

Recent Progress in Experimental Evaluation of a Helium Circulator for the Test Blanket System

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1. Introduction

The Helium Cooling System (HCS) of the Test Blanket System (TBS) circulates helium at a nominal pressure of 8 MPa with a loop mass flow rate of the order of 1.3 kg/s and blanket module inlet/outlet temperatures of 300/500 °C during plasma operation [1,2]. In the current HCS design, two identical circulators operating in parallel provide the loop flow [3]. The helium circulator is therefore a key rotating machine for which not only aerodynamic performance but also operational stability and protection logic must be experimentally verified.

The Korea Atomic Energy Research Institute (KAERI) constructed the Helium Supply System (HeSS) test facility and has performed component-level validation of the HCS [4], including performance tests of a prototype helium circulator following earlier circulator and economizer (recuperator) testing [5]. A comprehensive evaluation of the circulator performance and operational characteristics has recently been completed and submitted for journal publication [6]. This paper summarizes the recent test results and presents the development directions identified through the evaluation and the subsequent peer-review process, including reverse-flow protection, parallel installation considerations, and the emergency-stop sequence.

2. HeSS Test Facility and Circulator

The HeSS test loop is a closed high-pressure helium loop with a figure-eight flow configuration centered on a PCHE-type economizer, equipped with a pre-heater and a water cooler. Three control valves adjust the flow split among the flow paths, enabling control of the total system pressure drop and simulation of various operating conditions.

The circulator is a single-stage centrifugal machine with a rated speed of 70,000 rpm, driven by an inverter with an LC filter and managed by a dedicated controller. Non-contact gap sensors with 0.5 μm resolution continuously monitor the radial and axial vibrations of the high-speed rotor supported by oil-free gas bearings, ensuring contamination-free operation of the helium loop.

3. Summary of Recent Test Results

Speed-dependent performance curves were obtained at 60–100% of the rated speed (70,000 rpm) on a corrected-mass-flow basis. At the process operating point (1.0–1.1 kg/s at an inlet pressure of 7.6 MPa), the target compression ratio of 1.10 was satisfied, with a differential pressure of approximately 0.80 MPa measured at 1.10 kg/s. In the rated maximum-flow region (approximately 1.4 kg/s), the compression ratio was evaluated to be approximately 1.09, indicating marginal performance relative to the design target at high flow.

Operational stability was confirmed over a wide envelope. During overspeed testing, stable operation and performance measurement were achieved up to 71,520 rpm (102%), while the 103% speed ramp was terminated by an automatic inverter trip without any abnormal vibration. Under low-flow conditions, stable operation was achieved down to 0.2 kg/s at 14,000 rpm and an inlet pressure of 7.7 MPa. At an elevated inlet pressure of 8.33 MPa, a pressure rise of approximately 1.0 MPa was obtained at 0.8 kg/s.

The reliability of the measurements was assessed by a thermal–electric power balance: the thermal power computed from the measured mass flow rate and enthalpy rise agreed with the electric input power within 3.9% at the 95% and 100% speed conditions, of which about 2.5% is attributable to surface heat loss, leaving a residual discrepancy of approximately 1.4%. The overall efficiency, defined against the electric input power, was evaluated to be 61.7%. Approximately 10% of the pressure rise generated by the compression stage is lost in the downstream flow path, and an unintended vaneless radial diffuser region formed downstream of the vaned diffuser has been identified as a principal origin of this loss.

4. Development Directions

Based on the evaluation and the peer-review process, the following development directions are being pursued.

(1) Upgraded circulator and extended verification. The internal flow path is being adjusted in the design of the upgraded circulator to eliminate the vaneless diffuser region, and its contribution will be quantified through a comparative CFD analysis of the flow path with and without this region. The HeSS water cooler

will be replaced with a unit of lower pressure drop, allowing acquisition of performance data over an extended operating range, and the endurance test has been successfully completed.

(2) Protection logic and emergency-stop sequence. During the tests, the operating state of the circulator (rotor vibration, mass flow rate, motor current, and rotational speed) was monitored in real time, and the circulator automatically decelerates to a safe stop when a trip or emergency-stop command is issued. A monitoring and protection scheme covering motor overload, compressor surge, overspeed, abnormal rotor vibration, and motor and bearing overtemperature has been defined, and the corresponding trip setpoints for fully automatic two-step protection (alarm followed by emergency shutdown) will be implemented in the control software after the operating points of the final machine are confirmed.

(3) Reverse-flow protection and parallel installation. The present HeSS loop is a single-circulator configuration without a dedicated non-return (check) valve at the circulator discharge; upon a trip, the driving potential for reverse flow is limited to the pressure difference established by the circulator and is dissipated by pressure equalization within the closed loop. In the HCS two-circulator parallel configuration, however, a stopped unit could experience sustained reverse flow driven by the operating unit, and a discharge check valve has accordingly been identified as a key design consideration. The flow resistance of an idle unit, the allowable momentary reverse rotation of the bearings, and the valve arrangement are being reviewed with the manufacturer in support of the parallel installation that underpins the availability requirements of the HCS [3].

5. Conclusions

Performance and operational-stability testing of the helium circulator for the TBS HCS has progressed in the HeSS facility: the target compression ratio was satisfied at the process operating point, stable operation was demonstrated from 0.2 kg/s up to 102% overspeed, and the overall efficiency was evaluated to be 61.7%. The identified improvement directions (the upgraded circulator, extended performance-range verification, protection and emergency-stop logic, and reverse-flow protection for the parallel configuration) define the next phase of development toward the TBS application.

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