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Machinery Health Monitoring and Component Testing using a Magnetic Bearing with a Supercritical CO_2 Turbomachine

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ABSTRACT

Turbomachinery built for Supercritical Carbon Dioxide (sCO_2) service is designed with special consideration for the very high-density characteristics of the working fluid. The fluid density has strong effects upon the dynamic behavior of the machines and makes the machines sensitive to changes in the operating point of the power cycle. The power cycle control must consider the condition of the turbomachinery in order to maintain safe and reliable operation.

Concepts NREC is working with the DOE under an SBIR funded program to develop an sCO_2 turbomachinery bearing spindle with magnetic bearings. The magnetic bearing has been selected for its diagnostic and measurement feedback capabilities. Magnetic bearings will provide real time information about the condition of the machinery. This type of information can be valuable in component level testing, and for the operational control and monitoring of the machine in service.

Condition monitoring of machinery for the sCO_2 program can yield great benefits in the development stages, as well as in the future reliability improvement stages of the program. Understanding the machinery response to changes in operations, such as changes to the heat input or fast transients due to upsets, will help the development of process control algorithms for the power cycle.

This paper will describe the influences of the high-density fluid upon the machinery configuration and describe the machinery under development for the magnetic bearing spindle for sCO_2 turbomachinery.

INTRODUCTION

The evolution of turbomachinery for the sCO_2 power cycle is engaging the engineering community in a wide array of design disciplines. The state of the art in turbomachinery is being pushed to a higher level, largely due to two alluring promises: improved efficiency and lower size and cost. The efficiency improvements are especially relevant in today’s climate conscious mind. A 5% improvement in the power cycle is 5% less fuel burned. If that fuel is putting carbon in the atmosphere, then reductions are appreciated. The size and cost angle may be an even greater benefit in the overall scheme to reduce carbon emissions. The smaller machines are a better fit for distributed power stations. A small footprint matters when we want to install plants in a decentralized strategy utilizing clean energy sources.

The sCO_2 machines are smaller because they use a higher density working fluid. The supercritical fluid is operating at very high pressure and very high temperatures. The effect of the high-density fluid is to increase the fluid forces within the turbomachinery. These forces can contribute to machinery dynamic behavior, largely due to fluid whirling within the impellers interstage seals. The forces can also influence machinery behavior during transient conditions, such as startup and shut down and due to variations in the heaters, coolers, and recuperators.

DISCUSSION

Supercritical Fluid Influences Upon the Machine Design

Supercritical sCO_2 is a very high-density fluid, nearly the density of water. Figure 1 shows the commonly referenced T-S diagram and a chart of the fluid density coincident with that diagram. The typical operating regime is just above the point noted.

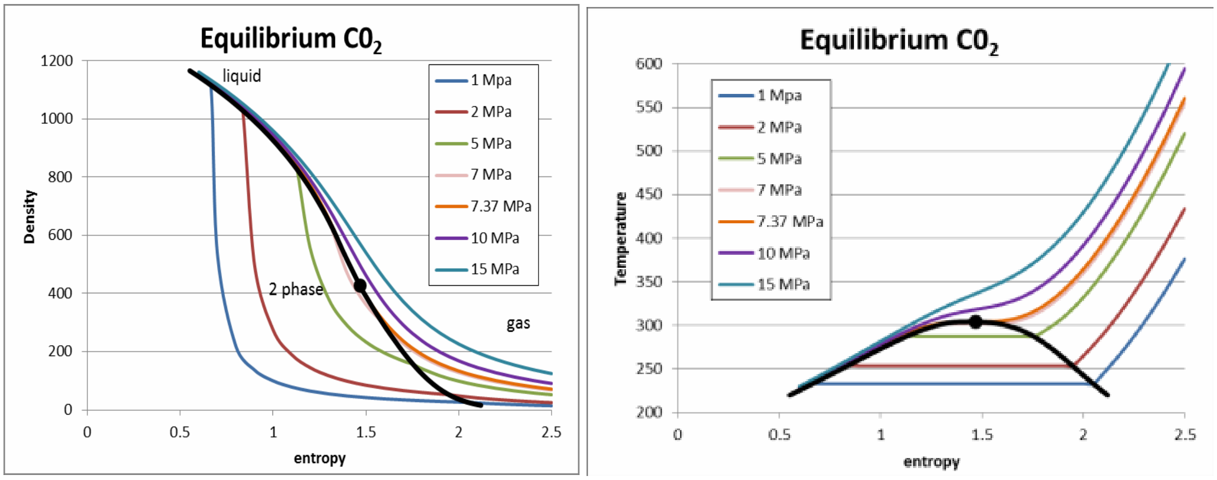

Figure 1: Density of sCO_2 and the sCO_2 T-S diagram

The units for the density are Kg/m3, and the temperature is degrees C. As a reference, the density of air at atmospheric condition is approximately 1.2 kg/m3. The sCO_2 cycle operates at approximately 400-500 times the density of a typical air compressor.

The effect of the high density is to produce a similar power with a much smaller machine. As a machine gets smaller, the flowrate is reduced. At the lower flows the specific speed is reduced. The specific speed relation is shown in equation 1.

$$N_s = \frac{\phi^{1/2}}{\psi^{3/4}} = \frac{\omega\sqrt{Q}}{(gH)^{3/4}} \quad \text{or} \quad \frac{\omega\sqrt{m/\rho_{01}}}{(\Delta h_0)^{3/4}}$$

Equation 1: Specific Speed

The machinery efficiency as a function of specific speed is shown in figure 2. Given a specified flow and head, the variable remaining for the designer is speed. At the lower power levels, in the

1-10 MW range, the optimum speeds can be in the 20,000 - 30,000 rpm range. As the power increases, the flowrates increase, and the optimum speed can be at synchronous generator speeds.

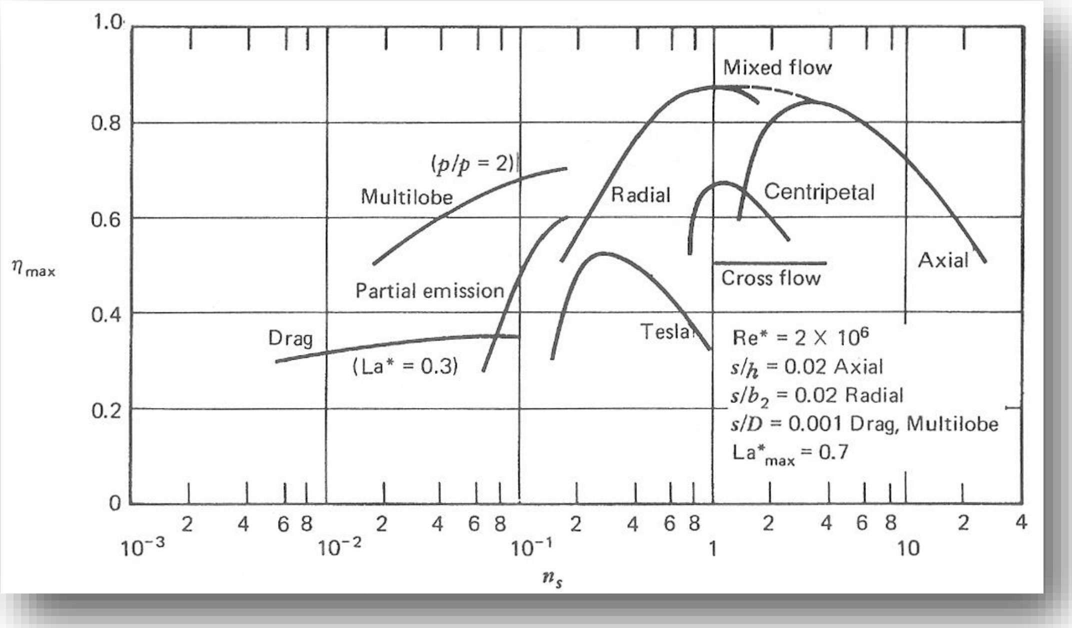

Figure 2: Compressor Efficiency as a function of Specific Speed

The performance of the turbomachines is sensitive to velocity of the fluid in the impellers, and low flow, high speed machines will maintain smaller bladed geometry. Size is also important in terms of flow channel dimensions. Very small blade heights have clearance sensitivity for the open blading, and friction loss becomes a greater portion of the total power as the channels become smaller. For radial machines, these smaller impellers will require smaller shafts in order to keep the hub diameters, and therefore blade velocities, low.

The high temperature working fluid also influences the geometry. It is important to keep the seals cool and to minimize the heat flow in the adjacent bearing housing. The bearing temperatures and clearances can be affected by the hot casing nearby. The typical solution is to add a thermal barrier and some separation between the casing, seals, and bearings. This separation adds to the shaft length.

The high speed serves to limit the bearing and seal diameters. Typical journal bearing velocity limits are approximately 300 ft/sec. For a 25,000 rpm machine, the bearing would be 2.75 inches in diameter. The seals also have surface velocity limits, but they are typically limited by the bearing shaft diameters. In the case of an overhung machine, the seal size has an influence upon the thrust seen by the thrust bearing. A larger seal will result in more axial thrust for an overhung machine and require a larger thrust bearing. As a result, the bearings and seals both have an influence upon the shaft diameter.

As the shafts become smaller, the rotordynamic concerns begin to become more acute. Long thin rotors will have lower natural frequencies. The term “flexibility ratio” is often used to describe the ratio of the running speed to the first critical speed. As the flexibility ratio increases, the machine is more sensitive to forces acting upon the impellers. It is intuitive that a given force will have a greater influence on a more flexible beam.

Rotordynamic analysis includes the effect of the fluid forces upon the rotating elements. The typical radial forces in a compressor or turbine are low. However, there can be a dynamic force generated by the fluid whirling around the components. The forces are modeled as cross-coupled stiffness values, which is the destabilizing component of the bearing characteristics in a rotordynamics stability model. Essentially, the fluid tangential velocity is zero at the wall, and 100% of the rotational speed on the rotating surface, with a resultant average velocity of half speed. The whirling fluid can excite a natural frequency of the rotor.

The magnitude of the aero cross-coupling is difficult to calculate accurately. However, general equations are established to estimate the force. The equations are directly related to power and fluid density. The codes that evaluate the cross-coupling forces are also difficult to validate. The typical method is to calculate the stability of a machine, then test the machine. If the machine runs well, then no further work is done. If the machine is unstable, then urgent and often expensive work is done to modify the machine. If a single change is made, then that component can be attributed to the net change in performance. The rotordynamic characteristics that are modeled in the analysis are then attributed to the new geometry. However, if multiple changes are made it becomes difficult to attribute the improvement to any single element.

Operational Forces in the Supercritical CO2 Machine

The static fluid forces that act upon the machine are also greater in the sCO_2 environment. The high-density, high-pressure fluids will impose a high force per unit area. The thrust forces in a turbomachine are based upon pressure profiles acting across the faces of the rotating surfaces. The smaller machine and higher pressures mean that the profiles are much stronger. Therefore, the changes that take place within each cavity in the machine can have a very large influence upon the thrust. If the fluid conditions at single point in the machine undergo a rapid change, then there may exist a strong axial force applied to the internal components. If the compressor and turbine are on a common shaft, and the control of each section is managed independently, then the conditions exist to have a wide variation in the net thrust of the machine.

The variations in the internal pressures are also highly influenced by the transient operations of the heater, cooler, recuperator, and control valves. For example, if the heat input makes a rapid transient, then the fluid properties at the turbine may change rapidly, while the conditions at the compressor may remain unchanged. The compressor operating point is controlled with a recycle valve and turbine is controlled by a bypass valve. The fast and potentially strong forces produced are all absorbed by a thrust bearing. However, as is true with the sources of stability, it may not be clear about the source of the thrust.

There is no shortage of influences upon the machinery. In most traditional power cycle machines, the changes to the operating conditions are slower and well understood. The high pressure, high speed, and increased power density of the sCO_2 machines changes that traditional assumption. Supercritical fluid can operate near the dome, and properties can change quickly with changes in pressure and temperature. There can be a large change in density for a relatively small change on the operating map.

Solutions for the Problems

Concepts NREC is currently engaged in the design of a magnet bearing spindle to serve as the bearing body for sCO_2 compressors and turbines. Concepts NREC has experience using magnetic bearings as test instrument for measuring the characteristics of turbomachinery components. It would be a reasonable next step to utilize this technology to measure the characteristics of turbomachine components in actual operation with sCO_2 working fluid. The greatest promise of the technology lies in the real time diagnostics and control capabilities of the magnetic bearing spindle. As a process variable is monitored, so can the turbine response to a change in that variable be monitored in real time. The ability to monitor the thrust on the machine will also become a valued benefit. Thrust failures can be very expensive, often resulting in the total loss of the machine.

The magnetic bearing spindle is shown in Figure 3.

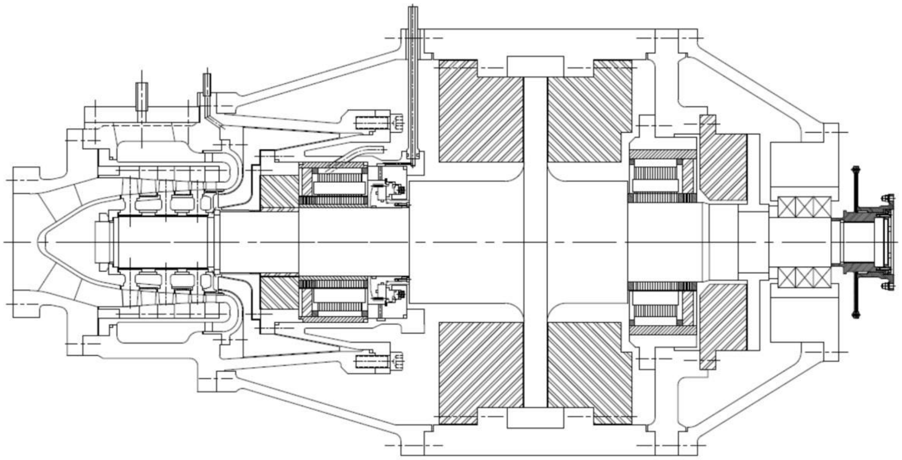

Figure 3: Magnetic Bearing Spindle With a 10 MW sCO_2 Turbine

Note that the magnetic bearing adjacent to the turbine is on the hot gas side of the seal. This configuration serves to locate the bearing closer to the article under test. This provides for an improved response when measuring and controlling the machine with the bearing. It also serves to move the seal out of harm's way.

The most popular containment seal for sCO_2 is currently the dry gas seal. The seal reliability depends upon diligent temperature control and minimum shaft bending at the seal location. Moving the seal behind the bearing serves to reduce the shaft bending at the seal. This configuration also allows for the bearing to reside in the space that is normally reserved for thermal isolation of the seal. The focus for the cooling is then applied to the bearing. The general cooling circuit for the bearing cooling is shown in Figure 4.

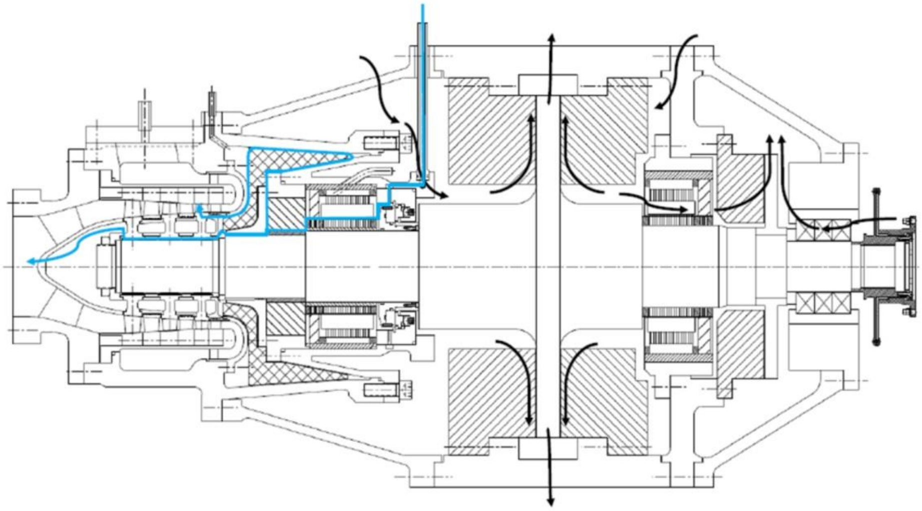

Figure 4: General Cooling Schematic

The overhung design of the turbine on the spindle serves to increase the sensitivity of measurement. It also makes it convenient to use the spindle as a common bearing system for different machine configurations. As a test tool, the spindle could be used to characterize the rotordynamic behavior of the internal seals. Figure 5 shows a labyrinth seal testing apparatus that would be run on live gas.

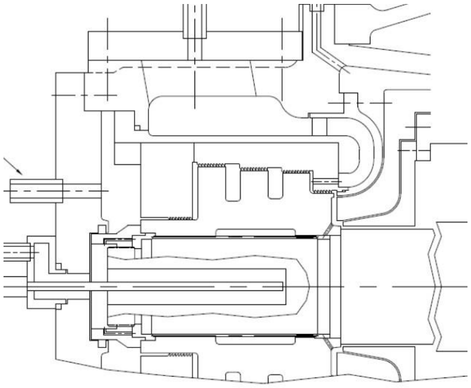

Figure 5: Labyrinth Seal Test Apparatus

SUMMARY

The service for the sCO_2 machinery will be utility grade applications. There is not a more risk averse industry, with the possible exception of the aircraft industry, than the utilities. Utilities want reliable machines because their customers demand it. It is unacceptable to the utilities to accept any operating risk with a new technology. The currently available technologies set a very high bar for reliability expectations.

The development of the sCO_2 machinery is driven by the thermodynamics of the working fluid, with the promise of greater efficiency. But the requirement is to deliver that improvement reliably.

The measurement of loads in a typical turbomachine is rarely done. Add the complexity of 4000 psi and 700 degree C supercritical carbon dioxide working fluid, and the instruments available for on-board measurements become very limited. The magnetic bearing will serve to provide the critical rotordynamic data that is very valuable in this phase of the technology development. At this point, we are seeing machinery being tested to validate the technology and viability of the power cycle. After validation, we will experience the development of the machines for use in the public domain. Reliability development is never the most exciting phase of a technology rollout. But it can be a very critical phase for the technology. The court of public opinion and the flow of investor funding relies on machinery that will not fail.

The magnetic bearing spindle is conceived to support the development of the technology in its current phase, and to support the reliability that will be required in the next phase of the technology rollout.