efficiencies
experienced if using the accepted definition, given by Equation 1, but the rationale is less readily apparent from simply studying the equations. OCR most likely scales with the amount of oil adhering to the cylinder and piston walls during the compression process. The presence of more oil during the compression process has the effect of decreasing the swept volume of the compressor, thereby requiring more compressor movement (and therefore more friction) to obtain the same flow rate.

Figure 6 shows that higher concentration of refrigerant in the lubricant at the compressor suction leads to lower efficiencies. Concentration in the lubricant plays a strong role in viscosity, which was shown in Figure 3, however it should be noted that this curve was made while holding viscosity constant. This was possible from the experimental data set used in this project because advanced polyol ester lubricants have different viscosity index values and solubility than traditional ester lubricants. Typically, there is little change in the concentration of refrigerant in lubricant as it passes from the suction to the discharge of through the compressor due to the offsetting effects of temperature and pressure. However, within the compression chamber, higher solubility lubricants are able to store and release more refrigerant. As the compression chamber is enlarged in order to create suction, refrigerant comes out of solution from the lubricant. This effectively increases the pressure inside the compression chamber, thus decreasing the amount of new refrigerant which can be drawn in for the subsequent compression stroke. Likewise, during the compression process, refrigerant is forced into the lubricant. Therefore, as with OCR, the piston the same piston sweep yields a lower refrigerant flow rate.

The density of the refrigerant-lubricant mixture was found to have little effect on efficiency. The effect was less than 0.01 change in isentropic efficiency in the range of mixture densities used in these experiments.

![Figure 3. Change in isentropic efficiency at nominal condition with respect to viscosity of liquid at the compressor suction](image-url)
Figure 4. Change in isentropic efficiency at nominal condition with respect to oil circulation ratio

Figure 5. Change in isentropic efficiency at nominal condition with respect to refrigerant concentration in lubricant at the compressor suction

6. CONCLUSIONS

Compressor or isentropic efficiency are two terms used in various sources to describe how much power is consumed by the compressor in comparison to the power necessary to isentropically compress a certain mass flow of refrigerant. The commonly used definition, which makes sense thermodynamically, does not account for the lubricant content in the flow; therefore an alternative definition was presented. A series of experiments were conducted with different lubricants used for the same compressor being operated in the same lab at nearly identical conditions. From these experimental results a polynomial fit was created to study the effect of various properties of...
the lubricant rich liquid introduced to the compressor. Lubricant-refrigerant mixture density, oil-circulation ratio, and refrigerant concentration in the lubricant were all found to affect efficiency. In practice, oil circulation ratio was seen to have the most dramatic effect.

**NOMENCLATURE**

\[ C \quad \text{constant for polynomial fit (various)} \]
\[ h \quad \text{enthalpy (kJ/kg)} \]
\[ \dot{m} \quad \text{mass flow rate (kg/s)} \]
\[ OCR \quad \text{oil circulation ratio (-)} \]
\[ P \quad \text{pressure (kPa)} \]
\[ s \quad \text{entropy (kJ/kgK)} \]
\[ v \quad \text{specific volume (m}^3\text{/kg)} \]
\[ \dot{W} \quad \text{compressor power (kW)} \]
\[ x \quad \text{concentration refrigerant in oil (-)} \]
\[ \eta \quad \text{efficiency (-)} \]
\[ \nu \quad \text{kinematic mixture viscosity (cSt)} \]

**Subscript**

\[ \text{oil} \quad \text{oil} \]
\[ \text{ref} \quad \text{refrigerant} \]
\[ s \quad \text{isentropic} \]
\[ 3 \quad \text{compressor discharge} \]
\[ 2 \quad \text{compressor suction} \]

**REFERENCES**


**ACKNOWLEDGEMENT**

Financial support for this work was generously provided by the Department of Energy (grant DOE-EE0003986).