Feasibility of gas-expanded lubricants for increased energy efficiency in power turbines

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Abstract
Lubricants are necessary in rotating machinery to ensure separation between solid surfaces but they are also responsible for undesirable power losses that can occur through a bearing in power turbines. Here, a novel method to reduce these losses is proposed in which a conventional lubricant is substituted by a binary mixture of synthetic lubricant and dissolved liquid-phase CO_2. These gas-expanded lubricants (GELs) would be delivered to a reinforced bearing housing capable of withstanding modest pressures up to 5 or 10 MPa. Experimental measurements of viscosity for mixtures of polyalkylene glycol + CO_2 at various compositions demonstrate that significant reductions in mixture viscosity can be achieved with relatively small additions of CO_2 that could lead to 20% reductions in power through a turbine bearing. For turbines subject to loads that are both variable and predictable, GELs could be used to tune lubricant properties in real time.

Introduction
Petroleum-based lubricants are ubiquitous in rotating machinery, such as gears and bearings, where they perform a range of vital functions[1]. These can include the support of the shaft, stabilization of the rotor components in response to perturbations, and protection of solid surfaces from wear[2]. The chemical properties of the lubricant and the impact on both mechanical (e.g., viscosity, density) and thermal (e.g., heat capacity, conductivity) properties are key to achieving these functions[3]. Generally, lubricants are selected with properties most closely aligned with the operating demands of a mechanical application. This approach is adequate for mechanical systems that do not deviate much from a prescribed operating range of loads or speeds. Many next-generation mechanical devices, such as wind turbines, must operate under a very large range of operating conditions including temperatures and forces. A one-size-fits-all lubricant could lead to substantial power losses or system failure[4].

Many of the drawbacks associated with conventional lubricants could be solved if mixtures with tunable properties could be delivered. In the chemicals sector, gas-expanded liquids (GXLs) are being developed to carry out separations, reactions, and other processes in mixtures with tunable properties. GXLs are typically solutions of solvent, often organic, and an industrial gas, most often CO_2. The mixture is liquid but the composition can be controlled so that it has properties between those of a pure solvent and a gas. The mixture is maintained at elevated pressures[5] but the properties (e.g., diffusivity, density, etc) can be controlled by increasing or decreasing the pressure. The presence of the compressible CO_2 in the mixture enhances mass transfer of dissolved solutes relative to the straight solvents and imparts the tunable characteristics to the mixture. GXLs are also desirable because they reduce the amount of solvent needed to carry out an operation and replace it with dense liquid CO_2, a largely inert byproduct of numerous industrial processes. When the presence of gas is no longer desirable, it can be separated easily by dropping the pressure of the mixture and venting the gas. An analogous type of tunable fluid would be useful in lubricated settings for operations under variable and predicable operating conditions.

In this work, a novel form of 'tunable' lubricant in proposed which consists of binary mixtures of lubricant and liquid or supercritical carbon dioxide. Gas expanded lubricants (GELs) could provide the adaptive qualities to lubricants in much the same way that GXLs have expanded the capabilities of traditional solvents. Lubricant/CO_2 mixtures under pressure have been studied in the recent past, mostly for refrigeration applications[6]. Mixtures of synthetic lubricants and CO_2 have been studied as environmentally superior alternatives to chlorinated organic refrigerants[7]. At low gas concentrations (<40%), the characteristics of these mixtures can be adjusted by several orders of magnitude by controlling CO_2 composition. Figure 1 demonstrates this relationship for viscosity for polyalkylene glycol (PAG) + CO_2.

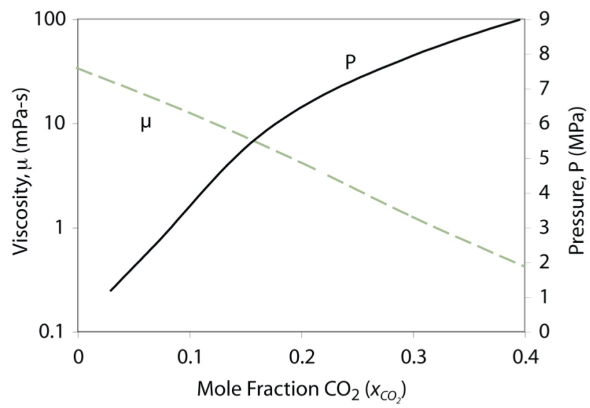

Figure 1. The viscosity of a lubricant-gas mixture is a function of composition, which can be controlled by increasing the system pressure. As pressure of gas increases in the mixture, the viscosity drops by several orders of magnitude. These data, for polyalkylene glycol (PAG) + CO_2 binary mixtures, are from[8, 9]

Empirical relationships to describe the viscosity of these mixtures have been proposed as in Equation 1[10].

$$\ln \mu_m = x_1 \ln \mu_1 + x_2 \ln \mu_2 \qquad (1)$$

Where μ_m is the viscosity of the lubricant mixture and x and μ are the mass fraction and viscosity of the components under the same temperature and pressure. This convenient relationship relies on easily measured properties that are usually readily obtained. For a diverse range of lubricant molecular structure, Eq. 1 has been shown to be an effective guide to mixture properties though the relationship has not yet been tested for mixtures of lubricants with compressed gas. A goal of this work was to measure the viscosity of lubricant/CO_2 mixtures under the conditions that would be found in a typical bearing used in power production or petroleum refining. The measured values were then used in a computer model of bearing behavior to estimate the impact of GELs on bearing performance.

Experimental. The viscosity of the lubricants and lubricant-CO_2 mixtures was measured using an Anton-Paar MCR 301 rheometer equipped with a high-pressure measuring cell rated up to 15 MPa. Measurements of viscosity were made over a range of shear rates to ensure that the mixtures exhibit Newtonian or near-Newtonian behavior and also to ensure that phase separations did not occur.

Modeling. A modeling approach outlined elsewhere was used to evaluate the performance of GELs in tilting-pad journal bearings[11]. The model estimates key bearing performance measures including journal operating position, power loss, maximum temperature and the bearing dynamic coefficients.

Results and Discussion

Measurements of GEL viscosity showed that CO_2 can be effectively used to reduce the viscosity of the PAG lubricant tested here. PAG was selected here because experimental values for this mixture have been reported but also because the solubility of CO_2 in synthetic lubricants is easier to control [12]. Petroleum-based blends tend to have heterogeneous chemical composition making resulting in highly variable phase behavior under high-pressure equilibrium with CO_2.

The viscosity results demonstrate reductions of nearly 65% over the range of compositions tested here at 40ºC (Figure 2). At 100ºC the effect is equally pronounced. Figure 2 shows experimental values along with predicted values (using Eq. 1) and modeled values used to obtain the modeling results in Figure 3. To evaluate the effect of variable shear rates on these binary mixtures, lubricant viscosity was measured over a range from 1-1000 s^{-1}. The results, not shown here because the lubricant behavior was Newtonian, suggest that GELs will not experience significant phase separation over the range of shear values typically encountered in most rotating machinery.

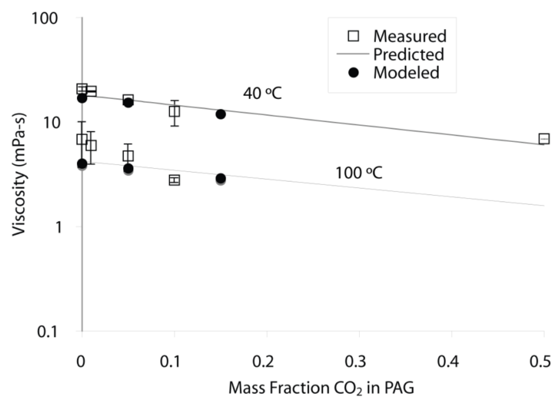

Figure 2. Viscosity of PAG-CO_2 mixtures as a function of mixture composition at 40ºC and 100ºC. The measured results were obtained experimentally while the predicted value is obtained using Eq. 1. The modeled values represent those that were input to the TEHD model of tilting-pad journal bearing performance.

Using the values reported in Figure 2, which are consistent with other published values of lubricant/CO_2 mixtures, the bearing model was used to estimate performance in the presence of GELs. Three lubricant/CO_2 conditions were modeled here to represent a range of easily achieved mixtures (PAG with 0%, 5%, and 15% CO_2). The results are shown for an ISO 32 reference fluid (petroleum based). The particular PAG modeled here was selected to have viscosity behavior similar to the ISO 32 reference fluid.

The results for power loss, shown in Figure 3, demonstrate that significant reductions in power loss, on the order of 20, are achievable. This result makes intuitive sense since most of the power loss that occurs through a bearing occurs as a result of shear forces in the lubricant that impede rotational velocity. Naturally, lower viscosity lubricants will result in lower power loss. In effect, by dialing down viscosity in a GEL, it is possible to directly lower the power loss in the bearing, without substantially changing the function of the mechanical system in which the bearing is used. When the high viscosity is needed, the gas can be vented and the original viscosity restored. Other modeling parameters (results not shown) show that the lower viscosity of GELs would not impede bearing function and could in fact enhance the resilience under certain conditions.

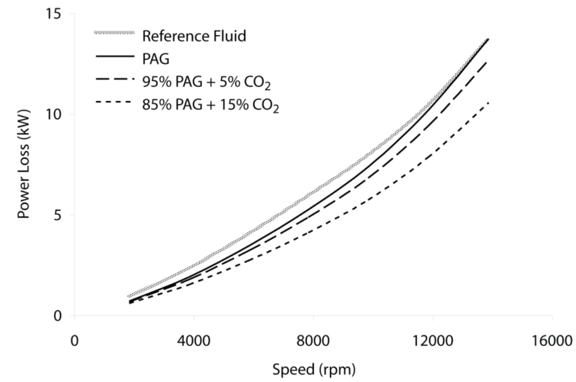

Figure 3. Power loss as a function of speed. Efficiency improvements of nearly 20% are observed over a range of operating speeds when using GELs compared to a reference lubricant.

Conclusions

The results highlighted here represent a promising new way to deliver adaptive lubricants to machinery used in power production and petroleum refining based on gas-expanded lubricants. Measured viscosity values for polyalkylene glycol + CO_2 mixtures suggest that these lubricant blends behave as expected between two liquid mixtures. When measured values are input to a computer model of tilting-pad journal bearings, the resulting drop in power loss is approximately 20% over a wide range of speeds. Future work will evaluate GEL properties for several types of lubricant classes. It will also include experimental validation of the bearing model results presented in Figure 3. If these experimental results are as promising as the model would suggest, GELs could represent a significant step toward improving energy efficiency of limited fossil fuel resources.

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