PRELIMINARY TESTS FOR THE HTR-10 HELIUM CIRCULATOR WITH ACTIVE MAGNETIC BEARINGS

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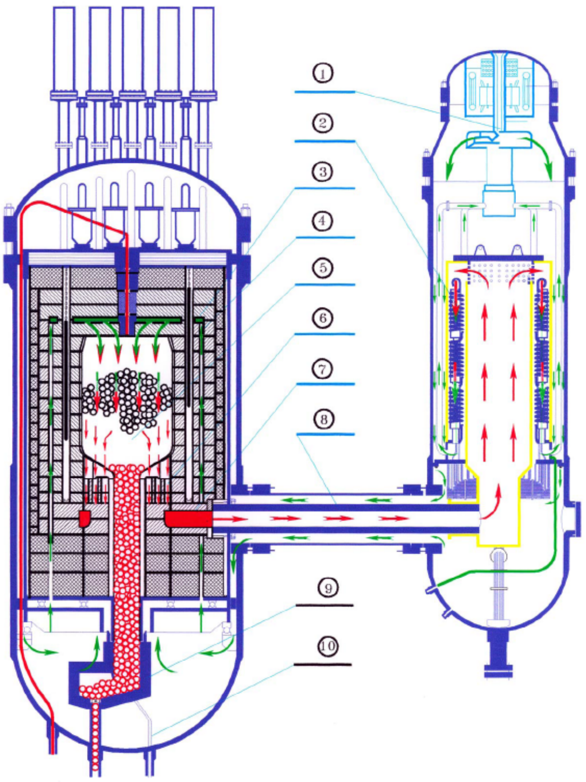
ABSTRACT
The Helium circulator is one of the key equipment of the high temperature gas-cooled reactor (HTR), which directs helium to flow through the reactor core and the steam generator to achieve the thermal energy transfer between them. At present, there are two optional schemes in the design of the helium circulator. One is the dry gas seal, another is the active magnetic bearing (AMB), but both of them haven't been used in the reactors beforetime. After the 10 MW High Temperature Gas-cooled Reactor-Test Module (HTR-10) was brought to criticality in December of 2000, Institute of Nuclear and New Energy Technologies (INET) of Tsinghua University dedicated to upgrade the technology of the helium circulator. It takes 3 years to manufacture a helium circulator with the active magnetic bearings in Shanghai Blower Factory, which has the same rated parameters as the one of HTR-10. It stood all the tests in November of 2007, including the 100 hour test at the conditions of high temperature(250°C) and high speed (5000r/min). All of these means INET made a great progress in the area of the active magnetic bearing technology. This circulator will be installed to HTR-10 to endure the further tests at the reactor conditions such as high temperature, radiation, graphite dust and the inert helium atmosphere. In the foundation of these successful tests, the design of the larger scale and higher power level helium circulator with AMBs for the HTR-PM project will enter the official implementation stage. This paper covers the philosophy behind the design and descriptions of the HTR-10 helium circulator and the preliminary tests. Significantly useful information is also derived from temperature distribution in the AMBs.

INTRODUCTION
Based on the successful experience and technology of HTR-10 project, at present INET is mainly engaged in the HTR-10 second phase project (HTR-10GT) and the 500MW High-temperature Gas-cooled Reactor Pebble-bed Module project (HTR-PM). In the HTR-10GT project, a power conversion unit (PCU) with direct gas-turbine cycle is designed for converting thermal energy generated in the reactor core into the electric energy. AMBs are chosen to support the turbomachine rotor in the PCU vessel. In the HTR-PM project, AMBs are also adopted to support the rotor of the helium circulator. The AMB helium circulator described in this paper is just a test sample to demonstrate the feasibility and reliability of the AMB technology in the HTR field.

HTR-10 HELIUM CIRCULATOR ON SERVICE
The reactor core and the steam generator of HTR-10 are arranged side-by-side in two steel pressure vessels, which are connected to each other by a hot gas duct pressure vessel. Helium at a pressure of 3 MPa flows through the reactor core, where it is heated to 700℃ by the fission heat. From the reactor the helium is directed to the steam generator, and then returned to the reactor by the helium circulator. The helium circulator is installed on the top of the steam generator inside the steam generator vessel, , as shown in Figure 1.
At the rated condition, the mass flow rate is 4.32 kg s^{-1} and the pressure rise can reach 51.7 kPa at the rotational speed of 5000 rpm [1]. A single-stage centrifugal compressor is chosen as the helium circulator, which is driven by an electric motor. The impeller is overhung at the lower motor shaft end. Grease lubricated bearings are selected for the circulator for simplicity and reliability. The compressor and the motor drive are both submerged in helium environment and divided by a partition plate. The motor is cooled by forced convection supplied by the motor cooling fan (an auxiliary impeller mounted on the upper end of the shaft). The heat generated by the motor and transferred from the downside and outside is finally vented to the outside by the motor cooler and the cavity cooler. Two sets of bearings are installed at the upper and lower positions of the motor shaft. In the upper position, a pair of angular contact ball bearings is mounted face to face to carry a combination of radial and thrust loads, while in the

lower position, a single angular contact ball bearing is mounted to carry mainly radial load. Since it is a high speed and high temperature bearing system, cooling and lubrication are very important. Two bearing coolers are machined in the upper and lower bearing bases. In addition, a bearing cooling fan (a small auxiliary impeller) is installed near the lower bearing. A high performance grease is chosen as a bearing lubricant. Lubricant tubes lead to the outside of the steam generator vessel for the regular grease supply.



1 Helium Circulator 2 Steam Generator 3 Control Rod 4 Absorb Ball 5 Pebble Bed 6 Helium Channel 7 Helium Mixture Chamber 8 Helium Conductor 9 Fuel Discharging Channel 10 Broken Fuel Separator

FIGURE 1: The Arrangement of Helium Circulator in HTR-10

AMB HELIUM CIRCULATOR

The main difference between the AMB circulator and the circulator on service is the rotor support system. Because the AMBs are adopted in the circulator, the bearing coolers and the grease lubrication system can be omitted, which are essential in the circulator on service. The motor rotor geometry also has to be changed a little to match the AMBs.

The AMB system consists of catcher bearings, sensors, controllers, power amplifiers, A/D and D/A conversion, electromagnets, power supply, etc, which are divided into elements inside the primary boundary and elements outside the primary boundary. The catcher bearings, electromagnets and sensors are located in the primary boundary, while other AMB control system equipments are located beyond the primary boundary, including computer facilities and power modules.

As depicted in Figure 2, two radial and one axial AMB are provided to support the motor shaft. In the upper position of the motor shaft, one radial and the axial AMB are mounted to carry a combination of the radial and thrust loads, while in the lower position, another radial AMB is mounted to carry mainly radial load. Catcher bearings is a part of AMB and intended to support the AMB helium circulator in the following cases: Scheduled shutdown of the AMB helium circulator when AMB is de-energized; Ensure the AMB helium circulator shutdown when AMBs fail to work; Protect the AMB helium circulator when dynamic loads exceeding AMB load-carrying capacity. The nominal air gap of sensors and the rotor is 0.8mm, and that of the radial AMB stator and the rotor is 0.7mm. The axial and radial gap of the upper catcher bearing and the rotor is 0.15mm and 0.3mm respectively. The distance between the thrust plate and the stator of the axial AMB is 1mm.

AMB is intended to take up radial and axial loads and provide stabilized supporting of the AMB helium circulator in operation. The design carrying forces of the radial and axial AMB shall consider the unbalance forces and dynamic loads. The design margin of the carrying forces should also be taken into account for engineering requirements[2]. The AMB axial load includes the weight of impeller, motor rotor and cooling fan and the impeller aerodynamic force, which is defined as:

$$f_a = \frac{\pi}{4}(D_s^2 - d^2)\Delta p - \frac{m}{g}C_0$$

where, D_s is the diameter of the wheel cover (m); d, the diameter of the wheel hub (m); Δp, the pressure rise (Pa); m, the mass flow rate (kg/s) and C_0 is the helium velocity at inlet.

The AMB radial load includes the motor rotor unbalance force and the magnetic unbalance force. The unbalance force is the centrifugal force caused by the rotor eccentric mass, which is defined as:

$$f_e = me(\frac{\pi n}{30})^2$$

where, m is the rotor mass (kg); e, the eccentric distance (m) and n is the rotation speed (rpm). The unbalance magnetic force is the magnetic pull force caused by the eccentricity of the rotor and stator, which is defined as:

$$f_m = 9.8 \times 10^4 \pi D_i l \frac{e}{\delta} (\frac{B_g}{0.5})^2$$

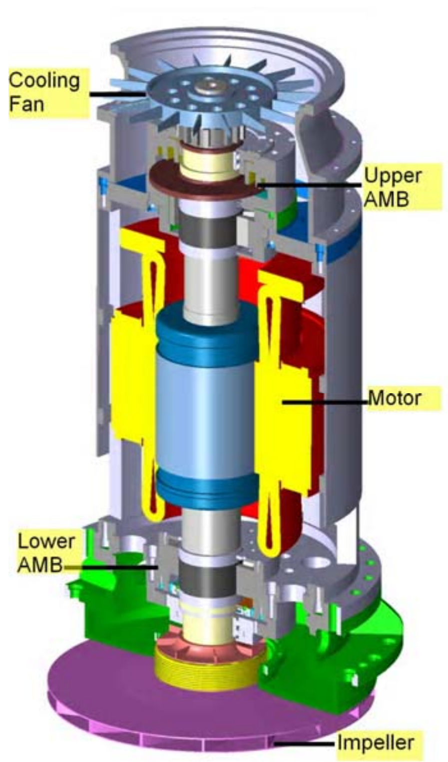


FIGURE 2: Configuration of the HTR-10 helium circulator with AMBs

where, D_i is the inner diameter of the stator (m); l, the length of the stator (m); e, the eccentric distance (m); δ, the nominal air gap of the rotor and stator and B_g is the even magnetic flux density of the air gap. The carrying force margin of the axial AMB is 50% of the actual load, and that of the radial AMBs is 10%. The load of AMBs is shown in Table 1.

TABLE 1: Load of AMBs

Parameter	Value
Impeller aerodynamic force, kg	150
Impeller weight, kg	100
Motor rotor weight, kg	240
Cooling fan weight, kg	10
AMB axial load, kg	750
Motor rotor unbalance force, kg	150
Motor rotor magnetic unbalance force, kg	218
AMB radial load, kg	400

PRELIMINARY TESTS FOR THE AMB HELIUM CIRCULATOR

Compared with the helium circulator on service, the AMB circulator has longer duty lifetime and demands less maintenance cost thanks to its outstanding features: non-contact support, no mechanical wear and no friction [3]. The most important feature of this type circulator is lubricant-free which keeps the HTR-10 helium environment from being polluted by the possible leakage of the lubricant system.

The preliminary tests for the AMB helium circulator are carried out in the test loop with the purpose to:

1. Verify the operational stability and reliability of the circulator at the conditions of high temperature and partial load.
2. Test out the temperature distribution of AMBs and not exceeding the design limits.
3. Demonstrate if the motor's electromagnetic interference to the AMB sensors is acceptable, especially the motor operated at full power.

The test loop for the AMB helium circulator is shown in Figure 3. It can be divided as three parts of test equipments, test rig and I&C system.

FIGURE 3: Picture of the test loop for the HTR-10 helium circulator

The test equipments include AMB helium circulator, frequency converter and AMB control system. The design parameters of the AMB helium circulator are shown in Table 2, and the parameters of AMB control system are shown in Table 3.

The test rig consists of impeller chamber, power adjustment loop, temperature adjustment loop and electric heaters. The power adjustment loop injects compressed air into the impeller chamber to raise the pressure and density of the air, thus the circulator can be operated at a higher power level. The temperature adjustment loop includes heat exchanger, valves and pipes, which keeps the impeller chamber operated at the pointed temperature.

TABLE 2: Design Parameters of the AMB Helium Circulator

Item	Value
Inlet Pressure, MPa	3.0
Mass Flow Rate, kg/s	4.3
Pressure Rise, kPa	60
Medium Temperature, ℃	250
Electric Motor Power, kW	165
Rated Speed, r/min	5000
Speed Range, r/min	1620~5220
Working Medium	Helium

TABLE 3: Parameters of the AMB Control System

Item	Value
Maximum Coil Current, A	15
Coil Voltage, V	300
Maximum Capacity of Radial AMB, kg	400
Maximum Capacity of Axial AMB, kg	1200
AMB Stiffness, N/m	5×10^{6}
Control Band Width, kHz	1
Sensor Sensitivity V/mm	5/0.3

The I&C system is composed of the electric motor parameter measurement and control, the AMB monitoring system, the test rig operational parameter measurement and the over-load protection system.

The following tasks were accomplished in the preliminary tests for the AMB circulator:

1. The temperature of the impeller chamber was raised to 250℃ by the electric heater while the circulator rotor was suspended by AMBs, but the motor of the circulator didn't run. It simulates the heat transfer from the steam generator chamber to the circulator house when the reactor is shutdown. In this case the AMBs lose forced cooling, and the temperature of AMBs is shown in Figure 4. The highest predicting temperature of AMBs may reach 150℃ in the reactor condition.
2. The circulator was gradually raised to the rated speed of 5000 r/min. At the same time the temperature adjustment loop was launched to keep the impeller chamber at the pointed temperature. The impeller chamber was heated to 250℃ only by the rotation of the impeller. At this temperature point the test lasted for 100 hours. The typical axes track of the circulator is shown in Figure 5. It indicates that the circulator can be operated steadily at the rated speed. In this case the largest vibration amplitude of the circulator rotor is less than 30 percent of the AMB's air gap. As shown in Figure 6, the AMB temperature is lower than that of the static heating test due to the forced cooling.

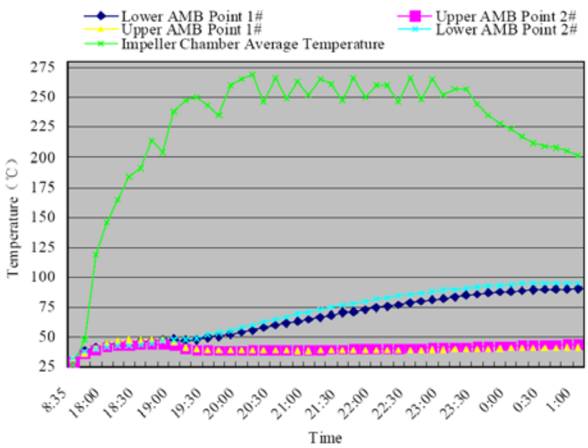


FIGURE 4: Temperature of AMBs in the static heating test

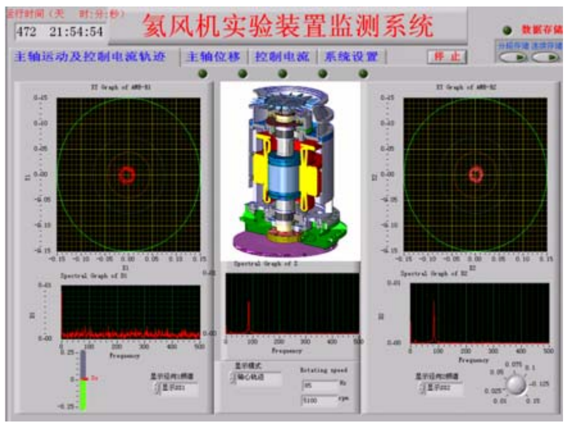


FIGURE 5: Typical axes track of the circulator rotor

3. The circulator was operated at the rated speed, and the temperature of the impeller chamber was kept under 60℃, then the compressed air was injected into the impeller chamber via the power adjustment loop. The motor power raised from 73kW to 99.8kW when the chamber pressure reached 0.135Mpa. In this case the coil current of the axial AMB reduced from 5.5A to 3.15A mainly due to the pressure difference of the chamber outside and inside, but that of radial AMBs didn't have the distinct changes. The more severe electromagnetic interference to the AMB sensors didn't take place either when the motor operated at a higher power level.

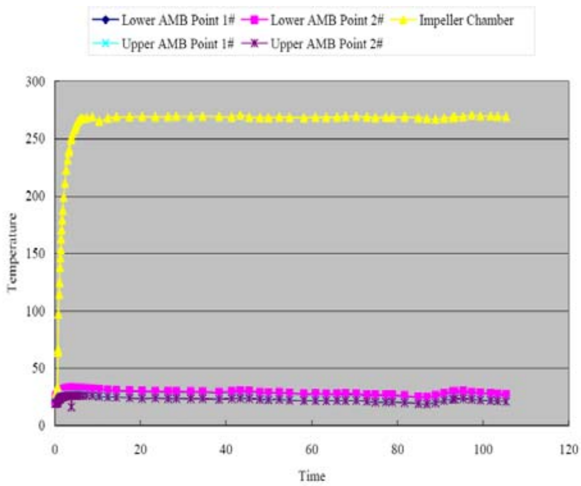


FIGURE 6: Temperature of AMBs in the 100 hour test

CONCLUSIONS

The helium circulator is a key component of the HTR. The integration of AMBs into the circulator is helpful to promote the circulator technology level. The design and research work described in this paper indicates such attempt is absolutely feasible. It takes 3 years for INET to manufacture the AMB helium circulator in Shanghai Blower Factory. It stood all the tests including the 100 hour test at the conditions of high temperature(250°C) and high speed (5000r/min), and it will be installed to HTR-10 to endure the further tests at the reactor conditions such as high temperature, radiation, graphite dust and the inert helium atmosphere. The experience gained from this paper provides valuable information for HTR-PM project in design of the larger scale and higher power level AMB helium circulator.

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REFERENCE

1. H.Z. Zhou, J. Wang, 2002. Helium circulator design and testing. Nuclear Engineering and Design 218, 2002.

2. Dumm, K., Donaldson, J., 1987. Considerations on the design of a helium circulator for a high temperature modular reactor system. Proceedings of the Specialists Meeting on Gas-Cooled Reactor Coolant Circulator and Blower Technology, San Diego, USA.

3. Gerhard Schweitzer, Hannes Bleuler, Alfons Traxler, 1994. Active Magnetic Bearings, Basics, Properties and Applications of active Magnetic Bearings. 1994 vdf Hochschulverlag AG an der ETH Zürich. ISBN 3 7281 2132 0.