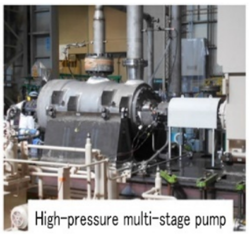
Activities to Improve Reliability and Operability of Pumps for Nuclear Power Plants



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In nuclear power plants, a wide variety of pumps are used for heat transport in the power generation cycle, as well as for safety system equipment for injecting cooling water. Mitsubishi Heavy Industries, Ltd. (MHI) has been supplying various large-capacity pumps and high-pressure pumps for domestic PWR (pressurized water reactor) nuclear power plants, utilizing our design and manufacturing technology in which technical knowledge from the founding period of numerous domestic plants to the latest plants is brought together. This report presents the latest technology adopted in circulating water pumps and high-pressure multi-stage pumps aiming for increased power generation output, improved economic efficiency and the further improvement of safety and reliability in nuclear power plants in recent years, as well as newly developed maintenance tools.

1. Introduction

Large-capacity pumps and high-pressure pumps used in domestic PWR nuclear power plants include reactor (primary) coolant pumps, charging pumps with safety functions, safety injection pumps and residual heat removal pumps in the nuclear island, as well as main feed water pumps, condensate pumps and circulating water pumps in the turbine island. Among these, the circulating water pump is a pump for feeding seawater to the condenser and is the largest-capacity pump in a nuclear power plant. The capacity of circulating water pumps has been increasing for the purpose of increasing power generation output, saving space by reducing the number of pumps and simplifying the system configuration, and MHI supplies one of the world's largest circulating water pumps. The impeller of our circulating water pump uses an adjustable-vane mechanism to reduce the power consumption required to drive the pump. High-pressure multi-stage pumps, such as the charging pump that is responsible for charging the primary coolant into the reactor system and the safety injection pump that is responsible for the core cooling function in the event of a reactor coolant loss accident, are pumps that inject water at high pressure and MHI supplies high-pressure multi-stage pumps with high reliability.

This report describes the structure of the large-capacity adjustable-vane mechanism used for our circulating water pumps, improved economic efficiency due to the adjustable-vane mechanism, design and manufacturing technology for the realization of large capacity, as well as the latest design for improving the reliability of our high-pressure multi-stage pumps and the improvement of maintenance tools for workability enhancement.

2. Large-capacity adjustable-vane circulating water pump

2.1 Structure and configuration of adjustable-vane mechanism

Figure 1 shows an appearance and structure of a large-capacity adjustable-vane circulating water pump. This pump has the basic structure of a vertical mixed flow pump and is driven with the impeller submerged in a seawater intake pit. A larger model of this pump takes in seawater with a flow rate of as much as 150,000 m^3/hr or more. **Figure 2** depicts the adjustable-vane mechanism. The control rod in the main shaft is moved in the axial direction with oil pressure. The axial movement of the crosshead connected to the control rod changes via the ball joint and arm to rotational movement of the runner vane, which controls the vane angle. The vane angle can be

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continuously adjusted from fully open to fully closed and can be changed even while the pump is running.

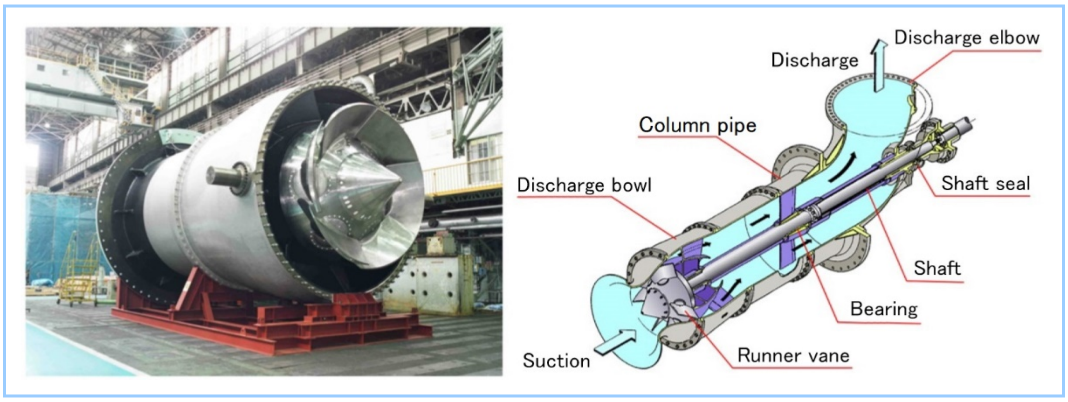

Figure 1 Appearance and structure of large adjustable-vane circulating water pump

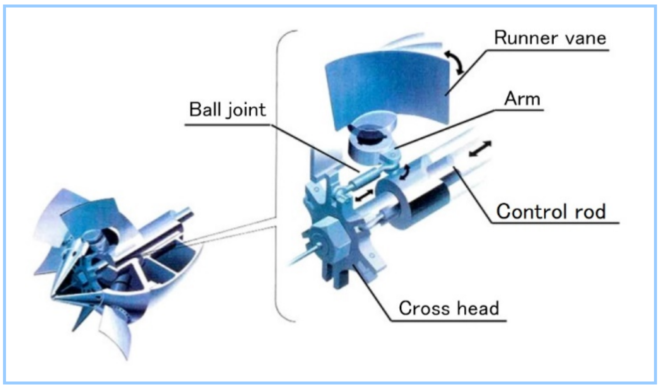

Figure 2 Adjustable-vane mechanism

2.2 Advantages of adjustable-vane circulating water pump (improvement of economic efficiency)

Figure 3 gives the performance curve of the adjustable-vane circulating water pump. The operating flow rate from the circulating water pump required by a power plant changes depending on the operating conditions of the power plant and changes in seawater temperature according to the season. However, a pump without a vane angle adjusting mechanism has pump flow-efficiency characteristics represented by a convex curve and reaches the highest efficiency at a single certain flow rate. It therefore unavoidably operates in an inefficient condition when the operating flow rate is changed. On the other hand, in the case of an adjustable-vane pump, the flow rate at which the pump reaches the highest efficiency can be changed arbitrarily by adjusting the vane angle. As a result, the adjustable-vane circulating water pump can always operate near the maximum efficiency point of the pump in response to changes in the required flow rate of the power plant, and the power consumption required for driving the pump can be significantly reduced compared to fixed-vane pumps.

2.3 Activities for increasing capacity

The size of our circulating water pumps has been increasing, with the pump weight exceeding as much as 200 tons, so careful pre-evaluation of the design and manufacturability are important. Typical design evaluations include strength, fatigue and vibration evaluations, and Finite element method (FEM) analysis and model tests with scale models are also conducted in some cases. The evaluation of examination results uses, in addition to standards and criteria, in-house design standards based on knowledge cultivated through numerous manufacturing results and experience to enhance the design evaluation.

(1) Strength evaluation

Figure 4 is an example of FEM analysis of a runner vane (pump vane). The runner vane is an important part related to the pump performance and its high stress part is grasped by stress evaluation using FEM analysis in order to confirm the integrity in terms of strength.

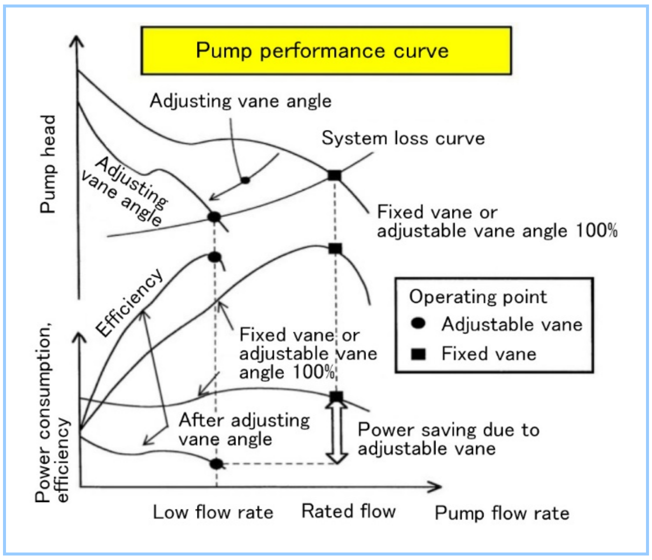

Figure 3 Adjustable-vane circulating water pump performance curve

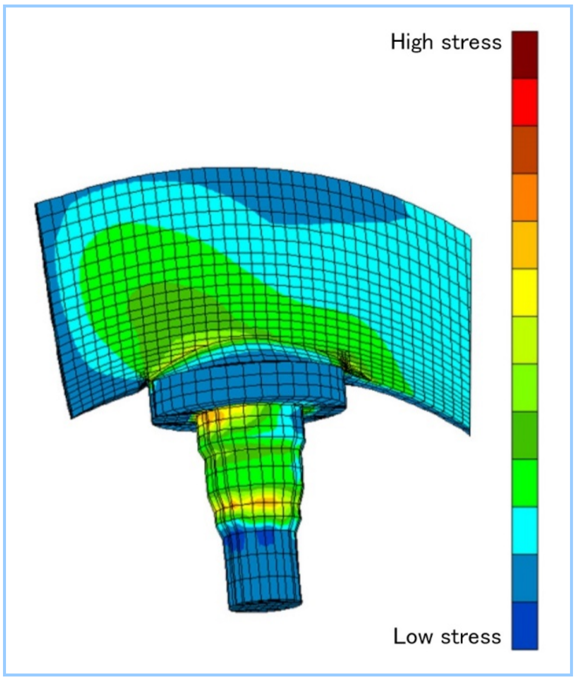

Figure 4 FEM analysis results (stress generated on runner vane)

(2) Fatigue evaluation

Since a fluctuating load caused by hydraulic force acts on the runner vanes, it is necessary to confirm there are no problems in terms of fatigue fractures. Therefore, the integrity against repeated fluctuating stress is ensured by manufacturing a model pump similar to the actual pump and attaching a strain gauge to the high stress area, etc., to measure the fluctuating stress during operation in addition to conducting the aforementioned static stress evaluation using FEM analysis.

(3) Vibration evaluation

If the excitation force generated by the operation of a circulating water pump matches the natural frequency of the shaft system or structural system of the pump, a serious vibration problem, etc., may result.

Since the weight and rigidity change significantly as the capacity is increased, it is important to confirm at the design phase that there are no problems with the natural frequency. We model the entire rotating body including the electric motor and evaluate the shaft system eigenvalues using our in-house analysis code, and also evaluate the structural system eigenvalues for the casing. **Figure 5** provides an example of the structural system eigenvalue analysis results.

(4) Examination of manufacturability

In response to the increase in pump capacity, we have adopted a special pump structure that takes the manufacturability into consideration. As an example of this, **Figure 6** shows a discharge elbow, which is a large casting product with a diameter of 4 m and a weight of more than 50 tons. Generally, a discharge elbow is manufactured as one curved pipe part, but in this example, it is manufactured as two divided curved pipes in consideration of the castability and workability. The discharge elbow is a component that makes up the bearing that supports the main shaft. Therefore, each of two divided parts must be machined and assembled with high precision, otherwise an unacceptable misalignment of the axes of the rotating body and the stationary body occurs and results in equipment that cannot act as a rotating machine. For this reason, we apply our unique expertise to areas that do not appear in the product external view, such as machining procedures.

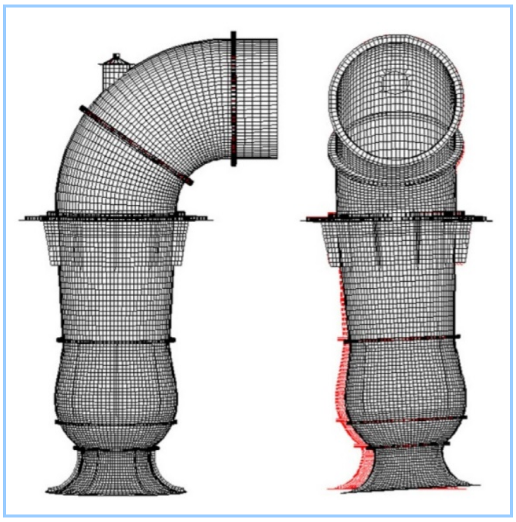

Figure 5 Eigenvalue analysis results (structural system)

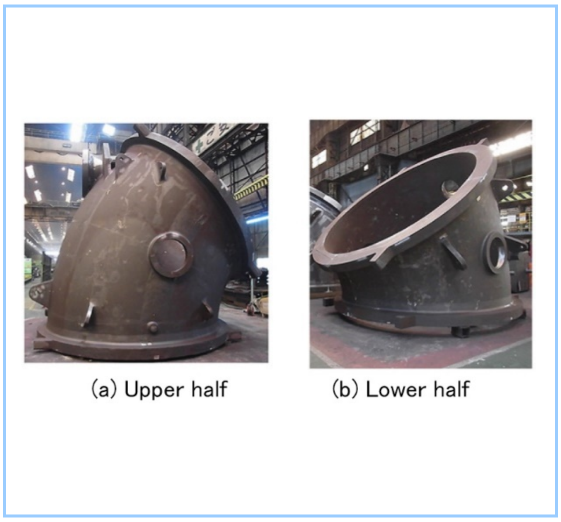

Figure 6 Two-piece discharge elbow

3. High-pressure multi-stage pump for PWR

3.1 Structure of high-pressure multi-stage pump

Figure 7 illustrates the structure of the high-pressure multi-stage pump used in PWR plants. This high-pressure multi-stage pump has a double-casing structure with an external casing and an internal casing that have excellent pressure resistance. It employs a multi-stage pump mechanism with around 10 impeller stages in order to obtain a high pump head. Pumps that adopt this structure include the charging pump that is responsible for a primary coolant charging function and the safety injection pump that is responsible for the core cooling function in the event of a reactor coolant loss accident. These adopt the optimum flow path design and component structure so that high reliability can be obtained as pumps featuring safety functions.

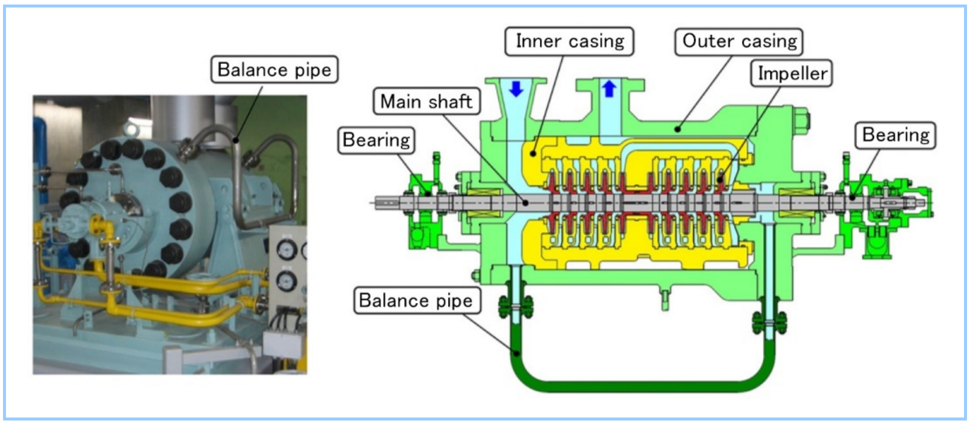

Figure 7 High-pressure multi-stage pump for existing PWR plants

3.2 Design improvement of high-pressure multi-stage pump for further improvement of reliability

We have also been improving high-pressure multi-stage pumps continuously based on our experience in operating nuclear power plants, as well as on cases and achievements in other fields such as thermal power plants. For the high-pressure multi-stage pumps, the special safety facility of Japanese nuclear power plant, etc. have been introduced in recent years, our latest design is adopted for the balance pipe and main shaft to further improve reliability (**Figure 8**).

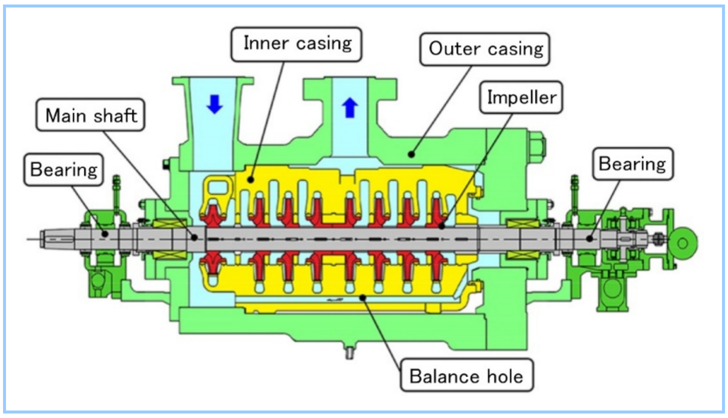

Figure 8 High-pressure multi-stage pumps for the special safety facility of Japanese nuclear power plant

(1) Abolition of balance pipe

On the main shaft of a pump, axial thrust is generated due to the pressure distribution around the impeller during operation. The load due to this axial thrust is supported by the thrust bearing and in the case of a high-pressure multi-stage pump, it is necessary to reduce the axial thrust to a level that the bearing can support. Conventional pumps use a balance pipe placed outside the casing to balance the pressure imbalance, but the latest design has a structure with holes for pressure balancing inside the casing and eliminates the balance pipe. As a result, the number of pressure retaining parts, welds, flange connections, etc., is reduced, which improves the reliability of the long-term pressure-resistant performance.

(2) Reduction of stress concentrating areas on main shaft

High-pressure multi-stage pumps used in nuclear power plants are characterized by the required high pump head and low required flow rate, so their small-diameter centrifugal impeller and main shaft rotate at a high speed. For this reason, ensuring sufficient main shaft strength is necessary to improve reliability. The main shaft of conventional high-pressure multi-stage pumps has multiple grooves for fixing the impellers, and stress during operation is concentrated there. However, in the latest design, the number of grooves of the main shaft is reduced as much as possible by reviewing the assembly structure of the impeller.

3.3 Workability improvement with new maintenance tools

In nuclear power plants, systematic overhauls are carried out during regular inspections. Especially for pumps in the primary system that handle fluids containing radioactive substances, simplifying the overhaul inspection work reduces exposure and contributes to maintenance cost saving of power plants. High-pressure multi-stage pumps require experienced skill in some disassembly and assembly work, but the workability is improved by applying new maintenance tools.

(1) Inner casing pull-out tool

High-pressure multi-stage pumps have a double casing structure in order to provide a robust structure. The outer casing is made of high-strength carbon steel or low-alloy steel and the inner wetting surface uses stainless-steel overlay weld to ensure corrosion resistance. For an overhaul, it is necessary to pull out the inner casing including the rotating parts such as the impeller, main shaft, etc., axially from the outer casing while maintaining the horizontal position with high accuracy. We devised an inner casing pull-out tool (**Figure 9**) to improve this work so that the inner casing can be disassembled without damaging on the stainless-steal, surface of the outer casing it even without work by highly skilled operators. The tool is mainly composed of a guide rail and shaft sleeve, as well as rollers that support and axially move them. Once the positioning of the guide rail and the shaft sleeve is completed, this tool can easily pull out the inner casing, greatly reducing the risk of damaging the casing during this work.

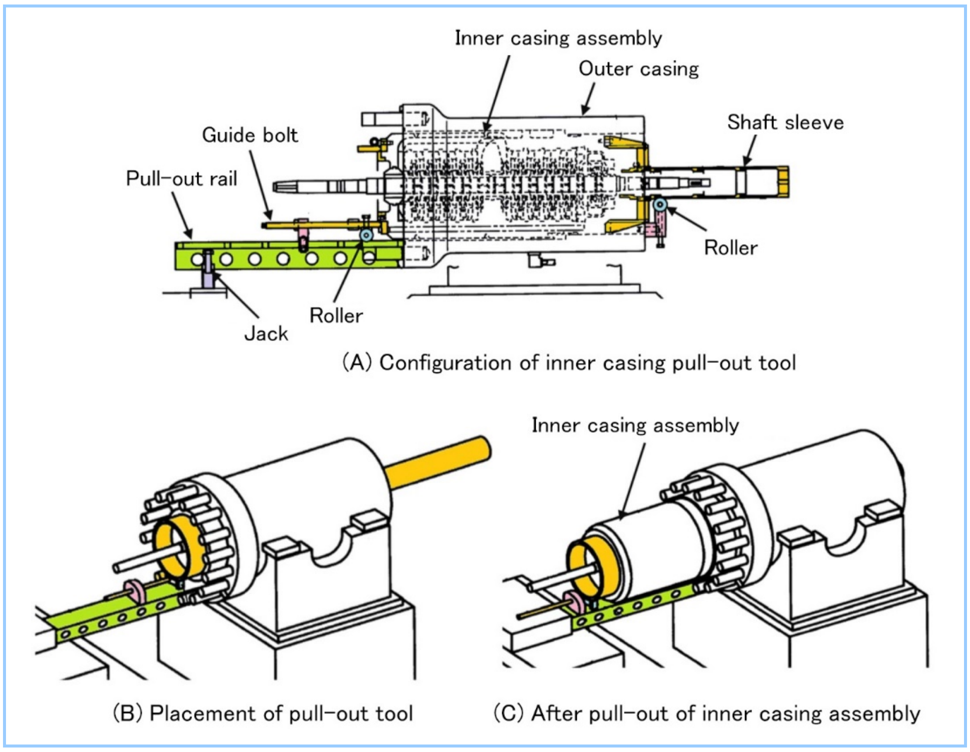

Figure 9 Inner casing pull-out tool

(2) Main shaft components disassembly tool using high-frequency induction heating method

The shaft coupling joint and other parts are shrink-fitted to the main shaft in order to prevent assembly deviation from being generated even during high-speed rotation. Conventionally, to disassemble these, it is necessary to heat the target part evenly over the entire circumference using gas burners and pull the part out from the main shaft while paying close attention to seizure. It is difficult to quantitatively determine the work procedure for such heating with burners and part removal, and judgment of the degree of heating, etc., must rely on the skills of experienced operators. To address this workability issue, we have put into practical use a tool for pulling out shrink-fit parts using a high-frequency induction heating method (**Figure 10**). The power supply conditions and holding time of the heating coil for heating the same part can be quantified. As a result, stable disassembly work can be realized independently of the experience or feeling of the worker. This tool can be applied not only to high-pressure multi-stage pumps, but also to various shrink-fit parts of pumps as long as a heating coil suitable for the shape of the target part is available.

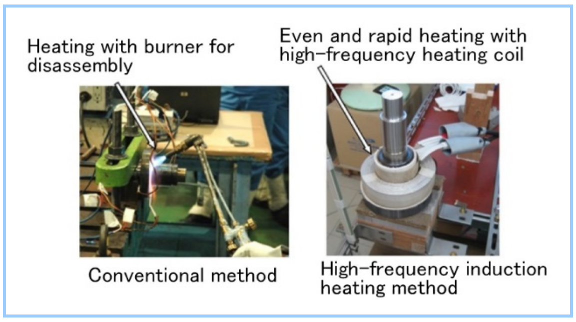

Figure 10 Main shaft components disassembly tool using high-frequency induction heating method

4. Conclusion

This report presented the latest design adopted for circulating water pumps and high-pressure multi-stage pumps for nuclear power plants and newly developed maintenance tools. Domestically, our circulating water pumps are used in some BWR plants in addition to all PWR plants. Overseas, they are adopted in the Sanmen Nuclear Power Station in China along with our main feed water pumps. MHI will continue to contribute to the improvement of reliability and the advancement of operations of nuclear power plants in Japan and overseas with our pumps and maintenance tools. These products will be utilized both for new installation in power plants to be constructed in the future and as replacements in existing facilities.