HTGR PROJECTS IN CHINA

ZONGXIN WU and SUYUAN YU*
Institute of Nuclear and New Energy Technology, Tsinghua University
Beijing, 100084, China
*Corresponding author. E-mail : suyuan@tsinghua.edu.cn

Received March 25, 2007

The High Temperature Gas-cooled Reactor (HTGR) possesses inherent safety features and is recognized as a representative advanced nuclear system for the future. Based on the success of the HTR-10, the long-time operation test and safety demonstration tests were carried out. The long-time operation test verifies that the operation procedure and control method are appropriate for the HTR-10 and the safety demonstration test shows that the HTR-10 possesses inherent safety features with a great margin. Meanwhile, two new projects have been recently launched to further develop HTGR technology. One is a prototype modular plant, denoted as HTR-PM, to demonstrate the commercial capability of the HTGR power plant. The HTR-PM is designed as 2X250 MWt, pebble bed core with a steam turbine generator that serves as an energy conversion system. The other is a gas turbine generator system coupled with the HTR-10, denoted as HTR-10GT, built to demonstrate the feasibility of the HTGR gas turbine technology. The gas turbine generator system is designed in a single shaft configuration supported by active magnetic bearings (AMB). The HTR-10GT project is now in the stage of engineering design and component fabrication. R&D on the helium turbocompressor, a key component, and the key technology of AMB are in progress.

KEYWORDS : HTGR, HTR-PM, HTR-10GT, Helium -Gas Turbine

1. INTRODUCTION

The high temperature gas-cooled reactor (HTGR) is a graphite moderated, helium cooled reactor with ceramic-coated fuel particles (TRISO fuel particles). The HTGR is inherently safe and expected to be applied to various industrial fields such as electric generation, hydrogen production, etc. with high efficiencies. It is also recognized as a representative advanced nuclear system for the future. At the beginning of the year 2006, China issued guidelines on a national medium- and long-term program for science and technology development (2006-2020), announcing that it planned to speed up the pace of research on 16 key technologies including the pressurized water reactor (PWR) and the HTGR.

In China, research and development on the HTGR technology has been ongoing for several decades. After an initial fundamental study, the 10MW High Temperature Gas-cooled Test Reactor (HTR-10) project was launched in 1992. It was built in the Institute of Nuclear and New Energy Technology (INET), Tsinghua University. The system, schematically illustrated in Fig. 1, reached its first criticality in 2000 and begun full power operation in 2003 (Wu, et al., 2002). Based on the success of the HTR-10, long-time operation and safety demonstration tests were carried out in order to record operation experiences and show the inherent safety features. Meanwhile, two new projects have been recently launched to further develop the HTGR technology. One is a prototype modular plant, denoted as HTR-PM, to demonstrate the commercial

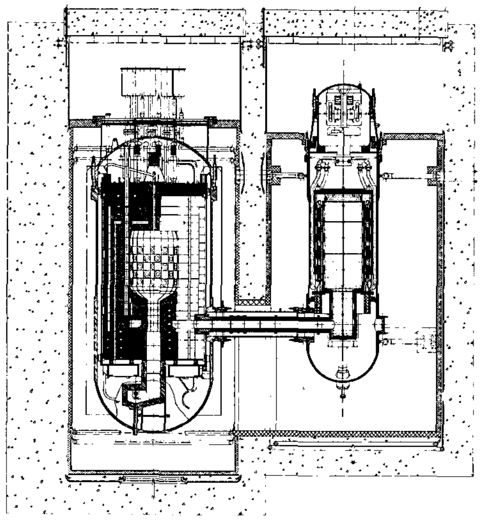

Fig. 1. Layout of HTR-10 Primary System

capability of the HTGR power plant. The other is a gas turbine generator system coupled with the HTR-10, denoted as HTR-10GT, to demonstrate the feasibility of the HTGR gas turbine technology.

2. HTR-10 TESTS

2.1 Operation Tests

After reaching full power operation of the HTR-10 at the beginning of 2003, a long-time operation test was carried out. Generally, the HTR-10 is operated to provide electric power to the grid only. However, in winter, the HTR-10 provides both electric power to the grid and district heating to the INET campus. After long and continuous operation, the entire system and main components were checked. The results show that all detected data are below safety values and all subsystems and main components, such as the loading and discharging system for fuel elements, control rod system, boron ball system, steam generator, helium circulator, etc. are under correct working conditions. It can be concluded that the operation procedure and control method are appropriate for the HTR-10.

Fig. 2 summarizes the operation records of the HTR-10 in 2006. It operated for a total of 97 days and the integrated reactor power reached 458.2 MWD. In addition to district heating for the INET campus, the HTR-10 also provided 660 MWh of electric power to the grid.

2.2 Safety Tests

A series of safety tests were carried out to verify and demonstrate the inherent safety features of the HTR-10. The tests included hypothetic accidents of the control rod system, helium circulator, the shut-off valve to prevent the primary loop from reverse natural circulation, the main pump of the secondary loop, the residual heat remove system, etc.. All the test results showed that the total safety related data fell below the limited values with wide margins.

Among these tests, the most important is Anticipated Transients Without Scram (ATWS), where the helium circulator is stopped while under the full power operation condition of the HTR-10. The test was performed at 4:00 PM on July 7, 2005. The HTR-10 was being operated on a full power level of 10 MW. The test began by turning off the electric power of the helium circulator. The circulator was then stopped and its shut-off valve was closed. The flow rate of the primary system was reduced sharply such that the protection system gave signals for reactor scram. The secondary system was separated from the primary system immediately. However, the control rods were locked and could not be inserted into the core. Even under these conditions, the reactor could reduce its power automatically and finally reach its subcriticality by mean of a negative feedback feature (negative temperature coefficient). During this process all safety related variables were under their limited values with wide margins. This test demonstrates that the HTR-10 possesses excellent inherent safety characteristics. Fig. 3 illustrates the process of the test.

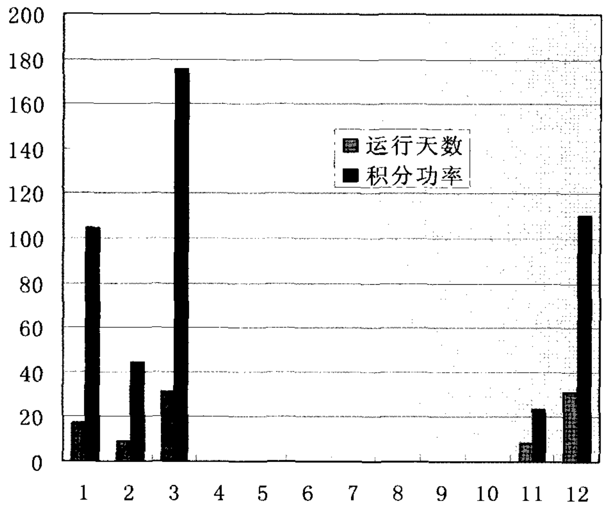

Fig. 2. Operation Record of HTR-10 in 2006

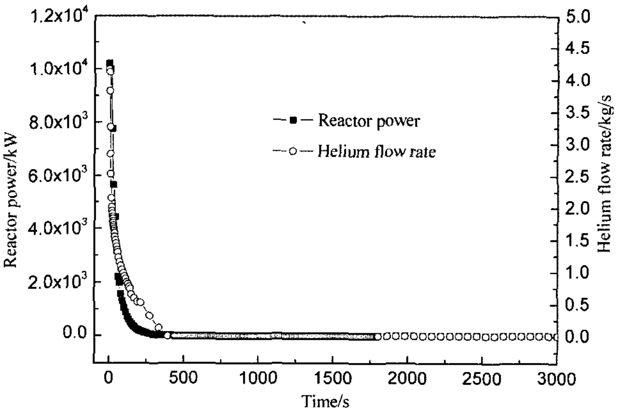

Fig. 3. ATWS Test for Stopping Circulator and Locking Rod Under 10 MW Operation Condition of HTR-10

3. HTR-PM PROJECT

3.1 General Plan

Based on the technology and experience of the HTR-10, preparation of the High-Temperature Gas-cooled Reactor-Pebble bed Module (HTR-PM) is currently in progress. The standard design of the HTR-PM, work on which started in the beginning of 2004, is scheduled to be completed in the middle of 2007. In the meantime, the selection of a site for the HTR-PM demonstration plant is being done in parallel. Potential sites are located in Shandong province. A combination of actual site parameters and the HTR-PM standard design will comprise the preliminary design of the HTR-PM demonstration plant. The construction of the HTR-PM demonstration plant is slated to begin in 2008 and is scheduled to be finished in 2012.

3.2 Design of HTR-PM

The main philosophy of the HTR-PM project is safety, standardization, economy, and proven technology. As a result of optimization and balance between the safety and economical features of the HTR-PM, the main technical features of the HTR-PM can be succinctly described as a pebble bed core with a conventional steam turbine. Fig. 4 presents a sketch of the primary system of the HTR-PM reactor.

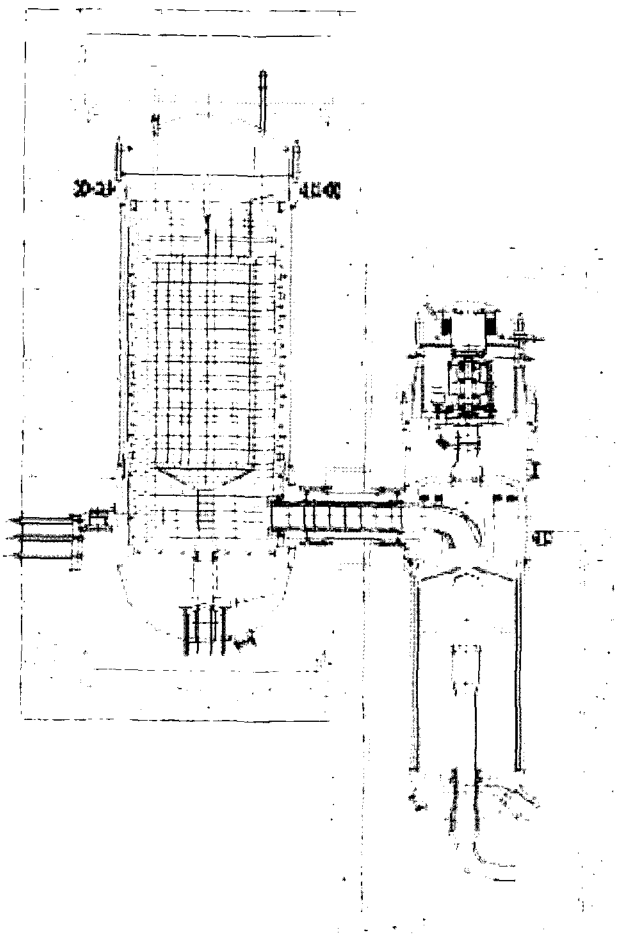

Fig. 4. Primary System of HTR-PM

3.3 Power Generation System

Based on proven technology requirements, the HTR-PM demonstration plant will adopt a mature sub-critical steam turbine proven in coal-fired plants for power generation systems. The aims are to demonstrate the feasibility and maturity of the reactor itself, the connection technology between the nuclear island and conventional island, and the adoptability of a new power generation system in the future. New power generation systems under consideration include the configuration of two reactor modules connected to one turbine, adoption of a super-critical steam turbine, and adoption of a super-super-critical steam turbine. All choices will depend upon Chinese state-of-the-art standard and mature turbine technology.

The re-heater is another technical issue. The efficiency gain from the re-heater is obvious, but the structural complexity and safety impact arising from the re-heater are also apparent. Hence, the re-heater is included in the conceptual design. A configuration without a re-heater and a configuration with a re-heater outside the reactor primary loop are also under consideration.

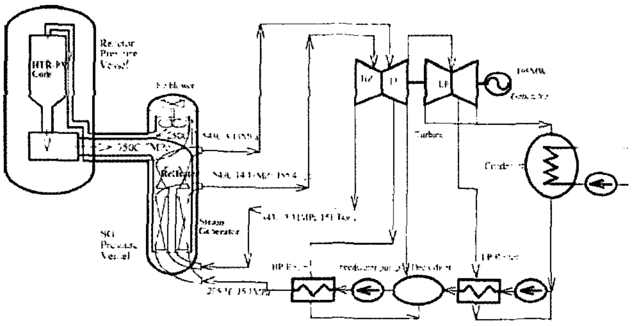

Fig. 5. Flow Diagram of HTR-PM Steam Turbine Cycle

4. HTR-10GT PROJECT

4.1 Introduction

For the HTR-10GT project, the initial basic design was a joint effort by the Institute of Nuclear and New Energy Technology (INET), Tsinghua University, and State Unitary Enterprise I.I. Afrikantov, Experimental Design Bureau of Mechanical Engineering (OKBM), Russia. The engineering design, component R&D, and key technology research were carried out by the INET. The following sections detail the main design features, component R&D, and current status of the HTR-10GT project.

4.2 Design Features

The layout of the HTR-10 primary system is shown in Fig. 1. The left side pressure vessel contains the reactor core and the right side the steam generator and helium circulator, which are connected by a horizontal hot gas duct pressure vessel.

For the HTR-10GT project, the previous pressure vessel of the steam generator at the right side will be removed and a new pressure vessel containing a helium turbine and generator will be installed, as shown in Fig. 6. The new pressure vessel is called a Power Conversion Vessel (PCV) and its role is to convert reactor core energy to electric energy. The turbocompressor and generator are supported by an active magnetic bearing system to prevent lubricant contamination in the primary system. Various heat exchangers are installed around the turbocompressor.

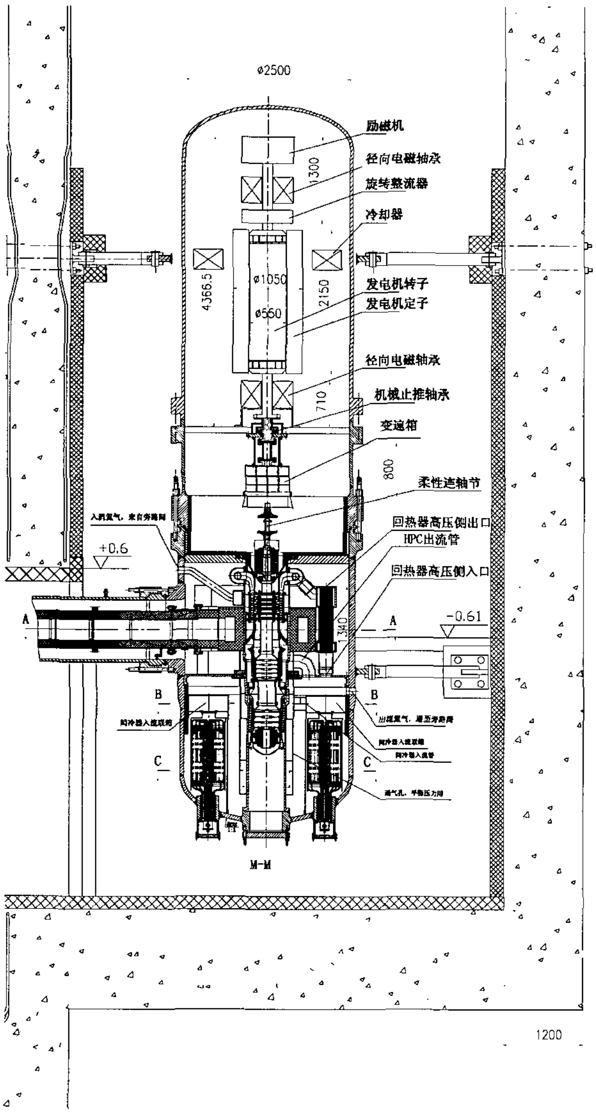

Fig. 6. Layout of Power Conversion System of HTR-10GT

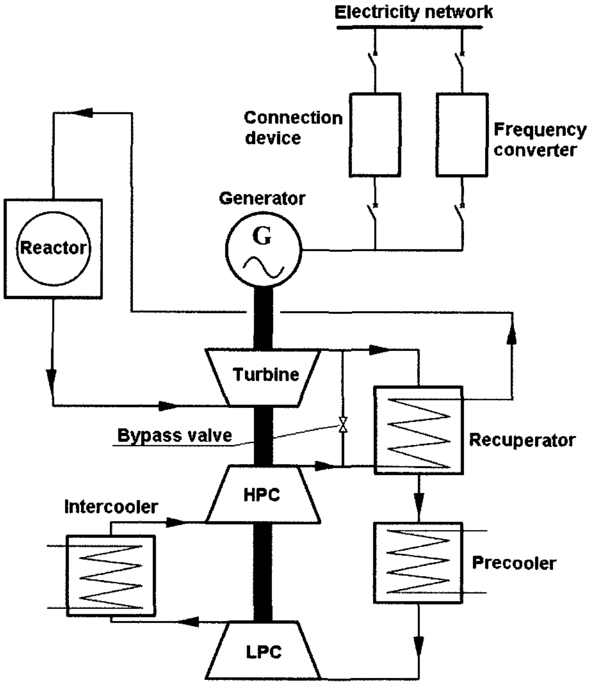

Fig. 7. Flow Diagram of HTR-10GT

The helium flow chart of the HTR-10GT is depicted in Fig. 7. Helium from the core with high temperature and pressure expands in the turbine and drives the turbine with the compressors and generator together. The exhausted helium enters the recuperator to heat helium at the other side from the compressor outlet. The helium is then further cooled in the precooler and pressurized to high pressure through a two-stage compression process with intercooling. The high pressure helium is preheated through the other side of the recuperator as mentioned above and then enters the reactor core to be heated and thus complete the Brayton cycle. The main parameters of the HTR-10GT in full power operation mode are shown in Table 3.

4.3 Component R&D

Inside the power conversion vessel, the main components can be divided into two groups. One is a rotating group containing the turbocompressor, gearbox, and generator, where the turbocompressor and generator are supported by an active magnetic bearing system. The other is a stationary group containing heat exchangers, a pressure vessel, metal works, valves, penetrations, etc. The component R&D is currently underway. Among these components, the turbocompressor is the most important and entails many technical difficulties.

Table 3. Main Parameters of HTR-10GT

Reactor Core	
Power, MW	10
Inlet /outlet Temperature (℃)	330 / 752
Inlet / outlet Pressure (MPa)	1.53 / 1.52
Mass flow rate (kg/s)	4.55
Turbomachine	
Turbocompressor speed (r/min)	15000
Turbine expansion ratio	2.2
Compressor ratio for HPC	1.58
Compressor ratio for LPC	1.58
Generator speed (r/min)	3000
Recuperator	
Power, MW	5.25
Helium temperature at inlet/outlet (LP) (℃)	494/278
Helium pressure at inlet/outlet (LP) (MPa)	0.687/0.682
Helium temperature at inlet/outlet (HP) (℃)	109/330
Helium pressure at inlet/outlet (HP) (MPa)	1.605/1.604
Precooler	
Power (MW)	5.94
Helium temperature at inlet/outlet (℃)	278/35
Helium pressure at inlet/outlet (MPa)	0.682/0.676
Intercooler	
Power (MW)	1.79
Helium temperature at inlet/outlet (℃)	108/35
Helium pressure at inlet/outlet (MPa)	1.040/1.031

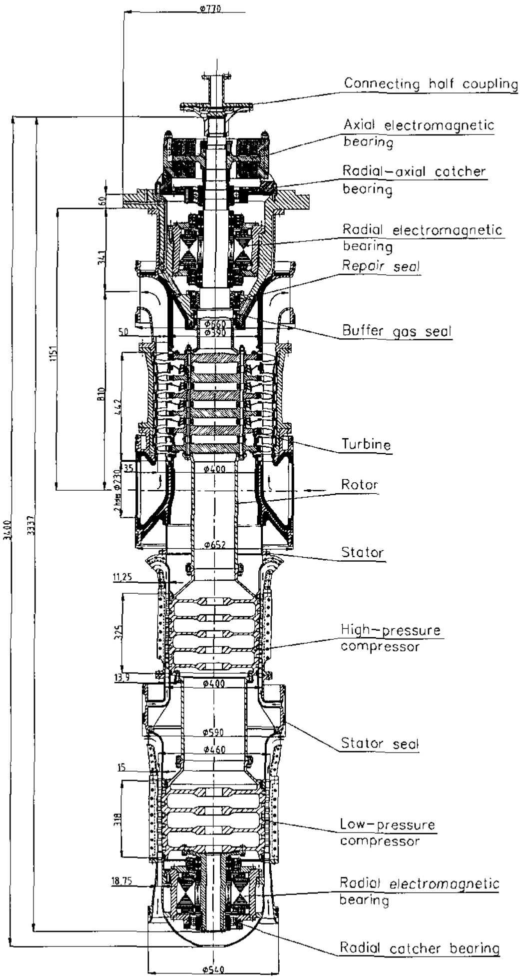

Fig. 8. Turbocompressor for HTR-10GT

4.3.1 Turbocompressor

The turbocompressor contains three components: a turbine, a low-pressure compressor (LPC), and a high-pressure compressor (HPC). The compressors and turbine are vertically arranged in the lower cavity of the power conversion vessel as shown in Fig. 8. From bottom to top, the turbocompressor is comprised of lower active magnetic bearing and catcher bearing, low pressure compressor, high pressure compressor, turbine, buffer seal, repair seal, and upper active magnetic bearing and catcher bearing. At the top of the turbocompressor shaft, a flexible coupling is used to connect the reduction gearbox and transfer the torque between the turbocompressor and generator.

The main features of the helium turbocompressor are lower compression ratio and expansion ratio, more stage numbers, and higher rotating speed than a combustion turbocompressor. Other important features in the design of the helium turbocompressor are its large hub diameter and short blade height in comparison with a combustion turbocompressor. The fundamental parameters of the turbocompressor are summarized in Table 4.

Recently, a closed areodynamic test facility with air or helium has been established to verify the design of the compressors. The test facility is a closed loop consisting of air and helium gas storage tanks, a desiccator, a flow regulating valve, a membrane compressor, a gas heater and cooling system, a pressure regulation system, a test section, a reduction gearbox, a motor, and a control system, as shown in Fig. 9. The helium or air is pressurized by the membrane compressor, and the test blades or compressor is placed in the test section. The blades or compressor is driven by the motor through the gearbox to reach the design rotating speed, 15000 r /min. The gearbox is lubricated by oil, and a dry gas seal is used to prevent leakage of helium from the shaft gap.

Table 4. Fundamental Parameters of the Turbocompressor

Component	LPC	HPC	Turbine
Power (MW)	1.74	1.77	5.73
Flowrate (kg/s)	4.76	4.77	4.66
Inlet temperature (°Ê)	23.9	26.7	750
Outlet temperature (°Ê)	94.3	97.8	502
Inlet pressure (MPa)	0.65	1	1.5
Outlet pressure (MPa)	1.03	1.58	0.68
Efficiency (%)	84.5	84.5	86.5
Blade height rotating (mm)	18.8	13.9	35
stationary blades (mm)	15	11.3	50
Tip diameter (mm)	460	400	490
Net length (mm)	318	325	442
No. of Stages	6	8	6
No. of rotating	650	1014	372
stationary blades	733	1122	252

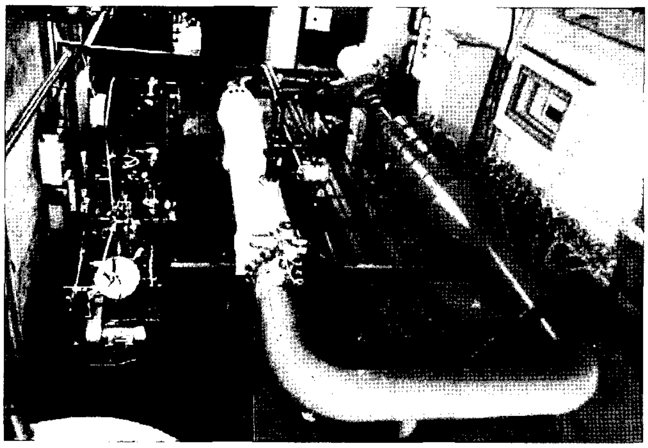

Fig. 9. Test Facility for Helium Compressor

Several experiments were carried out at the test facility. First, the design blade was tested in helium and air. In the second test a stage of blades of the compressor was evaluated in helium and air. Finally, the whole compressor was assessed. The aims of these tests are to determine and compare the helium and air behaviors in blades for the helium blade design, obtain the performance of the compressor, and check errors pertaining to the similarity law in data conversion. The blade experiments in helium and air have been completed, for which some important results have already been obtained.

4.3.2 AMB Technology

The Active Magnetic Bearing (AMB) is another key technology for the HTR-10GT project. INET has invested a great deal of effort into this aspect of the project. In order to explore the AMB engineering design and validate the technology, a full experimental plan was elaborately prepared. First, a small test rig was established to test the control method for a flexible rotor and accumulate experience for passing through critical speeds. A large size magnetic bearing with a rigid rotor was then constructed to verify the large magnetic bearing design and check its characteristics in long time operation. After the above two experiments are successfully conducted, a full-scale engineering test (1:1) will be performed outside the reactor to validate all the designed properties of the AMB system. Finally, the actual turbomachine rotor system along with the AMB system will be mounted in the HTR-10 reactor.

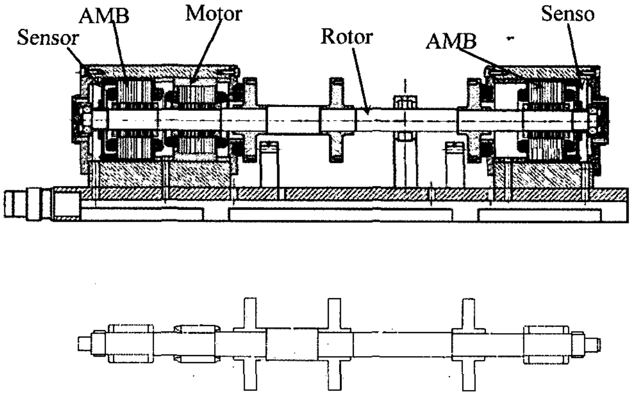

Fig. 10. Structure of Small Flexible Test Rig

(1) Small flexible rotor test rig

The emphasis of this experiment is on studying the control arithmetic for passing through the bending critical speed (BCS) and attaining experience for future turbomachine rotor control. The first and second BCS are designed as 300Hz and 700Hz, respectively, which are higher than those of the actual turbomachine rotor. Higher values were deliberately chosen to place some burden on the control research in order to compensate for the difference between the small rotor in the experiment and the large rotor in the reactor. The structure and main parameters of the setup are shown in Fig. 10 and in Table 5, respectively.

The experiment was successfully carried out through the second BCS, thus verifying that the modeling and control design method are feasible and effective. These experiences will be useful in the actual tuning process for the HTR-10GT AMB system.

Table 5. Main Parameters of the Small Setup

Design parameters (units)	Values
Rotor Mass (kg)	6.128
Rotor Length (mm)	613
Radial Moment of Inertia (kg m^2)	0.148
Polar Moment of Inertia (kg m^2)	0.00379
Air Gap (mm)	0.4
Coils (n)	300
Pole Area (mm^2)	320
Inductance (mH)	45.2

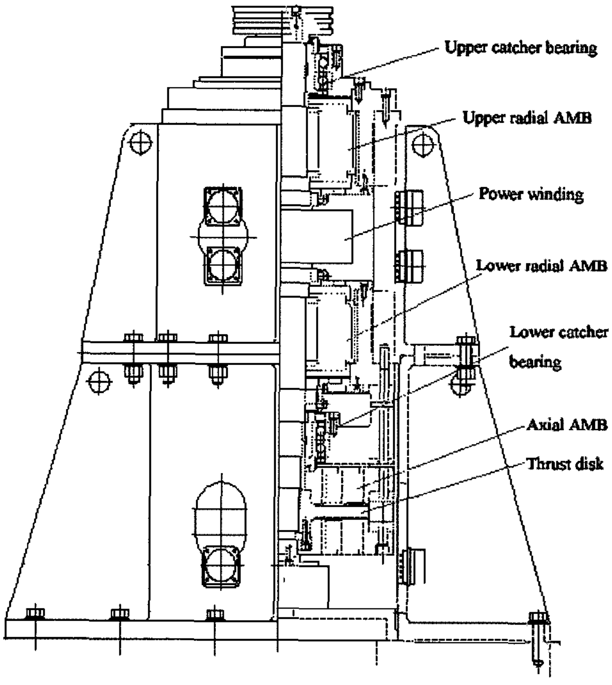

Fig. 11. Structure of Large Size Rigid Rotor Test Rig

(2) Large size rigid rotor test rig

This experiment's aim is to study the characteristics of the actual size AMB and verify the design. The performance of the prototype of the power amplifiers will also be tested and they will be thereupon improved in the subsequent design phase. In order to simplify the experiment, a rigid rotor is designed so as to place emphasis on the magnetic bearing itself. The structure layout of the test rig is shown in Fig.11 and the main parameters are listed in Table 6.

Table 6. Main Structure Parameters of the Rigid Rotor Test Rig

Parameter	Value
Height / weight of the rotor (mm/kg)	1,200/150
Radial AMB Lifting capacity (N)	3,000
Radial gap between bearing and rotor (mm)	0.7
Radial gap between catcher bearing and rotor (mm)	0.15
Axial AMB Lifting capacity (N)	10,000
Axial gap between bearing and rotor (mm)	1
Axial gap between catcher bearing and rotor (mm)	0.5
Sensitivity of the electric eddy current sensor (mV/um)	4
Switch Power Amplifier (kVA)	45

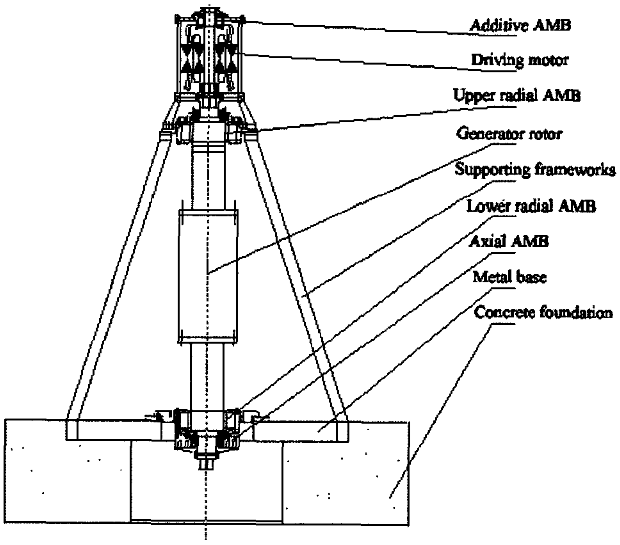

Fig. 12. Structure of the Full Scale Engineering Test Rig

Numerous characteristic experiments, including tests related to the stiffness, damping, force-current coefficient, and force-displacement coefficient, have been carried out, including a 72-hour continuously running test to validate the stability of the whole AMB system. At present, the test rig has completed more than 1000 start-ups, and fulfilled 5 drop-down experiments for testing the catcher bearing at 1200 rpm. All of the above experiments show that the technical index of the AMBs, the power amplifier, and catcher bearing satisfy the design goals. This is the basis for the full-scale engineering test rig.

(3) Full scale engineering test rig

Table 7. Main Structure Parameters of the Full Scale Engineering Test Rig

Parameter	Value
Height / weight of the rotor (mm/kg)	4,500/3,650
Radial AMB size (mm)	$\Phi 350 \times 150$
Radial AMB Lifting capacity (N)	22,000
Radial gap between catcher bearing and rotor (mm)	1
Axial AMB inner and outer diameter (mm)	300/560
Axial AMB Lifting capacity (N)	96,000
Axial gap between catcher bearing and rotor (mm)	1.2
DSP Controller working frequency (MHz)	75
Sensitivity of the reluctance sensor (mV/um)	8
IGBT Switch Power Amplifier (kVA)	90
Electrical cable length (m)	50

The experimental rig is designed for validation of the actual engineering full size AMBs of the HTR-10GT generator rotor, as shown in Fig. 12. The main parameters are shown in Table 7. All the mechanical and electrical AMB component types, sizes, and working principles correspond with those to be used in the actual HTR-10GT project in the future, including the magnets, catcher bearing, DSP controller, high precision sensors, large power amplifier, cables, and electrical interface.

Recently, a five-degree suspending and low speed running experiment was successfully carried out. In the following phase a high speed running experiment at a speed of 3600 rpm in long time operation will be carried out to test the properties of the whole AMB system.

5. CONCLUSIONS

The High Temperature Gas-cooled Reactor (HTGR) possesses inherent safety features and provides high temperature heat sources that can be applied to various industrial fields such as electric generation, hydrogen production, etc. with high efficiencies. It is recognized as a representative advanced nuclear system for the future. China has announced plans to speed up the pace of research on the HTGR technology, as it has been designated one of 16 special, key technologies in the national medium- and long-term program for science and technology development (2006-2020)

In China, the 10MW High Temperature Gas-cooled Test Reactor (HTR-10) project was launched in 1992. It reached its first criticality in 2000 and begun full power operation in 2003. Based on the success of the HTR-10, long-time operation and safety demonstration tests were carried out. The long-time operation test verifies that the operation procedure and control method are appropriate for the HTR-10 and the safety demonstration test shows that the HTR-10 possesses inherent safety features with a wide margin.

Meanwhile, two new projects have recently been launched to further develop the HTGR technology. One is a prototype modular plant, denoted as HTR-PM, to demonstrate the commercial capability of the HTGR power plant. The other is a gas turbine generator system coupled with the HTR-10, denoted as HTR-10GT, built to demonstrate the feasibility of the HTGR gas turbine technology. The HTR-PM is designed with two 250 MWt pebble bed cores and one energy conversion system, which is a steam turbine generator. The HTR-PM project is currently in the design stage. For the HTR-10GT project, the gas turbine system is designed in a single shaft configuration supported by active magnetic bearings (AMB). R&D on the helium turbocompressor and the key technology of AMB are now in progress.

REFERENCES

[1] Bathie, W. W., 1984. Fundamentals of Gas Turbines. John Wiley & Sons, New York, pp. 201-260.
[2] Ju, H. M., Xu, Y. H., Li, H. X., 1990. Program and Handbook of Thermal Property Calculation. China Atom Press, Beijing, pp. 1-15.
[3] Kostin, V. I., Kodochigov, N. G., et al., 2004. Power Conversion Unit with Direct Gas-turbine Cycle for Electric Power Generation as a Part of GT-MHR Reactor Plant. Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China.
[4] Kunitomi, K., Yan, X., et al., 2004. GTHTR300C for Hydrogen Cogeneration. Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China.
[5] Logen, E., 1993. Turbomachinery. Marcel Dekker, New York, pp. 9-27.
[6] Matzner, D., 2004. PBMR Project Status and the Way Ahead. Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China.
[7] Muto, Y., Ishiyama, S., Shiozawa, S., 2001. Selection of JAERI's HTGR-GT Concept. Gas Turbine Power Conversion System for Modular HTGRs, IAEA-TECDOC-1238.
[8] Wang, J., Huang, Z. Y., Zhu, S. T. and Yu, S. Y., 2004. Design Features of Gas Turbine Power Conversion System for HTR-10GT. Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China.
[9] Wu, Z.X., Lin, D.C., Zhong, D. X., 2002. The design features of the HTR-10. Nuclear Engineering and Design 218(1-3), 25-32.
[10] Zhang, Z. Y., Wu, Z. X., et al., 2004. Design of Chinese Modular High-temperature Gas-cooled Reactor HTR-PM. Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China.
[11] Reutler, H., Lohnert, G.H., 1983. The modular high-temperature reactor. Nucl. Technol. 62, 22–30.