Commissioning and Testing of Active Magnetic Bearings for HTR Production Fuel Ball Blowers

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***Abstract*—High temperature gas cooled reactor (HTR) nuclear power plants depend on high-performance fluid machinery, including helium circulators and fuel ball blowers, for safe, reliable and efficient operation. Active magnetic bearings (AMB) have been utilized in all recent high temperature helium-cooled reactor designs as the only mature oil-free bearing technology to provide high reliability and availability of operations for these highly demanding applications. With the successful operation of the prototype, HTR production fuel ball blowers have been manufactured and the commissioning and qualification testing have been recently completed. This paper describes the technical challenges, solutions and results in the commissioning phase, and the qualification testing of the HTR production fuel ball blowers. The qualification testing included running the machine with helium gas to ensure the cooling and thermal conditions of the machine were stable at the maximum speed condition. The bearing temperatures, vibration levels and bearing dynamic loads were measured and were all as expected. In addition, five full speed landings were successfully performed on one of the production fuel ball blower machines.**

Keyword: AMB, HTR, Helium, Fuel Ball Blower, Testing

I. INTRODUCTION

High temperature gas cooled reactors (HTR) represent fourth generation nuclear power generation technology. Since the nuclear accidents at Three Mile Island and Chernobyl, the world nuclear community has made great efforts to develop advanced nuclear power systems with enhanced nuclear energy safety. Among those systems, the modular high temperature gas cooled reactor is one of the most innovative and challenging technologies. The global efforts on high temperature gas cooled reactors have been applied so far in pilot projects such as the 200MW$_{th}$ HTR-module of Siemens/Interatom Company in Germany, the 350 MW$_{th}$ MHTGR of General Atomics (GA) in the U.S., and the 400MW$_{th}$ PBMR in South Africa, in the 1980s and 1990s, followed, in the early 2000s, by test reactors of HTR-10 of INET in China and the GTHTR in Japan. In 2008, the plan and the budget for the HTR-PM project was approved by the Chinese Government, enabling the implementation of the HTR-PM demonstration plant in Shidao Bay, Shandong Province. The project adopts a 2 x 250MW$_{th}$ reactor module scheme for both efficiency and cost reasons [1, 2].

HTR power plants depend on high-performance fluid machinery, including helium circulators and helium blowers, for safe and efficient operation. The main function of fuel ball blowers (aka helium compressors) in an HTR-PM system is to provide pressure rise for the working helium gas to allow transportation of the fuel balls to the reactor core while the reactor is operating. Additional functions are to convey the absorbing ball from the bottom of the reactor to the top and to transport helium when the helium purification system performs accident cooling operations. When the reactor is in operation, the fuel ball blower must operate continuously. Fig. 1 shows the schematic of the HTR-PM reactor and its fluid machines.

In the HTR-PM plant, two reactors share a fuel ball helium gas pneumatic transportation system, which contains two fuel ball blowers arranged in parallel. Two machines can run simultaneously or operate independently. During normal operation of the reactor, one fuel ball blower is in operation and the other is in standby state, and the two machines can be switched online.

The operating parameters of the fuel ball blowers are summarized in Table I.

TABLE I. OPERATING PARAMETERS OF FUEL BALL BLOWERS

	Transporting Fuel Balls	Transporting He for He Purification System	Transporting Absorbing Balls
Process Gas	He	He	He
Inlet Presure, MPa	7.0	7.0	4.0
Inlet Temperature, ^{o}C	50	50	50
Gas Volumetric Flow Rate, m^3/s	0.11	0.11	0.02-0.03
Pressure Increase, kPa	220	200	180
Operating Speed Range, rpm	3000~9800	3000~9800	3000~9800

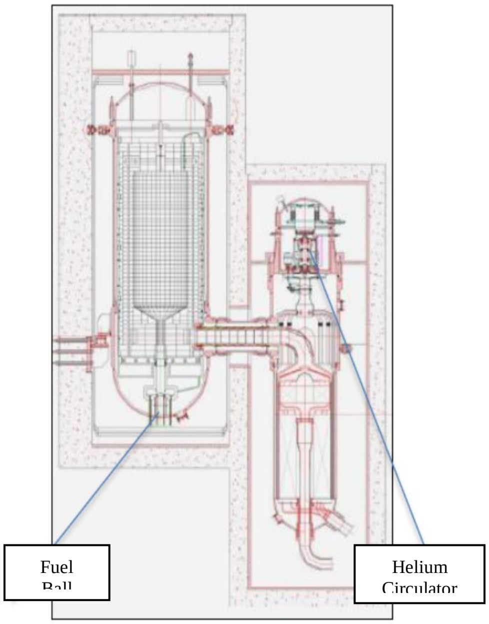


Figure 1. HTR-PM reactor and fluid machines.

Some of the primary decisions for the fuel ball blower design (e.g., single vs. multi-shaft design, horizontal vs. vertical orientation) are driven by thermodynamic and system level considerations. Flow losses in the piping connected to the reactor are an example of the thermodynamic considerations, and the building support structure is important for the machinery orientation. Another key decision in the turbomachinery design is whether the machine will be hermetically sealed or not. In a hermetic design, all the rotating parts of the machine will be fully contained in a sealed pressurized housing, or vessel, with no mechanical or buffer gas sealing systems required to prevent gas from leaking through annular gaps between the rotating and non-rotating parts of the machine. In a non-hermetic design, sealing systems are required to separate the cavities containing the pressurized gas (the rotating parts of the machine) and the external environment at 1 bar-a pressure. Implicit in these decisions is the choice between “wet” and “dry” bearings that affects whether there will be an external lubrication system or not. This choice, in turn, affects fire protection provisions.

Similar to other equipment and components of the nuclear power plant, active magnetic bearings (AMBs) are key technology enablers of the power plant. The bearings mounted on plant turbomachinery exposed to radiation have a significant influence on overall plant maintainability, reliability and availability, and on the safety of the personnel exposed to radiation during operation and maintenance cycles.

The use of AMBs dates back to the early stage of HTR development, when risks and concerns resulting from the application of lubricated bearings were identified from 30 years of pilot plant operating history in the U.S. and Germany. Referring to the HTGR at Ft. St. Vrain (U.S.) after a series of at least 14 failures of the circulator systems leading to several lubricant ingress events and long downtimes, Brey [3] concluded that “successful circulator operation requires nearly flawless performance of a complex circulator auxiliary system which includes…valves and instruments while supporting components such as pumps, compressors, heat exchangers, and vessels,…overall plant performance has been impaired”. Referring to the AVR reactor in Germany where fire of the oil in a turbine had been reported, Ziermann [4] concluded, “the reliability of a primary gas circulator in gas cooled reactors absolutely depends on the effectiveness of the buffer helium system (used to keep oil confined to the oil reservoirs)”.With regard to the THTR plant in Germany where radioactive gas escaped after graphite fuel balls got stuck in the fuel inlet, Glahe and Stolzl [5] noted that “further development work on the circulators is currently being continued for the only reason that active magnetic bearings permit vertical arrangement of the circulators…without requiring the operation of an extremely complicated and expensive oil system...The costs of the oil and gas seal systems are about twice as high as the costs of the (six) circulators themselves”. All three of these reactors were prematurely shut down and decommissioned, in large part due to issues that can be traced directly to inadequate design decisions, including decisions about the bearings.

As indicated by Swann et al [6], the precedent for equipping helium reactor machinery with magnetic bearings became well established and has led all recent helium cooled reactor designs to consider and specify magnetic bearings for the primary coolant loop machinery. This population includes the direct cycle designs for PBMR in South Africa, GT-MHR in Russia, and GTHTR in Japan, as well as the indirect cycle design for HTR-PM by INET in China. The magnetic bearing systems in this equipment must provide acceptable levels of reliability and availability while minimizing maintenance. This is accomplished through proper design, which includes the exploitation of provisions for remote observability and diagnostics.

To date, the magnetic bearing industry has evolved to serve a wide range of industrial applications, from high volume vacuum pumps for the semiconductor industry (with relatively standardized specifications) to some highly specialized applications in the oil & gas sector (with very demanding specifications) [7,8,9]. Application to gas cooled reactor machinery is more akin to the latter but with some very unique requirements for reliability and safety. In particular, remote observability and diagnostics becomes of vital importance in order to meet long term reliability and availability requirements while eliminating or drastically reducing maintenance requirements for many years. The specification and design of these bearings accordingly becomes significant to the nuclear power plant system design.

Within the past few years, the HTR-PM helium circulators and fuel ball blowers, both equipped with AMBs, were fully qualified for plant operation [10]. In the current paper, the commissioning and testing of the AMB systems for HTR-PM production fuel ball blowers will be discussed.

II. DESIGN OF COMPRESSOR AND MAGNETIC BEARINGS

The HTR-PM fuel ball blower (Fig. 2) is a pioneer of multi-stage high-speed direct drive compressor ever developed in China. A cross-section of the compressor housing and AMB interfaces is depicted in Fig. 3. The details of the motor and the compressor internals are omitted due to confidentiality.

Figure 2. Fuel ball blowers (helium compressors) for HTR-PM.

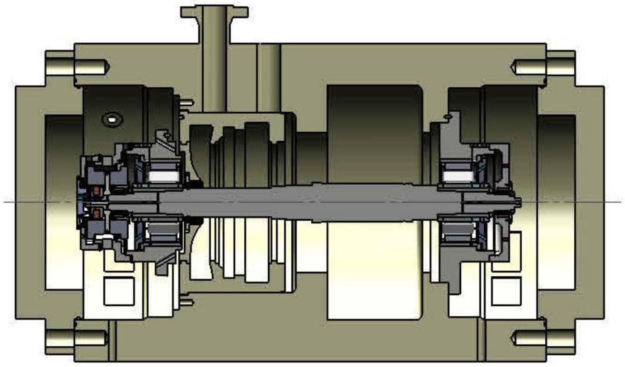


Figure 3. Magnetic bearings for fuel ball blower.

The motor, compressor and magnetic bearings are directly immersed in the pressurized process gas and hermetically sealed by the surrounding casing of the compressor. The machine features a single horizontal shaft with the motor and a three-stage impeller bundle, supported at either end by radial AMBs. An axial AMB at one end of the machine controls the position of the rotor in the axial direction and reacts to the external static and dynamic axial loads.

The capability of AMBs to operate while immersed in the process gas is key to achieving the hermetically sealed design, minimizing, if not eliminating, risk of gas leaking to the external environment. To achieve a full hermetic seal, the AMB power cables and signal cables run through penetrators to junction boxes located outside the machine.

Another key benefit of applying AMB technology is the elimination of lubricants. This not only eliminates the related sealing system but eliminates the need to periodically replace and treat a fluid that is subject to high risk of contamination from potentially radioactive gas.

Equipment for nuclear power plants demands a high level of reliability. A single failure mode in the magnetic bearing system has the potential to take down an entire plant, leading to a loss in power production. As in other systems, there are two fundamental approaches to achieving high reliability: ultra-high reliability of individual components, especially those that comprise a single point failure; and built-in redundancy that may be implemented either manually or automatically. The choice between these two approaches is usually governed by considerations of allowable failure rates versus the costs of implementation.

Condition monitoring is of particular concern when equipment is located inside a pressure vessel. In nuclear power plants, the safety concerns and costs related to worker exposure during visual inspection of equipment are significant. Therefore, the equipment must be supplied with various diagnostic capabilities to assess and predict machine operability. In this regard, the embedded AMB position, temperature and current sensors, together with AMB software capabilities, provide key information for monitoring the machine during operation. AMB system capabilities for measuring system transfer functions can be exploited to identify possible deviations of the dynamics of the machine from normal behavior, deviations that are associated with mechanical or electrical problems.

AMB design also considers the maintenance of the AMB system and overall machine across its operating life. The possibility of high concentrations of graphite particulates suspended in the gas stream, especially in pebble bed fuel elements, complicates the bearing environmental requirements. Over time these particles may become lodged in bearing crevasses and cavities, posing a risk of radiation exposure for plant maintenance personnel when the machinery is eventually decommissioned and disposed of, or in the unlikely event that periodic maintenance is required. For such circumstances it would be preferable if all bearing surfaces were smooth and without cavities where graphite particulates could become lodged. The canned AMB design, already applied on turbomachinery applications containing highly corrosive gas mixtures, can provide an ideal solution for decontamination, due to the flat and regular surfaces that the bearing would provide, as opposed to conventional “open” bearings. The presence of the canning structure, however, brings size and bandwidth (dynamic response) penalties that have to be addressed in the overall system design for machinery performance, especially rotordynamics.

As for auxiliary bearings, bushing type bearings are most resistant to particulate fouling. They also provide maximum reliability in the unlikely event that the rotor drops onto the auxiliary bearings due to loss of power or bearing overload. With no moving parts, bushing type designs were selected for their highest inherent robustness.

III. AMB COMPONENT TESTING

During operation, the HTR-PM AMBs are immersed in helium gas at 7 MPa pressure. In addition to qualification and selection of materials for long-term exposure to a radioactive environment, the AMB design must address other challenges for the insulation materials. Due to their small size and high pressure, helium gas molecules can penetrate the insulation material of the bearings and lead to potential damage in case of fast decompression of the AMB cavities. For this reason, special tests were performed on the AMB stator to verify the compatibility of the insulation material with the gas.

The insulation test was performed on a test mock-up equivalent to one quadrant of the supplied radial AMB and fully representative of the final AMB coils in terms of materials, coils, splices, insulation and manufacturing process.

A. *Test Procedure*

The insulation testing consists of two tests:

(a) The DC Hi-Pot insulation test, performed with a Hi-Pot tester by applying a DC voltage of 3000V between the one end of the coil lead and the radial AMB stator core (ground). The current between the coil winding and the ground was measured to detect possible current leakages representative of poorly insulated coils.

(b) The insulation resistance test, performed with a Megaohmmeter by applying 1000V voltage between one end of the coil lead and the radial AMB stator core and measuring the electrical resistance between coil and AMB stator.

The tests (a) and (b) were conducted with the sample quadrant immersed in air at atmospheric pressure (1 bar-a) first, and then immersed in helium, within a vessel pressurized to 1 bar-a. The helium used for the test was CP Grade Helium N5.0 (99.999% purity). The results from the air and helium tests were compared to identify possible effects of the helium gas on the insulation measurements.

B. *Test Set-up*

The test set-up consisted of a radial AMB quadrant fully representative of the delivered AMB magnets. The test sample was placed inside a pressure vessel and insulated from the metallic bottom with insulation foam (Fig. 4).

The helium gas was injected into the vessel from an external pipe connected to a helium bottle and its pressure controlled by a pressure regulator.

The presence of air or helium inside the vessel was measured with a digital oxygen sensor placed on the bottom of the vessel, next to the test sample. An oxygen percentage of ~20% indicates that the vessel is filled with air whereas an oxygen percentage of ~0% indicates that the vessel is filled with helium.

The pressure vessel was sealed with a hermetic cover and the coil leads and oxygen sensor taken out of the vessel by means of pressure pass-through.

The Hi-Pot test was completed with the Hi-Pot tester and a laptop connected to the oxygen sensor to verify whether the vessel was filled with helium or air.

For the insulation resistance test, the AMB coil and AMB core (ground) were connected to a Megaohmmeter in lieu of the Hi-Pot tester.

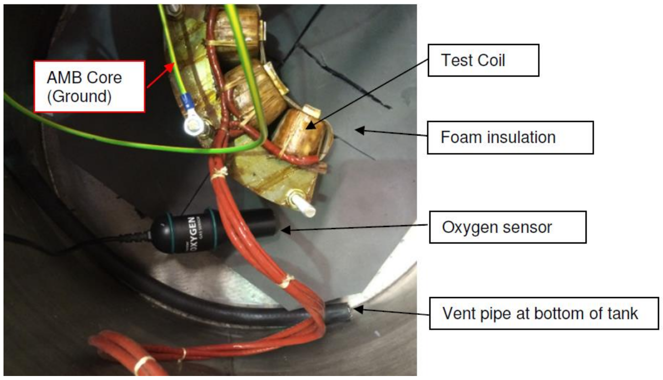


Figure 4. AMB stator insulation test set-up.

C. *Test Results*

The Hi-Pot test confirmed proper insulation of the coil from the AMB stator core with no current leakage from the coil to the stator part when a voltage of 3000V was applied between them. The Hi-Pot test provided the same values carried out in air and in helium.

The insulation resistance test confirmed proper insulation of the coil from the stator with insulation resistance higher than 4 GΩ (acceptance limit is 100 MΩ) when the coil was immersed in air or helium at 1 bar-a pressure.

Overall, the tests verified that the coil and core manufacturing and assembly were fit for purpose and the helium had no adverse effects on the insulation properties of the AMB coils. The test results are summarized in Table II.

TABLE II. AMB STATOR INSULATION TEST RESULTS

Test Sequence	Gas in Vessel	Purpose/Criteria	Results
1. Instrumentation Connection Check	Air at 1 bar-a	Check connection and instrument measurements	Passed
2. Hi-Pot Test in Air-3000V	Air at 1 bar-a	Check insulation coil/AMB core lamination in Air	Passed
3. Fill Pressure Vessel with Helium	He at 1 bar-a	Fill vessel with Helium for Hi-Pot test	N/A
4. Hi-Pot Test in Helium-3000V	He at 1 bar-a	Check insulation coil/AMB core lamination in He	Passed
5. Vent Vessel from Helium	Air at 1 bar-a	Fill vessel with Air for insulation resistance test	N/A
6. Insulation Test in Air	Air at 1 bar-a	Insulation resistance with Air. Acceptance criteria >100MΩ	Passed. Insulation resistance >4GΩ
7. Fill Pressure Vessel with Helium	He at 1 bar-a	Fill vessel with Helium for insulation resistance test	N/A
8. Insulation test in Helium	He at 1 bar-a	Insulation resistance with He. Acceptance criteria >100MΩ	Passed. Insulation resistance >4GΩ

IV. COMMISSIONING SET-UP AND RESULTS

The commissioning of the AMB system for production fuel ball blowers was conducted at the OEM test facility after assembly of the blower machine with AMB hardware and connection of electrical and electronic systems, including the VFD and AMB control cabinet, to the machine through electrical penetrators. Fig. 5 shows the test set-up of the AMB fuel ball blower machine at the OEM test facility.

The AMB commissioning conducted at the OEM facility includes general checking and testing of the magnetic bearing systems with all hardware and bearing controllers connected through electrical penetrators. The testing at this stage includes the AMB dielectric performance test, AMB static levitation test, and AMB low load and variable speed test.

Figure 5. AMB fuel ball blower test set-up.

A. *AMB Dielectric Performance Test*

The objective of the test was to examine the dielectric performance of all AMB windings with the magnetic bearing system integrated with the machine and penetrators. The AMB dielectric properties include the winding insulation resistance and winding voltage withstanding performance and are tested through the electrical penetrators. The acceptance criteria were insulation resistances of all AMB power and signal coils above 100 MΩ and no current leakages from the tested coils in the voltage withstanding test. Both tests were conducted in the helium environment with pressure of 1 bar-a.

The test results verified that the insulation resistances of all the tested coils were higher than 2 GΩ (the limit of the tester at the testing site).

The winding voltage withstanding test was performed per the test conditions and procedure with the specified endurance time. The test measurements confirmed no presence of current leakages on the tested coils and no insulation puncture or flash-over phenomena.

B. *AMB Static Levitation Test*

The AMB static levitation test is performed in the AMB commissioning stage to ensure all components of the AMB system are functional for an extended period prior to rotation testing. The test was carried out in helium environment with 1 bar-a pressure.

The temperatures (Fig. 6) and currents of the magnetic bearings were measured for the full 12-hour duration of static levitation. The testing was split between two days, creating the fluctuation in temperature seen at hour six.

Both the AMB temperature and current measurements were stable and well within the reasonable range.

C. *AMB Low Load and Variable Speed Test*

Under the same testing environment of helium, the AMB low load test with variable speed of operation from 0 rpm to the maximum continuous speed of 9800 rpm was performed. The objective of this test is to prove the AMB performance under low load and full speed range conditions. It is also needed to confirm that the tuning of the magnetic bearings is robust for running condition.

The recorded test measurements included vibrations, temperatures, currents, and cooling flows. Fig. 7 and Fig. 8 summarize the 1x vibration and temperature measurements for one blower. The results confirmed that all position and current signals were well within normal range and well below the referenced API standard. All the magnetic bearings remained well below the specified bearing design temperatures and winding temperature specification.

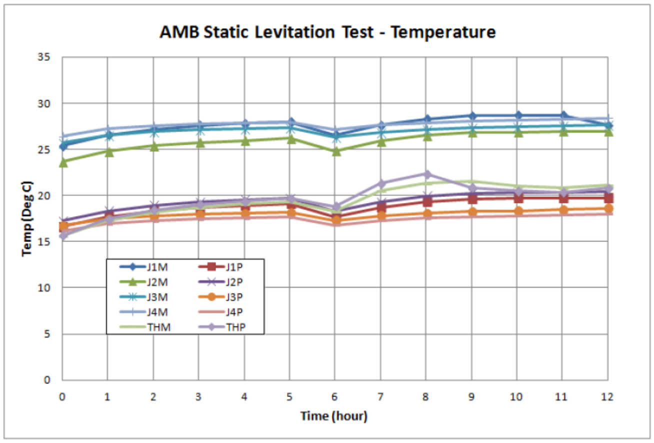


Figure 6. AMB temperatures in static levitation test.

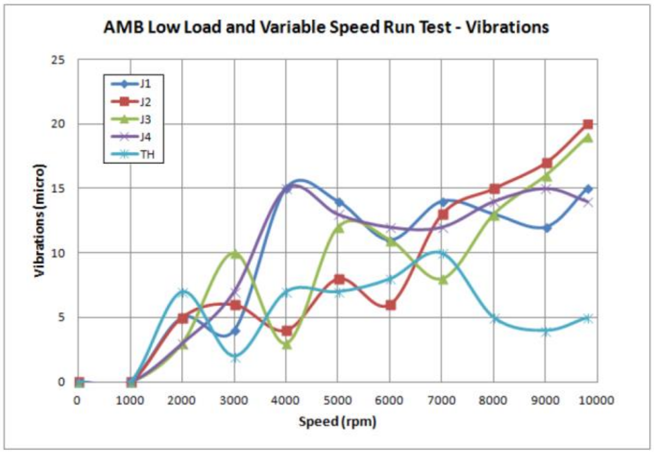


Figure 7. 1x vibrations in low load and variable speed test

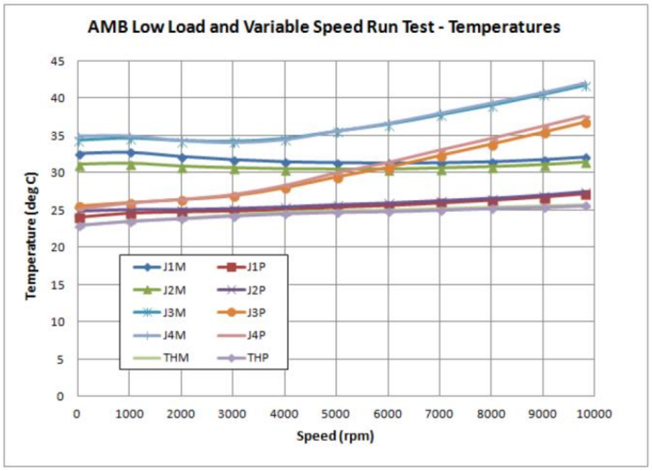


Figure 8. AMB temperatures in low load and variable speed test.

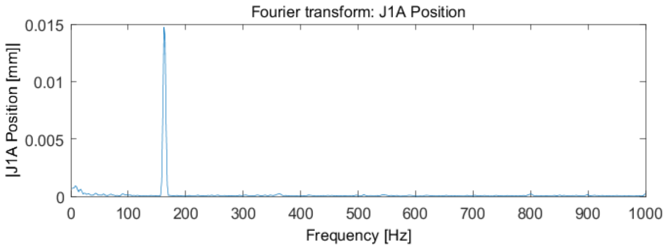
V. QUALIFICATION TESTING

The qualification testing was conducted after finish of the AMB component testing and the commissioning testing. During this stage, the blower unit and its AMB systems were tested at full power and pressure conditions representative of final field operations. The machine casing for the AMBs contained helium at 7 MPa pressure. Tests included the mechanical run test under variable speeds, 100 hour machine stable performance test, and auxiliary bearing landing tests.

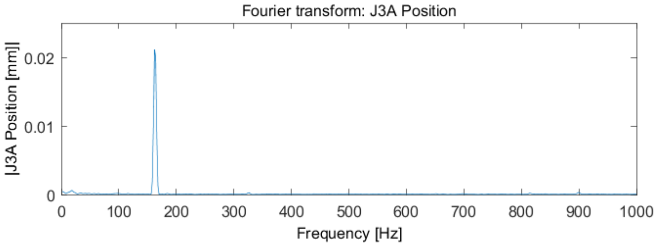
A. AMB Mechanical Run Test

The AMB mechanical run test was performed under varying speeds of operation within the speed range of 0 ~ 9800 rpm to test the AMB performance under the full machine loading conditions.

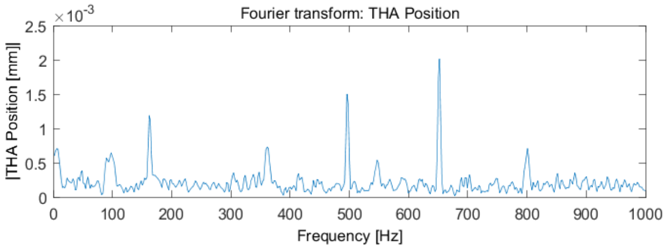
The vibrations, currents, temperatures and cooling flows of the magnetic bearings were measured and monitored. The 1x vibrations components from 0 rpm to full speed and the vibration spectra at full speed are shown in Fig. 10 and Fig. 9 respectively. During the test, all position and current signals were within normal working range and well below the requirements set by API 617 Standard. The spectra analysis of vibrations and currents also confirmed very limited low-frequency and high-frequency components, which indicated good noise rejection and stability of all the system modes. All AMB temperatures, Fig. 11, presented stable trend during the 100 hours test period, settling at approximately 65°C, well below the specified bearing design temperature and winding temperature limit.



(a) Radial bearing at impeller end



(b) Radial bearing at motor end



(c) Thrust bearing

Figure 9. Vibration spectra on J1, J3, TH axis at 9800rpm

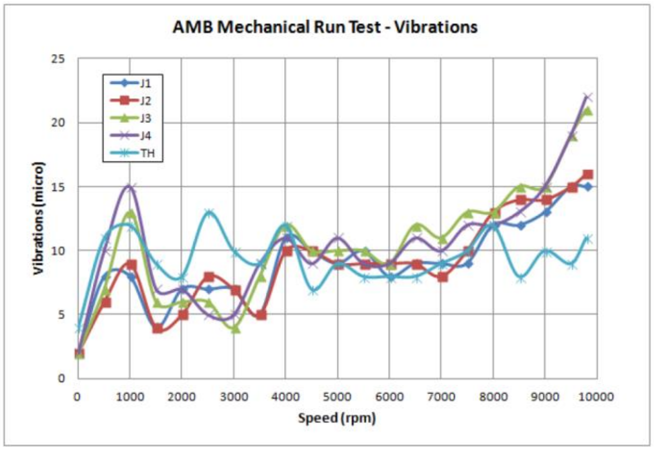


Figure 10. 1x vibrations in mechanical run test

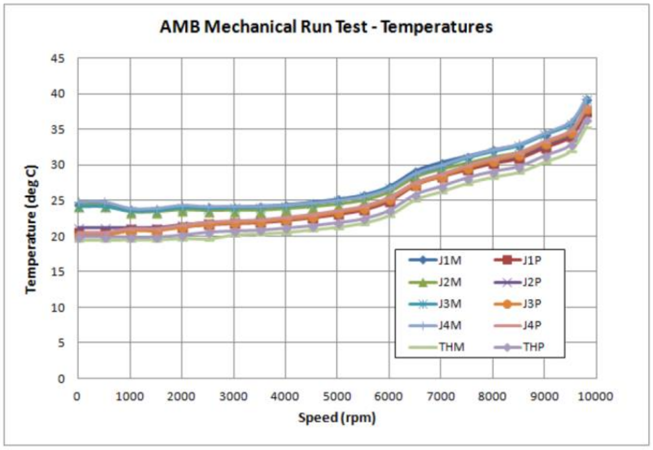


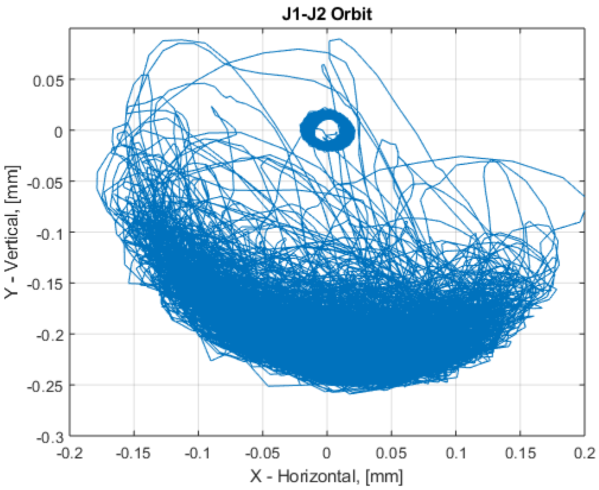
Figure 11. AMB temperatures in mechanical run test

B. Auxiliary Bearing Landing Test

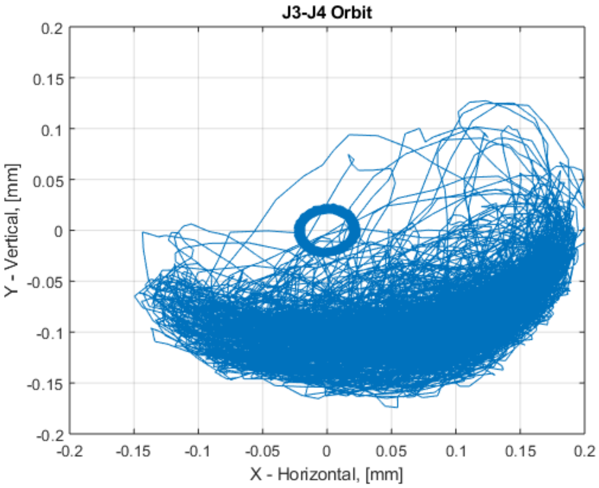
At the final stage of the qualification testing, the rotor landing onto the auxiliary bearing tests were performed. The tests were conducted with the rotor dropping on the auxiliary bearings while running at the maximum operating speed of 9800 rpm. This test was intended to confirm the capability of the auxiliary bearing system to tolerate a series of rotor emergency landings during machine service life. In total, five full-speed landing tests were completed on one of the production fuel ball blowers.

The auxiliary bearing landing tests were performed with the helium inlet pressure at 7 MPa pressure, representing the actual operating conditions. The machine braking capability enables a reduction to 20% of maximum continuous speed, i.e., from 9800 rpm to 1960 rpm, within 10 seconds. The decelerated speed profile of the machine was tested and proven before the landing tests were conducted. With the fuel ball blower operating at maximum speed, the magnetic bearings were de-levitated, causing a landing onto the auxiliary bearings. The coastdown curve of the landing event followed the expected decreasing speed trend due to the braking effect of the aerodynamic section of the machine.

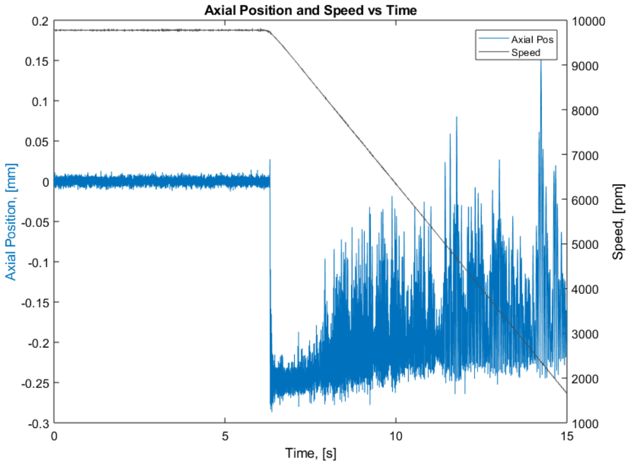
At each landing test, the trip data of the AMB system were recorded for the auxiliary bearing orbit information. Fig. 12 displays the orbit plots of the radial bearing at impeller end, radial bearing at motor end, and the axial bearing.



(a) Radial bearing at impeller end.



(b) Radial bearing at motor end.



(c) Axial bearing and speed

Figure 12. Auxiliary bearing landing test

Before and after each landing test, the auxiliary bearing clearances were checked using Automatic Bearing Clearance, one of the built-in monitoring function of the AMB controller. The clearance changes of the radial and axial bearings were comparably stable with the number of landings increased. No significant change in total clearance was observed. All five full-speed landing tests were fully successful. After the required landing tests were performed at the OEM test facility, the tested auxiliary bearing assemblies were shipped to the AMB supplier facility for further detailed inspection. The inspection results were reasonably in agreement with the clearance checks conducted on-site.

VI. CONCLUSIONS

Designing magnetic bearings into the HTR fuel ball blowers eliminates the risk of bearing lubricant contamination and eliminates the ancillary equipment associated with the sealing systems for bearing lubricant. The design of AMB systems for helium cooled reactor service follows many standard principles that have been applied in other demanding AMB applications over the past 30 years. This meets the requirements of fourth generation nuclear power plant design for safe and reliable operations of high-performance fluid machines.

The AMBs for HTR blower machines are immersed in helium gas at 7 MPa pressure during operation, which raises a concern on compatibility of the gas with the AMB insulation material. Special AMB stator insulation tests, including Hi-Pot and insulation resistance tests, were performed and verified that the coil and core manufacturing and assembly are fit for purpose and the helium has no adverse effects on the insulation properties of the AMB coils.

During the commissioning and qualification testing stages, the magnetic bearings and auxiliary bearing systems were fully tested in a helium environment inside the blower machines. The testing at commissioning phase included the AMB dielectric performance test, where the AMB system is fully integrated with machine and electric penetrators; AMB static levitation test; and AMB low load and variable speed test. The qualification testing included AMB mechanical run test under full power and full pressure conditions. As the final step of qualification testing, five full speed auxiliary bearing landing tests were performed. All indicators of the AMB system in terms of vibrations, currents, dynamic loads, stability and bearing temperatures, as well as overall machine performance, have met the design requirements.

AMB systems are now fully qualified for service in HTR fuel ball blowers. The machines have been delivered to the end user for operation on-site.

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