Engineering Design, Analysis and Testing of Helium Circulator used in HTR-PM

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Long Abstract

Introduction

The world's first high-temperature gas-cooled reactor-pebble bed module (HTR-PM) demonstration power plant is currently under construction in China [1]. The helium circulator is one of the key equipment in the primary circuit of the HTR-PM. It drives the helium gas circulating in the primary circuit for transferring thermal energy from the reactor core to the steam generator. The helium circulator should satisfy these basic requirements: (1) 40 years operation life, (2) high operation reliability with less than one failure per year, (3) safely operating under different operating conditions of the reactor, but without performing safety function, (4) operating stably at any given speed within the operational range, (5) ease of maintenance. To verify how to meet these requirements, one prototype of the helium circulator was designed, fabricated and tested. It will be reported in this paper that the engineering design, the FEM analysis of the mechanical and the aseismatic performance of the whole assembly, the CFD analysis of the aerodynamic of the impeller and diffuser, and the testing results to verify our design.

1. Engineering Design

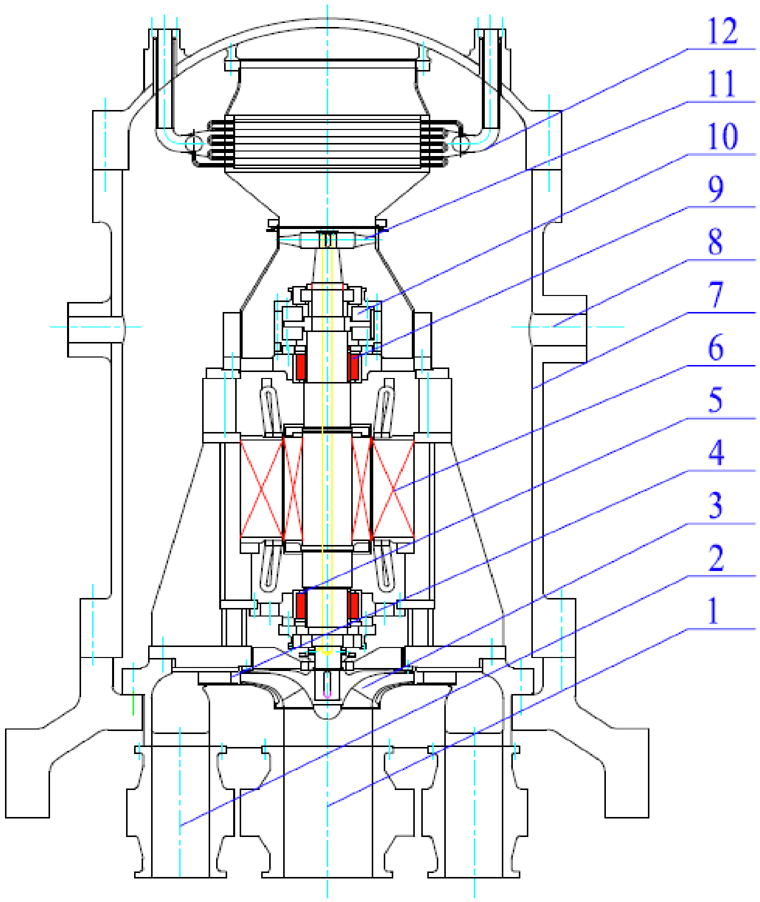
Table 1 shows the rated parameters of the helium circulator used in HTR-PM.

Table 1 Rated parameters of the helium circulator

Parameters	Value
Fluid	Helium
Inlet pressure, MPa	7.0
Mass flow rate, kg/s	96
Pressure rise, kPa	200
Inlet temperature,℃	250
Speed range, %	20~105
Type of impeller	Centrifugal
Rotational speed, r/min	4,000
Motor power, kW	4,500
Voltage, V	6,000

Fig. 1 shows the helium circulator layout within the pressure vessel. The helium circulator assembly comprises of one squirrel cage induction asynchronous motor and one inverter drive, one single stage compressor including an impeller, a diffuser and a volute casing, one set of magnetic bearing system, two coolers, three isolation valves and other supplementary parts. As shown in Fig. 1, the helium circulator is integrated and submerged within the pressure vessel. It features the impeller overhung at the lower end of the vertical shaft.

As discussed by C. F. McDonald, et al. [2-3], helium circulator with active magnetic bearings is a major innovative step in HTR technology, because with these bearings rotating machines can be arranged encapsulated in the process fluid without any risk of interaction with lubrication oil. In the present design, the upper bearings assembly consists of an assistant bearing, an axial magnetic bearing and a radial magnetic bearing. The lower bearings assembly consists of an assistant bearing and a radial magnetic bearing. The bearings assemblies are required to support all kinds of load existing in all operating conditions.



1. Inlet Valve, 2. Outlet Valve, 3. Impeller, 4. Diffuser, 5. Lower Radial Magnetic Bearings, 6. Motor, 7. Pressure Vessel, 8. Electric Penetration, 9. Upper radial Magnetic bearings, 10. Axial Magnetic Bearing, 11. Cooling Impeller, 12. Motor Cooler.

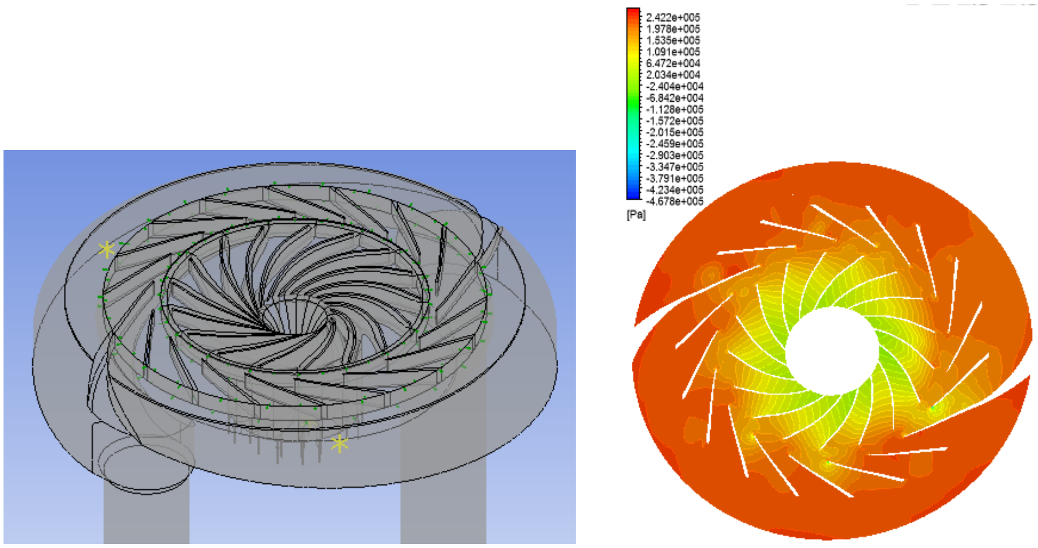
Figure 1 Helium circulator layout

2. Analysis

Aerodynamic design of impeller, diffuser and volute is one of the key designs in the helium circulator, since the layout space for these aerodynamic parts is compact within the pressure vessel. The design-by-analysis approach was carried out in the design process. Especially, a design approach based on 3-D CAD, CFD and 3-D inverse design method was used to optimize the 3-D impeller blade. As shown in table 2, the prediction of aerodynamic performance and efficiency of the helium circulator was conducted by 3-D CFD simulations in which 46M mesh elements were adopted. Figure 2 shows the 3-D CFD calculation domain and the predicted pressure distribution within the helium circulator.

Table 2, 3-D CFD predicted aerodynamic performance

Parameters	Value
Fluid	Helium gas
Inlet pressure, MPa	7.0
Inlet temperature,℃	250
Mass flow rate, kg/s	96
Rotational speed, r/min	4,000
Static pressure rise, kPa	213
Static polytropic efficiency, %	74



(a) (b)

Figure 2 3-D CFD calculation result.
(a) Calculation domain (46M mesh elements); (b) Static pressure distribution.

The FEM analysis of the mechanical and the aseismatic performance of the whole assembly were conducted to meet the basic mechanical requirements and will be reported in the full paper.

3. Engineering Test

In the engineering prototype of the helium circulator, the electric-magnetic bearings which developed by INET has been tested in order to fully verify the fit of bearings and shafts. A series of test program was conducted to verify the performance of the helium circulator. The engineering prototype has run full-power, full-speed tests in hot states and a nitrogen environment for 100 h and 500 h, and has also completed full-power tests under helium operation conditions (250 °C/7 MPa) that are identical to those of the HTR-PM. The measured aerodynamic characteristics of the helium circulator will be reported in the full paper.

References

[1] Zuoyi Zhang, et al. The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation, *Engineering* 2:112–118, 2016.

[2] C. F. McDonald, M. K. Nichols, J. S. Kaufamn. Helium Circulator Design Concepts for the Modular High temperature Gas-cooled Reactor (MHTGR) Plant, presented at IAEA Circulator specialists Meeting, San Diego, California, December 1, 1987.

[3] C. F. McDonald. Helium turbomachinery operating experience from gas turbine power plants and test facilities, *Applied Thermal Engineering*, 44:108-142, 2012