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ADVANCED GAS FOIL BEARING DESIGN FOR SUPERCRITICAL CO_2 POWER CYCLES

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Mr. Chapman is a Principal Engineer at Mechanical Solutions, Inc. in Albany, NY. He has been involved with development, testing, and evaluation of machinery systems throughout his career. At Mechanical Technology Incorporated (MTI) he held various engineering positions involved in development of Stirling engines and related mechanical systems. In 1998 Mr. Chapman joined Foster-Miller Inc. (now Qinetiq North America), to whom the MTI foil bearing business was sold, and where he was the principal designer of foil bearings and magnetic bearings for a variety of rotating machines ranging from miniature blood pumps and micro gas turbines to energy storage flywheels and high speed blowers. Mr. Chapman joined MSI following MSI's 2009 acquisition of the foil bearing business from FMI. He received his BSME Cum Laude from Union College and a Licensed Professional Engineer in the State of New York.

ABSTRACT

As new commercial applications arise for supercritical CO_2 (sCO_2) power generation, and higher output and efficiencies are achieved through higher turbine inlet pressures and temperatures, the need to improve component technologies becomes essential. Traditionally lubricated and cooled oil bearings cannot tolerate the higher temperatures, and the higher pressures make keeping the oil separate from the working fluid an increasingly difficult challenge. These conditions strongly promote the use of the sCO_2 working fluid itself as the lubricant, rather than oil.

The author is developing an advanced high load capacity gas foil bearing that meets these challenging needs by using the sCO_2 as the lubricating fluid. The concept combines the best features of current foil bearing technology with new-concept design enhancements that will substantially advance the art by providing increased load capacity, damping, and wear resistance, as well as tolerance to the service conditions of vibration, temperature, misalignment, and severe system transients. MSI has combined best-in-class technologies in pressurized hydrostatic gas bearings and hydrodynamic gas foil bearings to produce an advanced hydrostatically-assisted hydrodynamic gas bearing design that meets sCO_2 challenges.

Background

Because of its potential for high efficiency power generation in competition with traditional supercritical- or superheated-steam cycles, supercritical CO_2 (sCO_2) is receiving much attention as a possible power cycle working fluid. The high pressures and temperatures required for these systems pose unique challenges to the design of the turbomachinery and their components. These challenges require advancement of technology on the component level. Components are required to run faster and hotter to achieve the goals of these challenging system designs. Particularly critical are the bearings of these systems. Even the best synthetic oils currently available on the market cannot survive if exposed to the extreme temperatures (up to 800°C) that are anticipated with these machines. The higher pressures make the seal designs extremely complex in order to attempt to contain the working fluid and maintain separation of the oil and working fluid. The combination of extreme temperature and pressure obviate the practicality of an oil system, encouraging the use of the working fluid as the lubricant. By eliminating the lube-oil system, an opportunity to design a hermetically sealed system arises, thereby eliminating the need for complex seal designs and permitting the sole use of internal labyrinth or brush seals. Elimination of the ancillary equipment (oil pumps, coolers, oil de-aerators, etc.) has the added benefit of reducing cost, complexity, and reliability issues inherent with an oil lube system.

To address this challenge, the author's company, Mechanical Solutions, Inc. (MSI), is being funded by the Department of Energy (DOE) Office of Fossil Energy to develop a new gas foil bearing that meets these advanced needs by using the sCO_2 as the lubricating fluid. The goal of this project is to develop a reliable, high performance foil bearing system for supercritical CO_2 power cycle machinery. The bearing system will be capable of temperatures up to 800°C and pressures up to 300 bar. Key elements of the design include:

- An advanced hydrostatically-assisted hydrodynamic foil bearing concept capable of much higher specific loads and stiffness than traditional hydrodynamic-only bearing designs.
- An integral gas delivery system that incorporates flow passages into the assembly to distribute the flow throughout the bearing for the hydrostatic assist, without interfering with the hydrodynamic effect.
- The addition of overload protection designed to handle large shaft excursions in the event of system severe transients.
- An optimized foil arrangement that increases bearing hydrodynamic stiffness and damping, and provides additional load carrying capacity.
- The use of new high temperature materials and coatings that prolong the life of foil bearings, enabling sufficient start/stop cycles.

To achieve these features, the author's development group is combining best-in-class technologies in pressurized hydrostatic gas bearings and hydrodynamic gas foil bearings to produce an advanced gas bearing design that can operate under these conditions without oil lubrication, providing the enabling technology needed to meet the challenges of advanced sCO_2 power cycles.

Bearing Design

Foil bearings have been identified as viable replacements to conventional liquid lubricated bearings for a wide variety of rotating machinery from turbines, compressors, and pumps to motors and generators. They have been demonstrated to temperatures greater than 650°C and speeds in excess of 120,000 rpm[1]. With no moving parts these oil-free bearings are compact, lightweight, and tolerant of high frequency, low displacement shock loads. Research on high-speed hydrodynamic foil air bearings began in the early 1960s[2, 3]. This continued early work resulted in the development of various designs of radial and thrust foil bearings (see Figures 1 and 2), such as bump type[4, 5], leaf type[6, 7], and tape type[8]. In each case the spinning shaft is supported on a thin film of air or process gas. No oil sealing or liquid lubrication is required. There are no spinning bearing parts, so foil bearings are well suited to high shaft speeds. Since there is no lubrication, foil bearings are good for high or low temperatures. Unlike traditional rigid-pad gas bearings, foil bearings can tolerate significant shock loads, as well as substantial misalignment and dust/debris, and do not have inherent rotor stability problems at high speed.

Among the three styles of bearings shown in Figure 1, the bump type has been the most publicized and popular, and is the type undergoing further development by the author's group. Gray[4] and Chen et al[9] document the design methodology for bump-type bearings, and address issues involving materials and coatings, manufacturing procedure, fabrication accuracy effect, misalignment, Coulomb damping, shock tolerance, dynamic stability, analytical tools, and so forth.

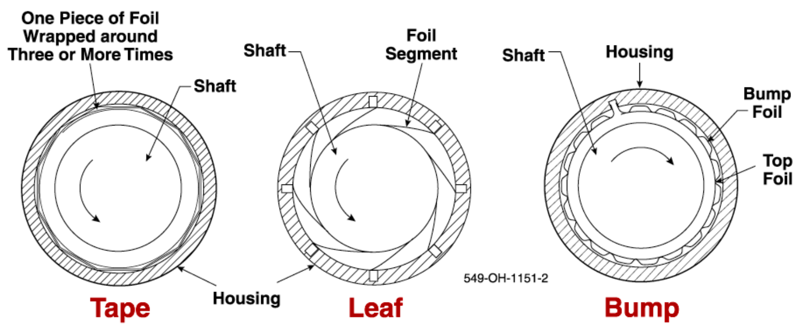

Figure 1. Three Types of Foil Radial Bearings – MSI Makes the Bump Style

A bump style foil bearing is comprised of three basic components: a top smooth foil, a corrugated foil underlayment or bump foil, and the support structure, usually a cylindrical shell for journal bearings and a flat disc for thrust bearings (see Figure 2). Thrust bearings are usually made up of an array of individual foil bearings, referred to as pads.

Foil bearings have been successfully applied in a variety of applications ranging from micro-turbines to turbo-expanders and compressors. Recent studies[9, 10] have also been conducted using sCO_2 as the working fluid in foil bearings. Figure 3 shows the range of applications MSI staff has accomplished using bump-type foil bearings.

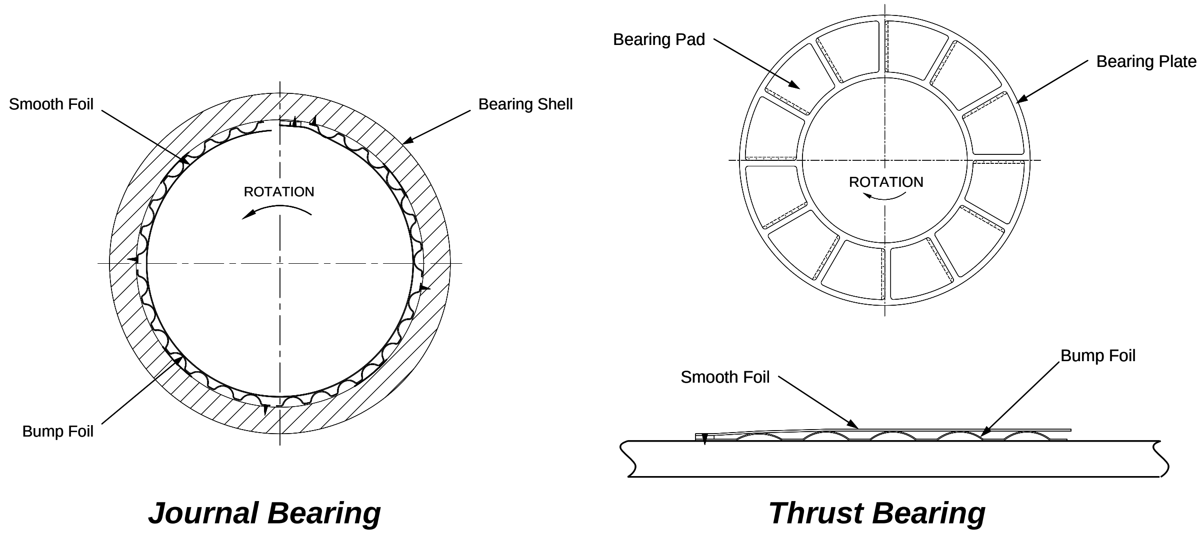

Figure 2. Typical Bump Foil Bearing Construction

The current size and speed bearing being investigated for this project is 63.5 mm in diameter by 44.5 mm long running at 60,000 rpm. Most foil bearing applications have been designed for shafts less than 100 mm in diameter. As the power level of supercritical CO2 machines approaches the 10 to 100 MW level, the sizes are anticipated to increase and the speeds decrease. The expected envelope is superimposed on the application chart. NASA[12] conducted a study looking at the scalability of foil bearings and cited that bearings up to 150 mm have been demonstrated to DN levels over 4 million (equivalent to 27,000 rpm) and concluded that there is conceivably no limit in size, as long as surface speed remains sufficiently high.

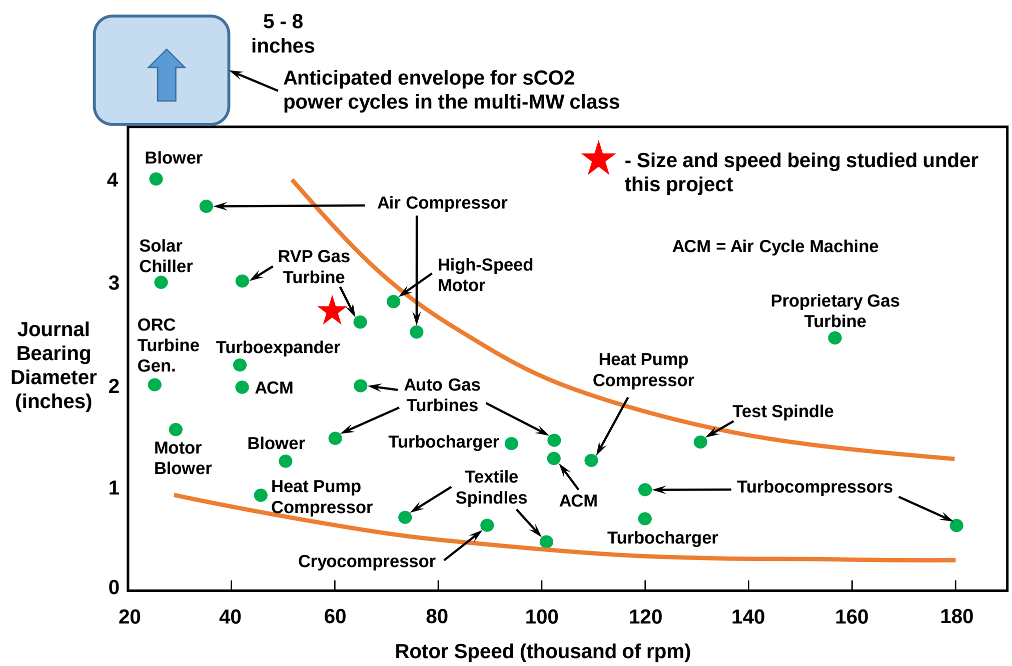

Figure 3. MSI Experience with High-Speed Machinery Applications for Foil Bearings.

Fluid Properties

Important questions as to the feasibility of using sCO_2 as the working fluid in a foil bearing are its gas properties and how the gas will perform in the bearing. The two properties that affect the bearing's performance the most are the gas viscosity and density.

<u>Viscosity</u>

The analysis of hydrodynamic lubrication is often simplified by using the Reynolds equation. This analysis method assumes that the fluid is Newtonian, that the flow is laminar so that the shear stress in the bearing gap is proportional to the velocity gradient, and that the fluid is incompressible. Though the latter assumption may be a stretch, the effects of compressibility are modest, and the theory is still an accepted method for designing of gas foil bearings has resulted in numerous successful designs, and has been used in recent studies[9] investigating sCO_2 as the working fluid. Using the Reynolds equation, the only property that is taken into account is the fluid's viscosity.

To determine fundamental feasibility, the viscosity of sCO_2 was researched to determine its potential to be the lubricating fluid in a foil bearing. The study revealed that, above 200°C, its characteristics are similar to air and thus favorable to foil bearing applications. The viscosity of liquids reduces as temperature increases, a potentially unstable condition thermally. Gases, on the other hand, exhibit an increase in viscosity with increasing temperature, thereby avoiding this viscosity-based thermal instability. As the viscosity chart in Figure 4 illustrates, the viscosity of sCO_2 behaves much like a liquid below 200°C, however, above this temperature it behaves like a gas.

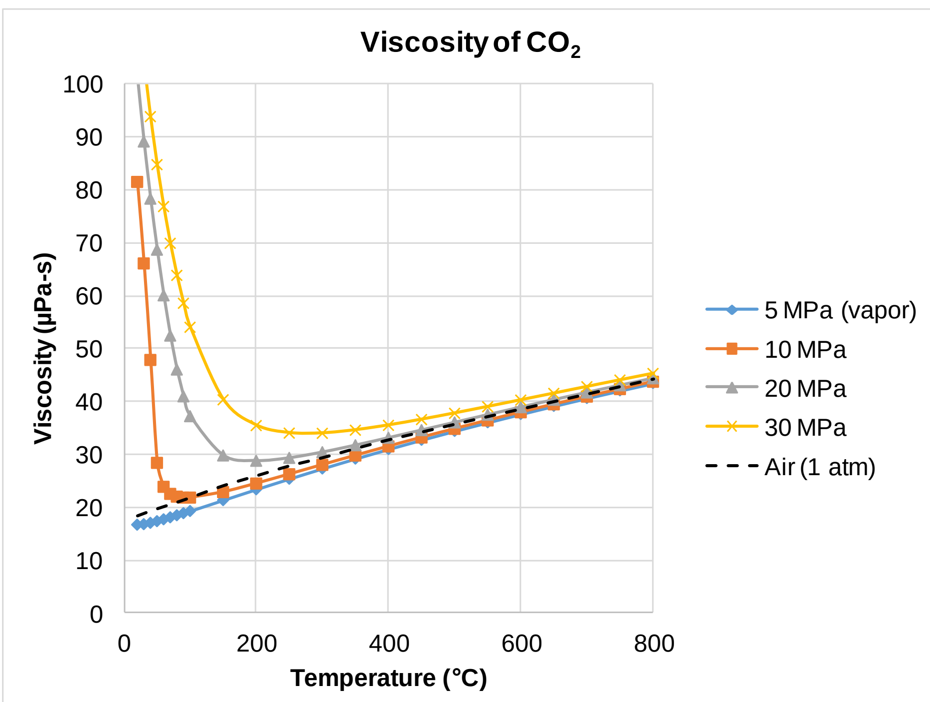

Figure 4. Viscosity of CO_2 as a Function of Temperature and Pressure
(Source: National Institute of Standards and Technology (NIST) http://webbook.nist.gov/chemistry/fluid/)

Some references[10] suggest that the viscosity of sCO_2 is more sensitive to pressure than liquids, which is true at lower temperatures. However, as the chart indicates, above 300°C the viscosity becomes insensitive to pressure. Therefore, hydrodynamic load capacity will remain essentially the same with varying pressure conditions.

Density

The more compressible a fluid becomes, particularly as the flow begins to exit the laminar regime, the more other fluid properties begin to influence the bearing's design. In particular, the fluid's density becomes an important parameter. Studies have shown that as the density of the fluid increases, so does the power loss in the bearing. The power loss within a bearing is a critical consideration, as the heat generated must be effectively removed to avoid overheating of the bearing and potential thermal instability. The windage power loss in gas foil bearings as a function of the rotor-stator gap was characterized in sCO_2 by Bruckner and Dellacorte[13] and Milone[14]. The density of CO_2 as a function of temperature and pressure is shown in the chart in Figure 5.

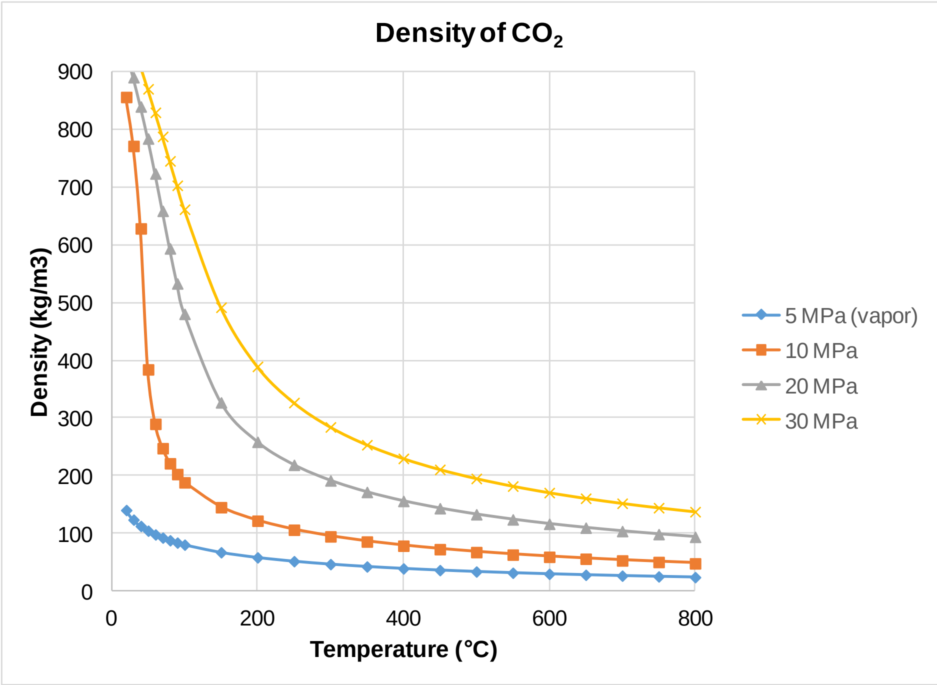

Figure 5. Density of CO_2 as a Function of Temperature and Pressure
(Source: National Institute of Standards and Technology (NIST) http://webbook.nist.gov/chemistry/fluid/)

Material Considerations

Due to the extreme temperatures that the bearings will potentially be exposed to in sCO_2 power cycles, the selection of materials must be given special consideration. The losses in strength and stiffness (modulus of elasticity) due to increased operating temperatures have to be factored in to the foil bearing design. As temperatures rise significantly above 500°C, the creep resistance of the material must also be considered.

Strength

In existing foil bearing designs by the author's company, the bearing foils are manufactured from Inconel X-750, a nickel-based alloy, because of its high strength at elevated temperature and fatigue and corrosion resistance. It is also readily available in sheet and coil form in a variety of thicknesses. A particular benefit that is essential for the sCO_2 application is that it is heat resistant, maintaining reasonable strength at 800°C, nearly half of its room temperature strength.

Figure 6 shows the yield strength as a function of temperature for a variety of nickel-based alloys. All of the alloys shown in the chart are available in sheet form, and therefore potential candidates for foil bearing materials. Out of these alloys, René 41 has the highest strength, with exceptional properties at temperatures from 650° to 980°C. It is commonly used for afterburner parts and nozzle diaphragm partitions in gas turbine engines, and is rolled in thicknesses down to 0.08 mm, suitable for foil bearing components.

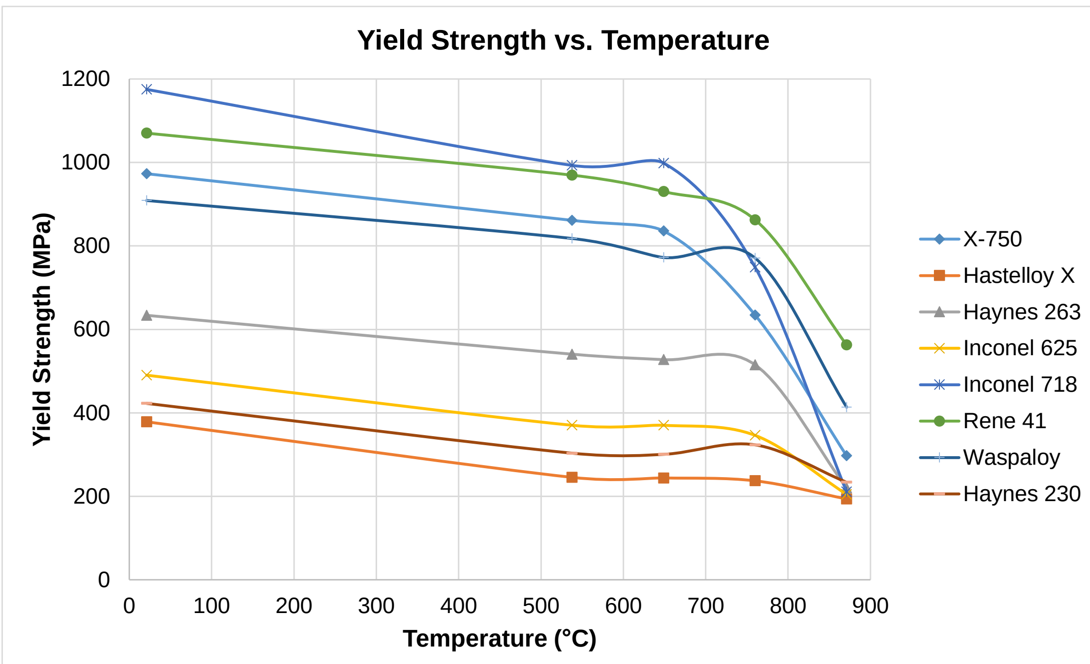

Figure 6. Yield Strength of Several Nickel-based Alloys as a Function of Temperature (Courtesy Haynes International, Inc.)

Corrosion

Consideration must also be given in regards to compatibility with sCO_2. Some materials have been shown to exhibit severe corrosion in sCO_2 environments, such as high strength steels[15]. In the same study, nickel-based alloys were shown to have good corrosion resistance to sCO_2. The material used for the bearing shell and thrust plate must also be resistant to sCO_2 corrosion. Typically an austenitic-grade stainless steel such as 304 or 316 is used for these components. Grade 316 has been shown to be susceptible to sCO_2

corrosion, yet grades 310 and 347[16] demonstrated resistance similar to the nickel-based alloys.

Advanced Coatings

Under normal, steady-state operating conditions of a foil bearing, the shaft is supported on a fluid film, and therefore there is no contact between the shaft and bearing. During machine start-up and shut-down, however, contact between the shaft and the bearing is inevitable when the shaft rotation is zero. Rubbing during start-up and shut-down can be avoided by energizing the hydrostatic feature of the bearing, but this requires an initial pressure source prior to start-up which may or may not be available or practical. In applications where a unit is cycled numerous times every day, the number of cycles can add up to tens of thousands over the life of the device, becoming the life-limiting aspect of foil bearings.

To extend the life of foil bearings, coatings have traditionally been applied to the top foil, the shaft journal, or both in order to minimize friction and wear. The type of wear that is of primary concern is adhesive wear. This wear occurs when opposing micro-peaks or asperities in the contacting surfaces successively adhere and fracture. If the generated debris remains in the bearing, abrasive wear becomes a concern. Most foil bearing applications use a positive flow of gas or air through the bearing for cooling purposes. This has the added benefit of flushing out any debris, thus reducing the chance of abrasive wear. In any event, the characteristics of good coatings must include low friction and resistance to adhesive wear. Additionally, the coating must have good adhesion to the substrate.

The author's group currently uses a blend of fluorocarbon lubricants in an organic resin binder as a foil bearing coating with good success. It has a low coefficient of friction (0.09 - 0.10 static and dynamic), is extremely durable and wear-resistant, and has a wide range of solvent and chemical resistance, allowing it to perform well in a variety of harsh environments. However, it has an operational temperature limit of 230°C, which prohibits its use in certain applications. For applications above this, the author's company has recommended a layer of thin dense chrome on the shaft, which has a published operating temperature limit of 980°C. In addition, the author's group evaluated a number of coatings for a high-temperature foil bearing application for small gas turbine engines. Tests were conducted to 650°C and the coatings with the best combination of wear resistance and low coefficient of friction were identified for high temperature applications.

A new family of coatings is starting to become available. These are referred to as adaptive coatings, or "chameleon" coatings[17]. These coatings are named due to their ability to adapt to changing temperature by preserving good tribological properties, from 25°C to 1000°C. These coatings are potentially the best of all the candidates considered, but are more expensive with long lead times, and therefore their evaluation is being reserved for the next DOE project phase.

Hydrodynamic Performance

Performance of the journal bearing was predicted with both air and sCO_2 as the working fluid. Since initial testing for DOE is being conducted in air, the ambient pressure assumed for the predictions was one bar. The estimated load capacity of the bearing as a function of speed for a range of temperatures up to 760°C is presented in Figure 7. As temperature increases, so does the viscosity of air, thereby increasing the load capacity of the bearing. The modulus of elasticity of the bump foil, however, decreases with an increase in temperature. This softer compliance tends to reduce the load capacity and overall stiffness of the bearing. However, the increase in viscosity more than offsets the decrease in stiffness up to 550°C. Above that, the effect of loss in stiffness equals the effect of gain in viscosity up to 760°C. In net, a substantial increase over room temperature capacity is still gained.

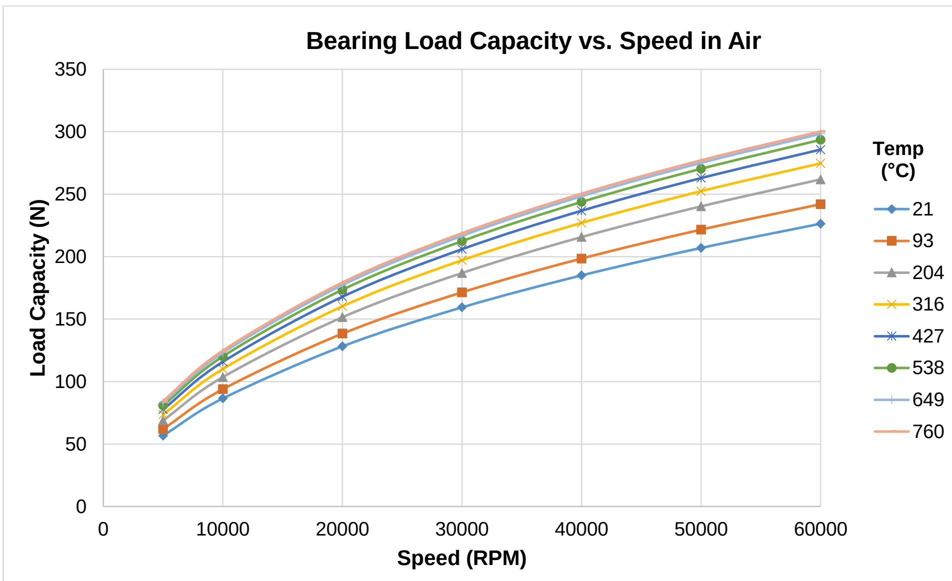

Figure 7. Performance of the Hydrodynamic Bearing in 1 Atm Air

Performance of the same bearing was predicted for sCO_2 over the same temperature and speed range, with pressures from 5 to 30 MPa. The load capacity for sCO_2 as the working fluid is presented in Figure 8. The charts reveal a trend that as the sCO_2 pressure proceeds deeply into the supercritical region for temperatures above 150°C, the change in bearing load capacity as temperature varies becomes less pronounced. This is in part due to the viscosity curve becoming somewhat flat.

Hydrostatic Performance

A characteristic of gas foil bearings that often limits their use in some equipment, particularly larger machines running at lower speeds, is low load capacity relative to liquid-lubricated bearings. The ability to supplement or enhance load capacity and stiffness would enable the use of gas foil bearings in a much wider range of applications. One way to potentially enhance these characteristics is to include a hydrostatic component into the

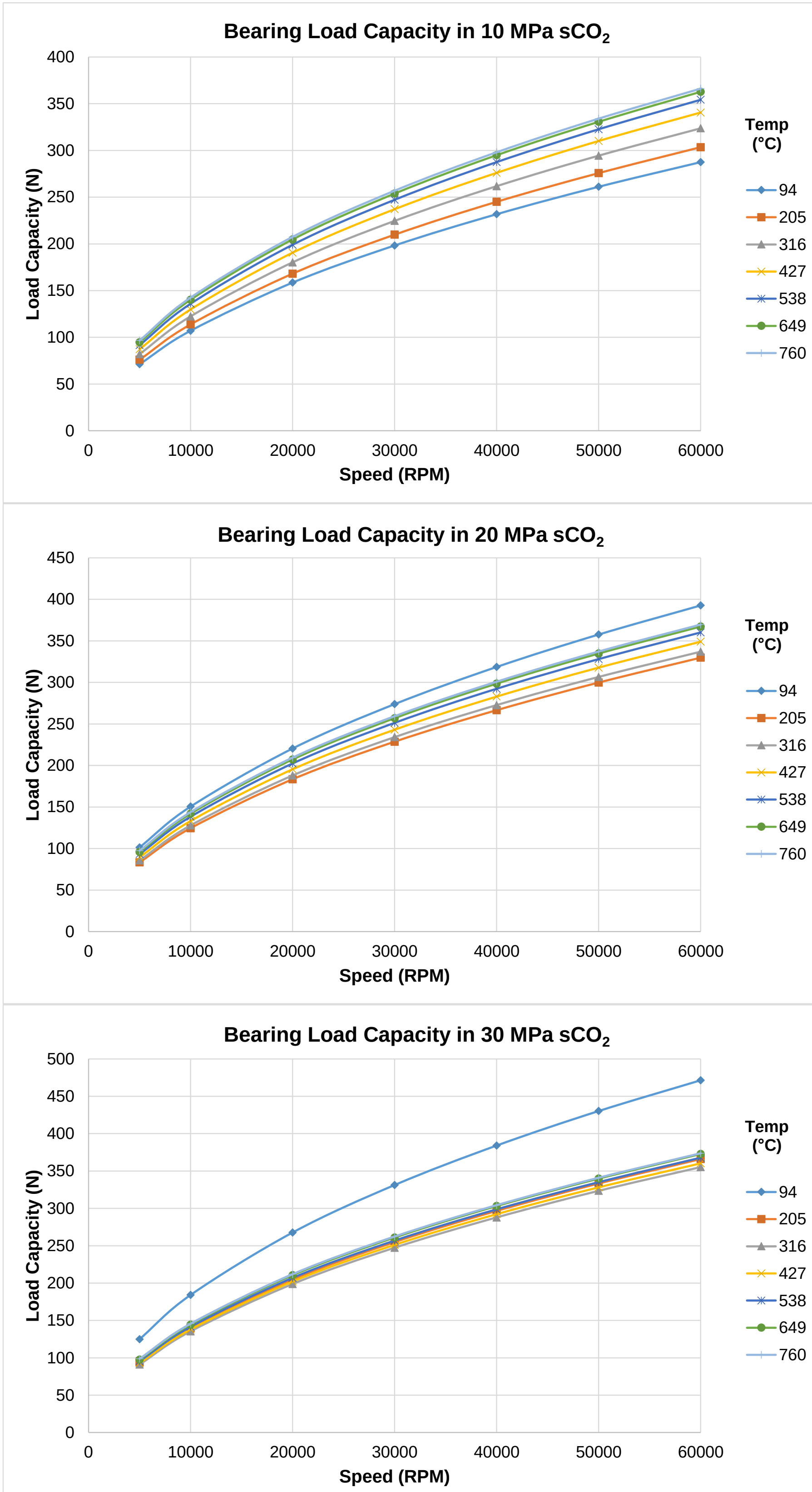

Figure 8. Performance of the Hydrodynamic Bearing in sCO_2

bearing construction. By injecting pressurized gas into the bearing cavity, a hydrostatic force effect can be obtained, potentially increasing both the load capacity and the stiffness of the bearing significantly. An additional benefit is that the bearing is effectively cooled by the resulting flow of gas between the top foil and shaft, thereby removing the generated frictional heat at the source.

This hybrid bearing concept was studied by Texas A&M University (Park[18] and Kumar[19]) and experimentally validated. A schematic of their hybrid journal design is presented in Figure 9. This same concept was analyzed by the author's group using computational fluid dynamics using the commercially available computer code CFX (ANSYS, Inc.). Results of the analysis are depicted in Figure 10. The analysis was run with a minimum clearance around the nozzle of 10 microns, a typical film thickness for a loaded bearing. As can be seen from the figure, the pressure distribution around the orifice drops off drastically.

Because a significant amount of pressure is not created in a large enough area around the hole, the force generated is low. Stability of the hydrostatic design can be an issue if the shaft is allowed to touch and cover the hole, effectively blocking the flow into the bearing. This tends to create instability in the bearing since there is greatly reduced restoring force from the zone around the blocked orifice to return the shaft to center, as well as no change in reaction force as additional load is applied. Because of these issues, the author's company has developed a proprietary design that avoids the potential for instability and also increases the hydrostatic force by a factor of at least ten. In the present 63.5 mm design, static load capacity of 120 N is currently estimated for hydrostatic effect alone for room temperature air with a supply pressure of 4.5 bar.

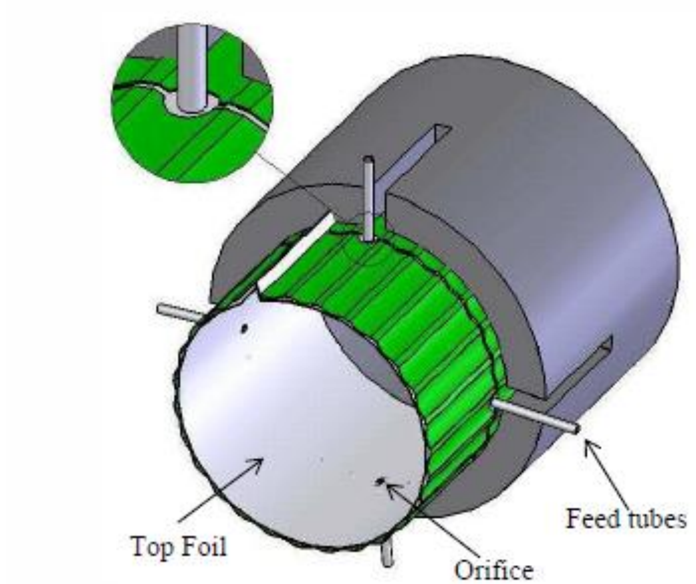

Figure 9. Schematic of a Hybrid Air Foil Bearing (HAFB) (courtesy Texas A&M University[19])

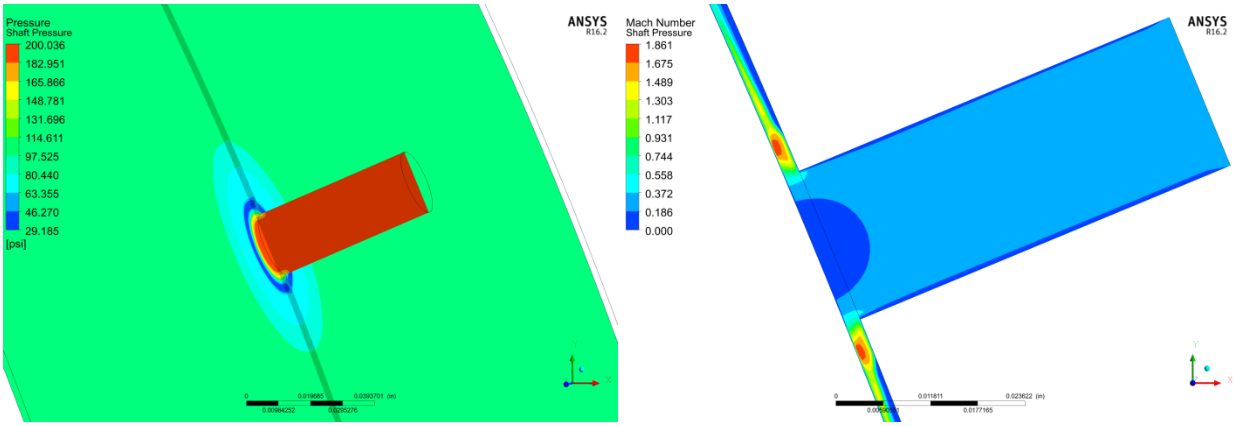

Figure 10. Plots of CFD Results of a Single Hydrostatic Nozzle

Future Work

Currently the author's group is in the process of fabricating bearings using the new proprietary hybrid bearing design. An existing foil bearing test rig is being modified to accept the hybrid design as well as allow for high temperature testing, up to at least 550°C (see Figure 11). The original test rig was driven by an air turbine. The modified test rig will be driven by a high speed variable frequency controlled motor, also suspended on foil bearings (conventional), and coupled through a quill shaft.

Near-term testing will be performed in air to validate the hydrostatic-assist design concept as well as to optimize details effecting the combined hydrostatic and hydrodynamic performance. Testing the bearing in a sCO_2 environment will be conducted during the Phase II part of the program, which is anticipated to be in late 2016 or early 2017.

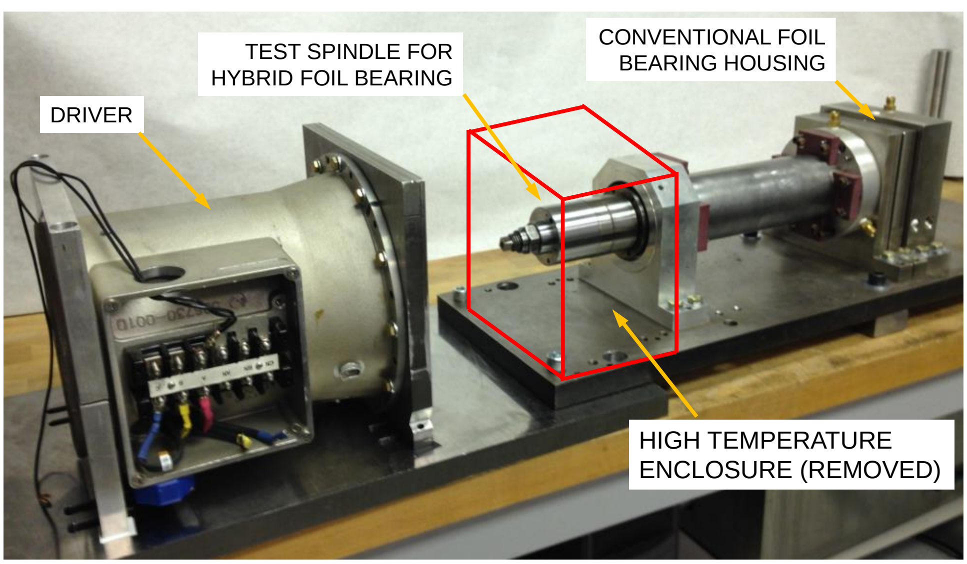

Figure 11. Foil Bearing Test Rig Being Modified to Test the Hybrid Bearing Design

SUMMARY

Based on the work conducted so far, foil bearings show great promise for applications where sCO_2 is used as the working fluid. The characteristics of the sCO_2 fluid pose interesting challenges, but so far do not impose any absolute limitations. To date, MSI has analytically shown that the hydrostatic assist can generate enough load capacity to provide an effective sCO_2 turbomachine bearing design. It is anticipated that near-term testing in air and Phase II testing in sCO_2 will demonstrate foil bearings' suitability in this very demanding environment.

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