The Sun on the Earth!? Realizing a Dream Energy Source

Supercritical helium circulation pump for the ITER

ITER — A magnificent project aiming to realize nuclear fusion reactions on the earth that are the same in principle as those in the sun. Realizing this goal requires keeping superconducting coils at temperatures close to absolute zero. What hardware plays the key role in this cooling?



©ITER Organization (www.iter.org/) International Thermonuclear Experimental Reactor (ITER)

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Cross section view of supercritical helium circulation pump

Appearance of supercritical helium circulation pump

ITER project

The International Thermonuclear Experimental Reactor (ITER), currently under construction in Saint-Paul-lez-Durance in the southern part of France, is an enormous international project to realize nuclear fusion reactions on the earth that are the same in principle as those that cause the sun and stars to shine and to demonstrate that nuclear fusion energy can be artificially harvested.

To realize the practical use of nuclear fusion energy, it is necessary to generate high-density plasma with a temperature over 100 000 000°C in a reactor and keep the plasma confined in the reactor. In addition, superconducting coils capable of generating a very high electric current and creating a strong magnetic field are also needed to control the plasma generated in the reactor. This unprecedentedly gigantic experimental reactor, approximately 30 m in diameter and weighing 23 000 tons, will comprise a combination of many different superconducting coils, which will be fabricated utilizing the comprehensive technologies of the countries participating in the project.

The reactor will also employ supercritical helium circulation pumps (i.e. SHe Cold Circulator) as the key hardware essential to maximizing the performance of those superconducting coils.

The role of the supercritical helium circulation pumps

In order to create strong magnetic fields, the superconducting coils need to be cooled to a cryogenic temperature and kept in that state. The refrigerant to be used to accomplish this is supercritical helium.

Supercritical helium is a fluid not occurring in nature that has a temperature near absolute zero of approximately -269° C. Having the characteristics of not freezing (remaining a fluid)



Role of cryogenic rotating machinery

even at such a low temperature and readily absorbing heat coming from the outside, supercritical helium is currently considered to be the best refrigerant for a cryogenic system that actively cools superconducting coils to maintain a superconducting state.

Each circulation pump sucks in and pumps supercritical helium to circulate it between the heat exchanger in the liquid helium dewar and the superconducting coil. As a result of cooling the superconducting coil, the supercritical helium to the contrary becomes warmer. However, heat is removed from the supercritical helium upon its returning to the heat exchanger, so the helium is re-cooled to the original cryogenic temperature.

Laboratories around the world engaging in research on nuclear fusion and accelerators utilize cryogenic systems that use cryogenic refrigerants. Of the components of such cryogenic systems, cryogenic rotating machinery, such as supercritical helium circulation pumps and the helium compressor for the European Organization for Nuclear Research (CERN) Journal of IHI Technologies, Vol. 53, No. 3 are considered to be the most important with respect to performance and reliability for two reasons. First, the better this cryogenic rotating machinery's performance is, the better the overall efficiency of the cryogenic system becomes, making it possible to reduce operating costs, and second the cryogenic system must operate stably over a prolonged period.

Required specifications for implementing the ITER

During nuclear fusion reactions in the ITER, the supercritical helium will experience temperature and pressure changes resulting from enormous fluctuations in thermal load. The ITER will be equipped with a cryogenic system designed with advanced controls to minimize such fluctuations and keep the coils in a superconducting state. In addition, the scale of the ITER is unparalleled anywhere in the world.

In order for this gigantic cryogenic system to work, a demanding specification was imposed on the development of the supercritical helium circulation pumps. A rated mass flow rate of 2.21 kg/s is over twice the mass flow rate of the world's largest supercritical helium circulation pump. Moreover, a high adiabatic efficiency of more than 70% is required across its rather wide operating range including the

rated mass flow rate. Performance requirements other than the mass flow rate and efficiency must also be cleared: the ability to stably operate in the presence of the strong magnetic field created by superconducting magnets; durability against the radiation that will be generated during nuclear fusion reactions; and compliance with international laws, regulations, and standards.

The requirement regarding the mass flow rate, in particular, has not been satisfied by any manufacturers in the world to date. Hence, the risk of failing to satisfy the requirement is high if one manufacturer attempts to develop the supercritical helium circulation pump independently. India, one of the countries participating in the project, is undertaking the procurement of the cryogenic system. India's research institution ITER-India solicited competitive bids from manufacturers of cryogenic rotating machinery around the world to reduce the risk associated with the development of this helium circulation pump. A paper screening was conducted to narrow the manufacturers down to the top two. Each of these manufacturers actually fabricated a helium circulation pump, which was then evaluated using a test device that simulates ITER's cryogenic environment. The prototyped helium circulation pumps were reviewed from various perspectives, including performance and reliability. Finally, the manufacturer judged to be superior will manufacture all the circulation pumps necessary for the ITER (five in total).



High-efficiency pump impeller



Helium flow inside the impeller at the rated point based on CFD analysis

High-efficiency pump impeller

In developing a supercritical helium circulation pump, the impeller is the most critical component in terms of performance. The impeller must pump supercritical helium efficiently and smoothly. By merging the huge amount of test data we have accumulated over the years with the state-ofthe-art, high-performance impeller analysis technology in a balanced manner, IHI has successfully elaborated optimal impeller and scroll geometries.

In order to ensure that the impeller fully exhibited its performance, we had to take the precise and complicated geometries designed to an accuracy on the order of 1/1 000 mm and actually fabricate it. The impeller was fabricated through the following processes. First, precision casting was performed using the lost wax method, which provides excellent stability in the finished geometry. Next, a three-dimensional measurement was then performed on the finished impeller to check its dimensions in detail. Finally, a rigorous quality inspection was performed using X-rays. This manufacturing process allowed us to achieve high quality.

Perfect adiabatic structure ensuring high efficiency

An atmospheric environment at room temperature was located only a few tenths of a meter above the impeller that circulated supercritical helium with a temperature of approximately -269° C, meaning that the difference in temperature between the impeller and the atmospheric environment was nearly 300°C. Another factor that affects the efficiency of cryogenic rotating machinery as seriously as the impeller is this severe temperature difference that causes heat to be transferred from the room temperature side to the casing of the cryogenic side. We must avoid letting this heat reach the cryogenic helium at all costs.

Heat penetration can be reduced by reducing the thickness of the metal casing because of the casing's characteristic of being a good conductor of heat.

On the other hand, however, all of the various loads that would be applied to the casing (e.g., stress arising from



Casing strength analysis taking into account pressure, thermal shrinkage, and external forces (Deformation scale : × 100)

autogenous shrinkage, internal pressure changes, external force from pipes connected to the casing) had to be predicted and the casing's geometry optimized to withstand such loads.

In order to meet these conflicting design requirements at a high level, we developed the casing taking into account temperature, pressure, and external force under every operating condition we could imagine and making full use of our stateof-the-art thermal/structural simulation technologies. As a result, we have achieved an optimal structure that allows the casing to be only several millimeters thick while maintaining sufficient strength but minimizing incoming heat.

The casing, a culmination of IHI's comprehensive manufacturing ability, did not show deformation or any other anomaly even after it had gone through a pressure proof test for safety verification and a trial run at approximately -269° C, demonstrating its high quality.

A high-performance heat insulating material was placed in the casing to minimize heat penetration. A heat-absorbing component called a thermal anchor was located near the midway point between the end of the room temperature section of the shaft and the impeller to give it a structure that has the ability to trap heat as it enters the supercritical helium from the shaft and release the heat to the outside.

Although vacuum insulation was provided around the pump's cryogenic part, a slight amount of radiation heat from the structure of the room temperature side entered the cryogenic part by passing through the vacuum space. In order to completely eliminate this heat, the entire casing of the cryogenic side was covered with a thermal shield to keep radiation heat out.

Pursuit of higher reliability in cryogenic rotating machinery

In order to ensure the purity of the helium flowing through the cryogenic system, we used a magnetic bearing, which lifts up the shaft using magnetic force and eliminates the need to use lubricating oil.

By performing extraordinarily precise balance correction on the shaft and impeller, extremely stable operation has been achieved over the entire operating range, from the minimum speed to the maximum speed.

Moreover, we have provided redundant safety measures: one is the ability to deal with the loss of power supply to the facilities through self-generation using the kinetic energy of the motor shaft to continue motor shaft lift-up control until



Shaft subjected to precise balance correction



Performance test results (source of data: ITER-India)

tests were carefully conducted one by one making full use of QST's facilities and mobilizing the efforts of every stakeholder in Japan and India, including Japanese researchers playing leading roles in their fields around the world.

The IHI pump underwent actual load tests for 1 month, resulting in the adiabatic efficiency requirement being cleared. Specifically, an adiabatic efficiency of over 73% was recorded at the rated mass flow rate of 2.21 kg/s, which is the required specification. In addition, during operation beyond the rated point, the pump demonstrated the ability to achieve the world's highest mass flow rate of over 3.0 kg/s.

In addition to performance in areas like efficiency and mass flow rate, other characteristics such as stability during prolonged continuous operation and reliability under operating conditions involving sudden pressure/temperature changes will also be critical to actual operation in the future. Actual load tests that simulated all of these conditions were also conducted on the IHI pump one after another, resulting in the pump demonstrating the ability to operate stably, safely, and continuously over a prolonged period of time.

Future development

After completion of the abovementioned tests, ITER-India evaluated the pump highly, acknowledging that IHI's supercritical helium circulation pump meets all of the required specifications.

IHI will continue to hone its cryogenic rotating machinery technologies to develop not only applied superconducting technologies, but also products that meet the cryogenic needs of various fields, thereby contributing to development in the world.

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Measurements were taken of the cryogenic circulation test device as it ran while connected to the current system of the National Institutes for Quantum and Radiological Science and Technology (QST) (located on QST's premises)



IHI pump installed in the cryogenic circulation test facility

the pump is safely shut down, and the other is configuring the shaft system to prevent the impeller from coming into contact with the casing and damaging it should the motor shaft go out of control and become unable to be lifted up.

Furthermore, we have newly developed a magnetic shield as well, which is intended to insulate the motor, magnetic bearing, and sensors from the strong magnetic fields created by the experimental reactor's superconducting coils in order to prevent these components from malfunctioning under the influence of the external magnetic fields.

Pump performance evaluation with a cryogenic environment test facility

The ITER is an international project, and the National Institutes for Quantum and Radiological Science and Technology (QST) (the former Sector of Fusion Research and Development of the Japan Atomic Energy Agency) takes the leadership of ITER-related activities in Japan. In accordance with an agreement between QST and ITER-India, IHI's pump was installed in a separately prepared cryogenic circulation test facility (Test auxiliary cold box), connected to the current operating facilities on the premises of the Naka Fusion Institute (in Ibaraki Prefecture), QST, and then subjected to actual load tests.

Testing started in November 2015, and a lot of actual load