[Commentary]

Boiler Feed Pump (BFP)

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Abstract

In a thermal power plant, the boiler feed pump (BFP) is one of the critical auxiliary machines that are equivalent to the heart of the plant. In pace with the increases in the capacity of equipment for thermal power generation, improvements to adapt to higher temperatures and pressures, and changes in operation method, BFPs have been improving and advancing. This paper explains how BFPs have been upsized and made compatible to higher pressures; main specifications of BFPs; structures and materials of typical BFPs for conventional supercritical thermal power plants and for combined-cycle thermal power plants; characteristics of the shaft seal and bearing; technological development for higher capacities and performance; actual development and delivery of 100% capacity BFPs; improvements to the structure design for increasing the stress resistance of BFPs so that they can adapt to more severe conditions in the operation of thermal power plants associated with the spread of renewable energy; and examples of efforts to streamline the BFP design for manufacturing cost reduction and space saving.

Keywords: Feed water pump, High pressure, Efficiency, Super critical thermal power, Combined cycle thermal power, Reliability, Specific speed, Shaft strength, Bearing, Double casing

1. Introduction

This paper outlines the history and structural and technical characteristics of boiler feed pumps (hereafter referred to as BFP), which are high-pressure pumps mainly used for thermal power generation.

In a thermal power plant, the BFP is one of the critical auxiliary machines that are equivalent to the heart of the plant. In thermal power generation, high-pressure steam is used to drive a turbine, which in turn rotates the generator directly connected to the turbine to generate power. The steam is produced by feeding hot water to the boiler from the BFP. This means that an unexpected stop of the BFP completely stops power generation and therefore the BFP requires a very high level of reliability. In recent years, with the popularization of renewable energy, thermal power generation requires load adjustment for a stable power generation system as well as operation under severe conditions such as rapid changes in load. The BFP is also required to provide even higher levels of capabilities and reliability because it must operate in more severe conditions such as partial load operation and increased frequency of start and stop actions.

2. History

2.1 BFPs for conventional thermal power plants

Since BFPs are used to feed high-temperature/pressure water to boilers, their history is closely related with the improvement toward higher boiler capacities and higher temperatures and pressures.

Boilers and other equipment for commercial thermal power generation have been improved to achieve higher per-unit capacities with the objective of reducing the percentage of equipment costs (for advantages of scale) as well as to achieve higher steam temperatures and pressures for higher thermal efficiency[1].

Looking at the history of boilers in Japan, the maximum unit capacity was 66 MW in 1955, which increased to 325 MW in 1965 and to 600 MW in 1969. In 1974, a boiler with a capacity of 1000 MW was brought into operation. Boilers in Japan thus have been undergoing rapid increases in capacity. After 1980, boilers with a unit capacity of more than 600 MW went mainstream,

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followed by many units with a capacity of more than 1 000 MW built after 1990.

Looking at the steam conditions, Japan's first boiler with a steam pressure of 16.6 MPa (at the inlet of the turbine) was fabricated in 1959. In 1967, Japan's first supercritical constant-pressure boiler was brought into operation for higher generation efficiency. Boilers subsequently underwent rapid increases in supercritical pressure, resulting in a situation where 82% of the power generating units built in 1974 were of a supercritical type[1].

When used in combination with a supercritical-pressure boiler with a unit capacity of more than 1 000 MW, the BFP is required to deliver a very high level of performance such as a flow rate of approximately 1 700 t/h, a discharge pressure of approximately 30 MPa, and a shaft power of approximately 20 000 kW. To achieve this high pressure, the BFP is required to achieve a high rotation speed of 5 000 to 6 000 min^{-1}. At that time, it was common to combine two 50% capacity BFPs driven by steam turbines (T-BFPs) and one BFP driven by a motor with a speed-increasing gear (M-BFP) as a backup and for start-up purposes. **Figure 1** shows the relationship between the increases in boiler pressure and BFP discharge pressure[2].

Note that EBARA supplied BFPs for both of Japan's first supercritical and ultra-supercritical (USC) power generating units. EBARA also delivered Japan's first BFP for a 1 000 MW power generating unit.

In the 1980s, many nuclear power plants were built,

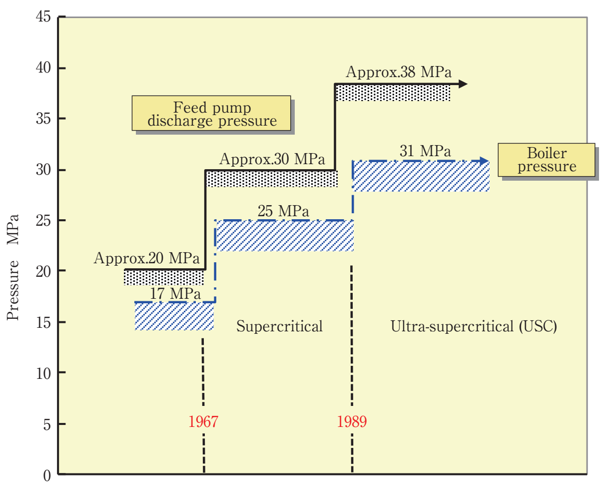

Fig. 1 Boiler pressure and BFP discharge pressure

Table 1 BFP specifications for 700 MW USC thermal power plant

Purpose		Main feed water	Start-up and backup
Capacity	t/h	1 200	730
Discharge pressure	MPa	38.05	37.26
Rotation speed	min^{-1}	6 000	6 300
Water temperature	℃	188.4	184.1
Drive		Steam turbine	Motor drive (with a fluid coupling)
Output	kW	17 500	12 000
Number of units		2	1

which started to act as base-load power plants. Under the circumstances, in commercial thermal power generation, many units that were compatible with middle-load operation started to be used, with supercritical variable-pressure once-through boilers, capable of maintaining high efficiency even in the middle-load area, going mainstream. This situation required variable-speed motor drives, leading to the introduction of motor drives with a built-in speed increasing gear and a fluid coupling.

Efforts to increase the thermal efficiency continued. In 1989, a 700 MW, USC plant was brought into operation with a main steam pressure of 31.1 MPa and a main steam temperature of 566 °C.

Table 1 shows the specifications of the BFPs used in this plant[2].

2.2 BFPs for combined-cycle thermal power plants

In parallel with the movement to improve the systems for the conventional thermal power generation toward higher capacities, temperatures, and pressures, combined-cycle power generation went into actual use in the middle 1980s, a thermal power generation system that achieves higher efficiency by combining two cycles: a gas-turbine combustion cycle and a steam-turbine cycle that uses the exhaust heat from the former cycle. With continuous technological development for cooling turbine blades and making them heat resistant, the gas-turbine combustion temperature has increased, resulting in further improvement in power generation efficiency. State-of-the-art combined-cycle plants (with a gas turbine that uses a temperature of higher than 1 600 °C) have achieved a sending-end efficiency of as high as 60%. In recent years, many combined-cycle thermal power plants have been constructed because they use, as a fuel for gas turbines, LNG – a fuel that emits less carbon dioxide – and therefore impose less environmental load. These plants require BFPs that feed water to heat recovery steam generators (HRSG).

3. Structures of BFPs

3.1 BFPs for conventional thermal power plants[3)]

(1) Casing structure

BFPs used in supercritical and USC plants are required to provide a high discharge pressure of 30 to 35 MPa with a feed-water temperature of as high as 180 ℃ or higher. These plants use double casing barrel-type multi-stage pumps designed to be adaptable to high-pressure and -temperature specifications. These pumps have a forged cylindrical outer barrel with a high rigidity that contains a single-piece structure consisting of an internal casing and a rotor, with one end of the outer barrel fastened to a discharge cover with bolts. They are designed according to the technical standard for thermal power generation or a similar public standard so that the thicknesses of the outer barrel, discharge cover, and discharge nozzle, and the size and number of cover fastening bolts will provide sufficient strengths against the design pressure (maximum allowable working pressure).

The outer barrel is a simple thick cylinder that is not affected by high pressures or changes in pressure. The barrel is fastened to the discharge cover with bolts with a spiral gasket inserted between them to prevent leakage of water. The fastening bolts are controlled with a hydraulic wrench, bolt heater, or bolt tensioner so that it will constantly provide appropriate fastening force.

By providing a middle extraction flange on the discharge cover side or the suction side as appropriate, intermediate pressure can be taken out so that it can be used for applications such as coolant spraying to the reheater.

(2) Internal structure

The structures of the internal casing, impeller, and other hydraulic components are divided into two groups: one group uses a combination of a axially split casing, back to back arrangement impeller, and a volute type and the other group uses a combination of a ring section casing, straight through impeller, and a diffuser type. The latter group requires a balance disk or a similar component for balancing the axial thrust.

(3) Material

The outer barrel and discharge cover, which are pressure-containing components, are made of forged carbon steel, and the gasket surface and high velocity sections are overlaid with austenitic stainless steel to prevent erosion. The internal casing and impeller are made of 13Cr or 13Cr-4Ni martensitic cast stainless steel.

(4) Shaft seal and bearing

Most commercial thermal power generation plants in Japan used non-contact throttle bushes or floating rings, which are not likely to wear under high-speed and -pressure conditions and are suitable to continuous operation. In recent years, overseas plants in particular use mechanical seals in many cases. As for the bearings, a forced lubricating type is used.

Figure 2 shows the structure of a typical BFP for conventional thermal power plants.

3.2 BFPs for combined-cycle plants[3)]

(1) Casing structure

BFPs for combined-cycle thermal power plants feed water to the heat recovery steam generator. They are required to provide a discharge pressure of 15 to 20 MPa and a feed-water temperature of approximately 150 ℃, which are substantially low compared to supercritical thermal power plants. For this reason, single case, ring section-type, multi-stage pumps are used in most combined-cycle plants. However, they absolutely require technologies for analyzing and evaluating thermal stress and deformation because they are required to adapt to quick plant starts and abrupt changes in feed-water temperature. The basic structure of a ring section-type casing consists of a suction casing, discharge casing, inter stage casing, and intermediate extraction casing, which are fastened with casing bolts, with the joints between the casings sealed with metal touch based on the fastening contact pressure of the bolts. Depending on the results of thermal deformation analysis, an O-ring is fitted as appropriate to completely prevent leakage of feed water even during thermal transient.

(2) Internal structure

Heat recovery steam generators for combined-cycle

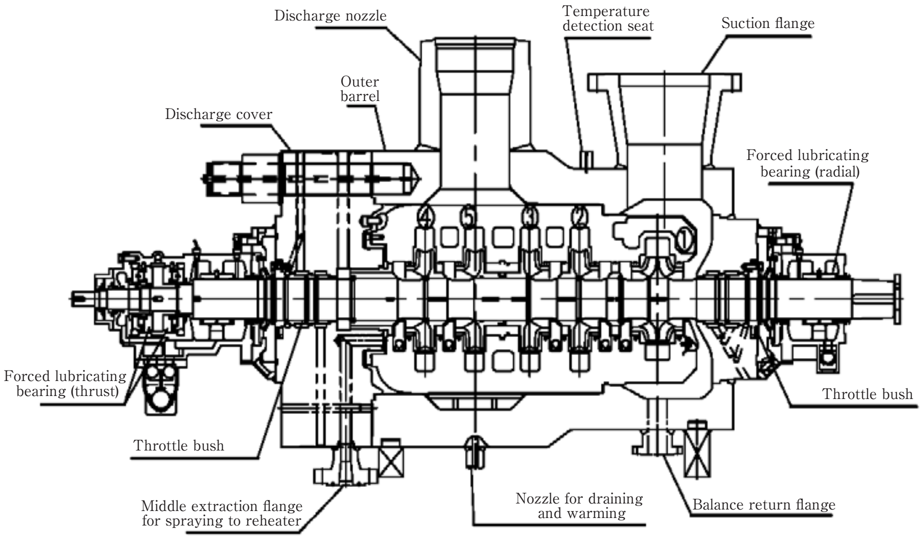

Fig. 2 Double casing barrel type BFP for supercritical thermal power plants

plants are often structured with three stages (high-, middle-, and low-pressure drums), and designed to extract intermediate-pressure feed water from the intermediate stage of the BFP to feed it to the middle-pressure drum. In other words, one unit of BFP can feed middle- and high-pressure water. Total amount of the middle- and high-pressure feed water are sucked from the suction casing. After the amount of the water to be fed to the middle-pressure drum is extracted from the extraction stage, only the amount of the water to be fed to the high-pressure drum is pressurized. For this reason, the specific speeds (Ns) of impeller and diffuser for the stage before the extraction are often different from those after the extraction.

In combined-cycle plants, ring section-type diffuser pumps are used. They have all impellers arranged in one direction and therefore require a thrust balancing component. Balancing components are available in two types: balance-disk and balance-drum types. Water leaked from the balancing component is normally returned to the suction side. When the pressure decreases in the balancing component, the water temperature rises. When the saturated vapor pressure of water with the temperature rise taken into account is higher than the suction pressure, the water may flush out and returns to the pump inlet. If this is the case, the pump does not operate soundly. If this happens, the balancing piping is connected to the deaerator.

Pumps structured to use double suction impeller at only the first stage are often used because this structure can reduce the required NPSH by halving the suction flow because of the double suction.

(3) Material

The suction, discharge, and extraction casings, which are pressure-containing components, are made of 13Cr-4Ni cast stainless steel and the inter stage casing of 13Cr-4Ni stainless steel.

(4) Shaft seal and bearing

For the shaft sealing device, a mechanical seal with almost no leakage is used because the pressure and peripheral speed conditions are slightly less severe than those for BFPs for supercritical plants. For the bearing, though a forced lubricating type is used, a self-lubricating type can also be safely used in some cases as will be described later since the peripheral-speed conditions are less severe than those in conventional supercritical thermal power plants. **Figure 3** shows the structure of a typical BFP for combined-cycle thermal power plants.

4. Upsizing and sophistication of BFPs

With the growth of equipment for thermal power generation in capacity and pressure, BFPs have been upsized and become sophisticated. Among the pumps used in a thermal power plant, the BFP uses the most power because it must produce high pressures required by the boiler. This means that the improve-

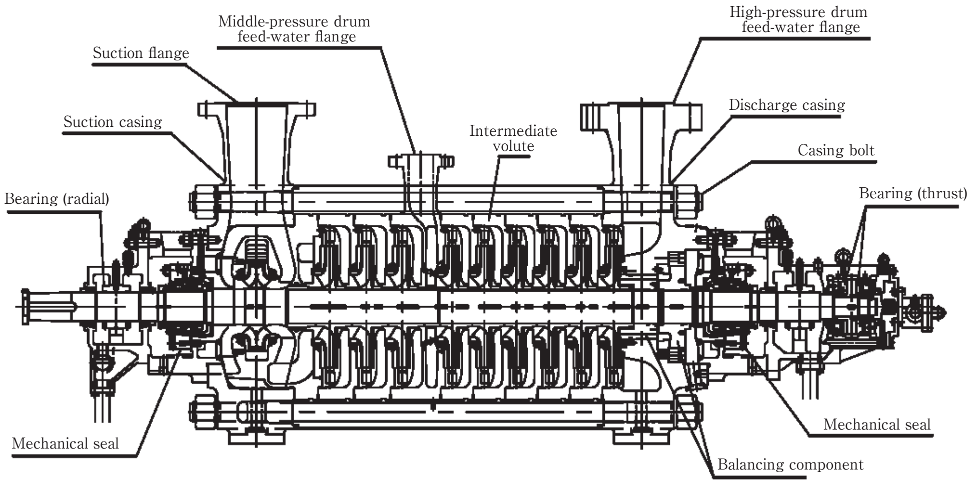

Fig. 3 Structure of a BFP for combined cycle thermal power plants

ment in BFP efficiency is a critical challenge that must be solved to reduce the environmental load. The impeller used in a BFP is a centrifugal pump with a specific speed (Ns) of approximately 120 to 250 (m^3/min, m, min^{-1}). Generally, the pump efficiency is higher when the specific speed is higher within this range or the flow rate is higher if the specific speed is the same. In a normal case, two BFPs each with a 50% capacity are used as the main feed pumps. If one BFP can provide a 100% capacity, it improves the efficiency through the increase in capacity and enhancement in specific speed as well as helps save space and resources[4]. In Japan, EBARA has experience in designing, fabricating, and delivering main feed pumps with a specification of 100% capacity per unit for 500 MW and 600 MW supercritical thermal power plants and these pumps are successfully operating. In some countries and areas, a system based on a single main feed pump with a 100% capacity is in actual use in 1000 MW plants. Recently, EBARA also manufactured and delivered a large BFP that satisfied this requirement. **Figure 4** shows actually shipped BFP and followings are the outlined specifications of this BFP.

Capacity of 3200 t/h × total pump head of 3800 m × shaft power of 37700 kW × rotation speed of 5000 min^{-1}

Specific speed of approximately 250 (m^3/min, m, min^{-1})

In general, higher capacities and higher specific speeds increase the pump efficiency. The shaft power increases with the increase in capacity; accordingly, if the rotation speed is the same as that of a 50% capacity

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Fig. 4 100% capacity BFP for 1000 MW supercritical thermal power plants

BFP, the main shaft has larger torque and is thus required to have a large diameter, compared to conventional BFPs, to maintain the required strength. If the rotational speed and pump head remain the same, the diameter of the impeller also remains unchanged. This means the main shaft with an increased diameter interferes with the flow passage of the impeller meridian plane. Under the circumstances, to achieve high efficiency, we determined the optimal hydraulic shape including the volute − which reduces the flow velocity of the water from the impeller, and converts it into static pressure − and the cross over passages between the stages. To this end, we made full use of CFD[note] including analysis of unsteady flows.

We also determined, through analysis of the main shaft strength, the optimal diameter that minimizes the increase in shaft diameter from that of the 50% capacity BFP (existing conventional design). For a system based on a 100% capacity BFP, only one unit is used and if it should unexpectedly stop, the power generation capacity is totally lost. For this reason, needless to say, we designed the main shaft so that each part of the shaft would maintain a sufficient strength.

Note: Computational fluid dynamics

Table 2 compares the performance of BFPs delivered to power plants of typical sizes and with typical outputs. The BFP shaft power consumes 3.5 to 4% of plant output; this ratio can be reduced through the increase in efficiency to be achieved by increases in capacity. For 500 MW plants, we successfully reduced the ratio to the rated plant output by approximately 0.5 point by using one 100% capacity BFP. Even if the output is the same, however, the water temperature (density), capacity, and total pressure are different from plant to plant and therefore it is not generally practical to make comparisons according to only the shaft power ratio. Looking at the efficiency, for the 500 MW plants, while the system based on two units exhibited an efficiency of 82%, the system based on a single unit achieved an 86% efficiency, resulting in a 4-point improvement as described earlier[4].

5. Improvement in BFP stress resistance

Recent years have seen increased introductions of renewable energies such as solar and wind power. Renewable energy is expected to continue to spread as one of the measures against global warming because it does not use fossil fuel and therefore emits no carbon dioxide when used for power generation. However, the power output based on solar and wind power significantly depends on the meteorological conditions such as the weather and wind conditions, resulting in the drawback that it is difficult to stably operate electric power systems based on renewable energy. In order to cope with this issue, thermal power plants are increasingly required to provide more flexible power system operation with a higher level of supply-and-demand adjustment capability. Specifically, they are required to improve the load change rate, minimize the minimum load factor, and shorten the start-up time.

In association with the supply-and-demand adjustment capability added to thermal power plants, BFPs are required to operate in more severe conditions such as increased frequency of start and stop actions, changes in feed water temperature, and increased frequency of low flow operation. To address these requirements, efforts have been made to improve the stress resistance (robustness) of BFPs by reviewing the structure, materials, and design. **Figure 5** shows an example of a BFP structure that has incorporated the structural and design considerations to adapt to the operational requirements above. **Table 3** shows specific items that must be improved and phenomena that must be addressed along with possible causes of them (some of the measures in the Table 3 are not always against the more severe operating conditions but have been introduced as part of the efforts to improve the general functional reliability of BFPs[5]).

6. Streamlining of BFPs

As described earlier, BFPs are the heart of the main piping system in thermal power systems and therefore required to provide high levels of functionality and reliability. On the other hand, it is also important to supply power at as low a price as possible, in developing countries in particular, where the demand for power is pressing and therefore the construction of many new thermal power plants is planned. For this reason, pump suppliers are also required to cooperate to simplify the equipment for power generation plants and make efforts to reduce the costs for such equipment as one of the challenges that they must address. Here are some of the efforts to streamline BFPs.

Table 2 Specifications of typical BFPs

Rated plant output	Capacity	Total pressure	Rotation speed	Shaft power	Efficiency	Number of unit	Power ratio
MW	t/h	MPa	min^{-1}	kW	%	Unit	%
500	890	29.67	5500	9999	82	2	4.00
500	1630	30.1	5500	17747	86	1	3.55
600	1000	30.1	5500	11157	83.5	2	3.72
600	1860	33.2	5000	22589	85.3	1	3.76
700	1120	30.6	5500	12711.7	85	2	3.63
1000	1650	30.5	5500	18393.3	86	2	3.68
1050	1700	31.2	6000	19279.5	85.5	2	3.67

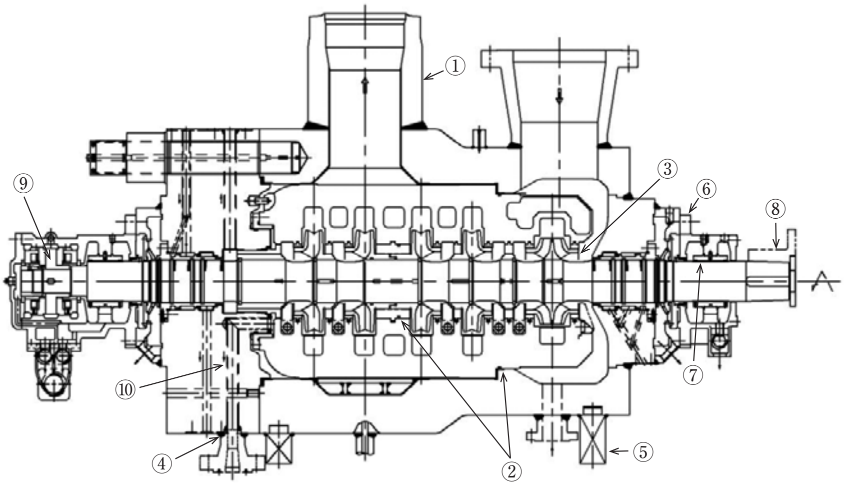

Fig. 5 BFP structure that has incorporated measures for increasing the robustness

Table 3 Measures for increasing the robustness of BFPs

No	Degradation	Causes	Measures for increasing the robustness
①	Wall thickness reduction of discharge nozzle	Erosion caused by high velocity and/or uneven flow	Overlaying austenitic stainless steel onto the inner surface
②	Erosion of high-differential-pressure part of the inner volute	Degraded seal performance of metal touch seal or self-compressed gasket associated with increased frequencies of start and stop actions	Using an auxiliary O-ring in combination
③	Incipient cavitation	Increased duration of low flow operation associated with the adoption of DSS, etc.	Replacing the first stage impeller with new one designed for low flow regarding with inlet configuration
④	Cracks at the portion to which auxiliary piping is attached	Impact of pulsation caused by increased duration of low flow operation	Modifying the nozzle stub so that it will be a more rigid structure
⑤	Vibration caused by misalignment	Changes in nozzle load associated with increased frequencies of start and stop actions	Installing an stabilizing device
⑥	Increased bearing vibration	Impact of pulsation caused by increased duration of low flow operation	Using a full circular bearing housing
⑦	Damaged bearing metal	Wire-wool damage of 13Cr steel shaft caused by foreign particles in lube oil	Overlaying carbon steel to the main shaft journal
⑧	Occurring of abruptly changing vibration	Torque locking caused by poor sliding of the gear-coupling tooth surface	Upgrading to a flexible disk coupling
⑨	Fretting corrosion on the fitting portion of the thrust disk	Decreased torque of the shaft-end nut. Loosened fixed disk caused by secular distortion of the disk contact surface	Using a shaft-end nut of a locking sleeve type Using a long hub type thrust disk
⑩	Degraded mechanical seal for inter stage bleed off	No maintenance for a long time because it is installed on the suction cover and not required when the inner-volute rotor disassembly	Discontinuing the use of the bleed off pipe and the mechanical seal as the structure for extraction from the discharge cover

The above number is the part that shows the number of the in Fig. 5.

6.1 Discontinuance of booster pumps

With a rotation speed of as high as 5000 to 6000 min^{-1}, BFPs for supercritical thermal power plants require a high required NPSH (NPSHR). With an increase in power generation capacity, the flow rate of the BFP increases, which requires an even higher NPSHR. The NPSH available (NPSHA) of a BFP, which is determined by the height of the deaerator installed, is normally approximately 20 to 25 m. For this reason, through the cross over piping, a booster pump is normally installed upstream of the BFP to ensure the NPSH required for the BFP.

Under the circumstances, M-BFPs for start-up purposes used in some plants are actually designed to include an impeller equipped with an inducer in the first stage to lower the NPSHR for elimination of the need to use a booster pump and cross over piping. This design helps reduce plant construction costs by saving space and resources. **Figure 6** shows the structure of a BFP with an inducer[4].

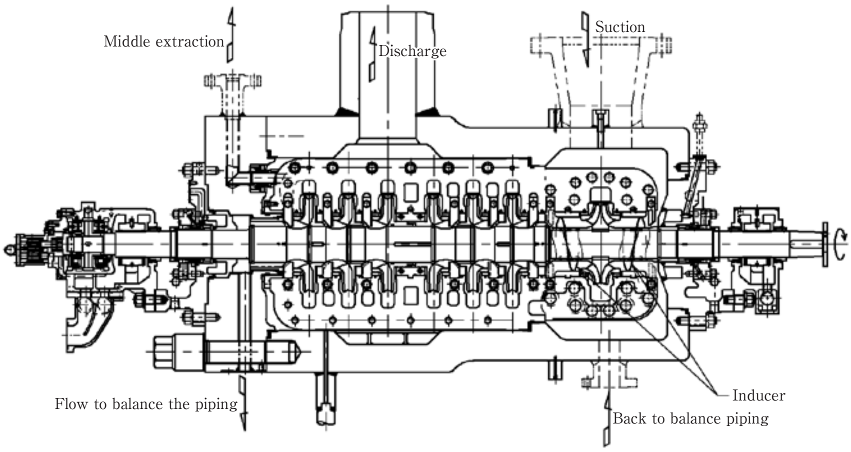

Fig. 6 BFP with an inducer

6.2 Full-cartridge, ring section, double casing BFPs

The BFPs shown in Figs. 2, 6, and **Figure 7** are structured with a horizontally split internal casing (inner volute). As Fig. 7 shows, a BFP with this structure allows you to take out the shaft and impeller as a rotor assembled as one unit if the upper half of the inner volute is disassembled. Since this facilitates inspection in power plants, this design has been adopted in many power plants inside and outside Japan. It also has the drawback, however, that the design requires a high manufacturing cost because the inner volute has a complicated structure made of cast steel. On the other hand, the structure with a ring section-type internal casing (inner case) offers the cost-related advantages that it does not require an inner volute, which is costly, and that when compared under the same performance (pressure), it allows you to slightly reduce the diameter of the internal casing, resulting in a smaller diameter of the outer barrel. This structure has the drawback, however, that it is difficult to inspect on site because inspection of the rotor requires you to vertically place the inner casing and rotor and then take out the inner case, guide vane, and impeller on a stage-by-stage basis. On the other hand, a full-cartridge structure allows you to take out, as one unit, all components, including the inner casing, rotor, outer-barrel cover, bearing, and shaft seal, except the outer barrel. This allows you to return the full-cartridge component to the factory for inspection, eliminating the need for on-site inspection. EBARA has experience in manufacturing and delivering a 100% capacity, ring section, double casing BFP for

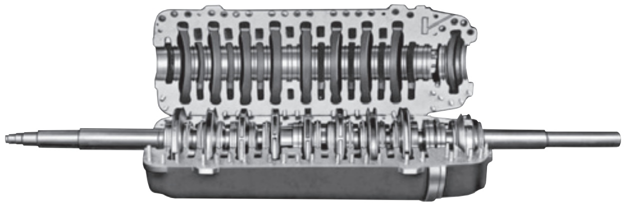

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Fig. 7 Disassembled inner volute and the rotor to be taken out

350 MW supercritical plants (equivalent to the 50% capacity BFP for 700 MW supercritical plants). **Figure 8** shows a full-cartridge, ring section, double casing BFP in assembled and dissembled states.

6.3 Self-lubricating bearing

Involving high rotation speed and high output, BFPs use a forced lubricating bearing. The lube oil unit (LO) requires arrangement of a main oil pump (MOP) and an auxiliary oil pump (AOP) for start-up and backup purposes. Normal oil supply pressure is between 0.08 and 0.12 MPa. When the oil pressure has decreased (to 0.05 MPa) during operation, the pressure switch or transmitter installed in the lubricant feed piping issues an alarm and, at the same time, automatically activates the auxiliary oil pump. When the oil pressure has further decreased (to 0.03 MPa), it stops the BFP for protecting the bearing and ensuring safety. The lube oil unit is provided with an oil reservoir for containing lubricant, oil-pressure regulating valve, oil cooler, switching twin filter, and other equipment. A normal oil reservoir requires a capacity three or more times the flow rate of the oil pump. The required instruments include devices for monitoring the differential filter

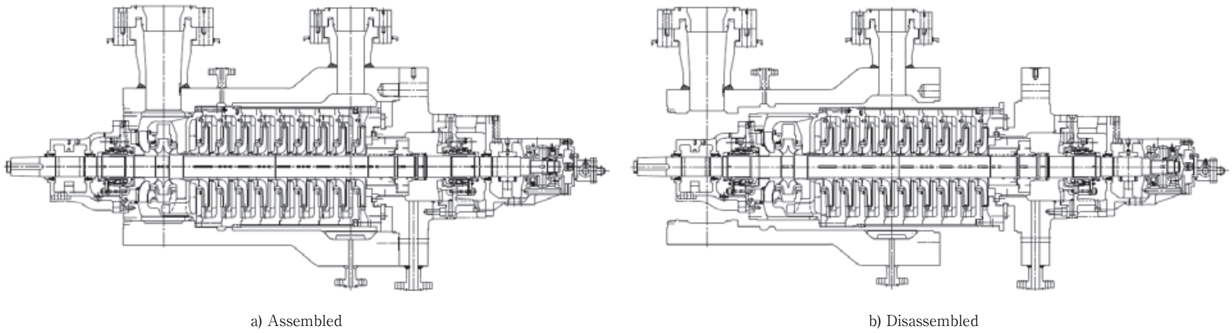

Fig. 8 Full-cartridge, sectional-type BFP

pressure, oil level of the oil reservoir, and oil temperature. Since the unit equipped with these devices and instruments make up a large percentage in terms of foot print and manufacturing cost, it is significant to streamline the lubrication system (**Figure 9**).

Whether the bearing requires forced lubrication or self-lubrication depends on the peripheral speed at the radial bearing and the type of the thrust bearing. Considering the fact that BFPs for supercritical thermal power plants provides a high rotation speed of more than 5000 min^{-1} with high shaft power, they will probably continue to require forced lubrication. Lubricant is fed from the turbine if the BFP is driven by a turbine or from the fluid coupling if the BFP is driven by a motor with a fluid coupling, meaning that the lubricating method of the pump bearing does not affect the manufacturing cost or installation space.

On the other hand, a typical BFP for combined-cycle plants is directly driven by a 2P motor and provides an output of approximately 2000 to 2500 kW, which is low compared with BFPs for supercritical thermal power plants. Equipped with no turbine or fluid coupling, this BFP requires a separately installed lube oil unit. The BFP, if equipped with a self-lubricating bearing, can streamline the power generation system by reducing the floor space for installation. While the current BFPs use a forced lubricating bearing based on the existing selection criteria, we think that it is possible to broaden the self-lubricating bearings to a wider range of applications by improving the self-lubricating mechanism and bearing cooling structure (**Figure 10**).

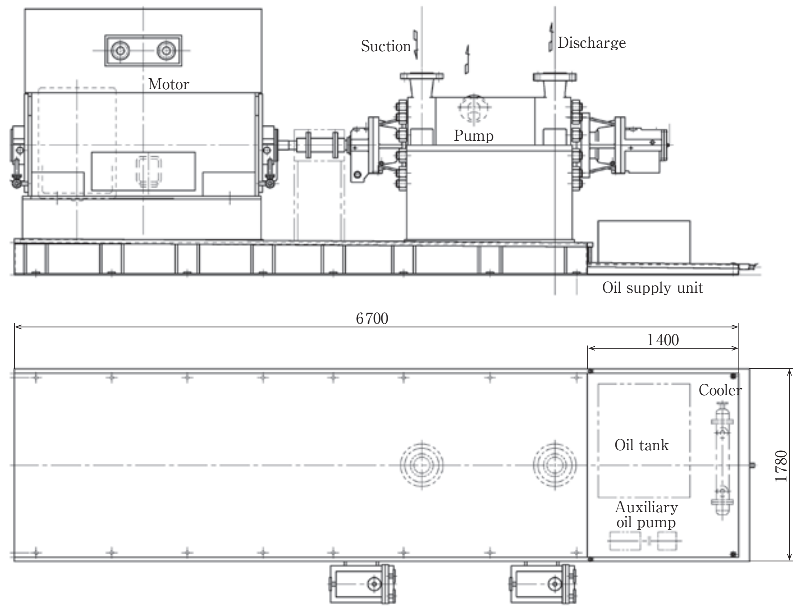

Fig. 9 Boiler feed pump outline drawing (with oil supply unit)

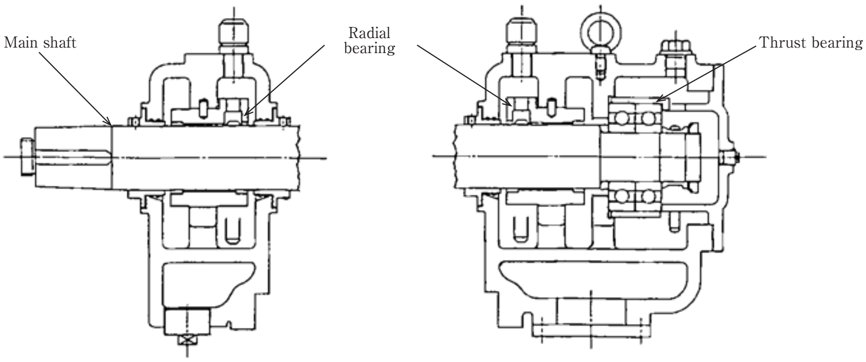

Fig. 10 Self-lubricating bearing

7. Conclusion

This paper outlines the history and characteristics of boiler feed pumps (BFPs) used for commercial thermal power generation along with technical improvements to them. In pace with the increases in the capacity of equipment for commercial thermal power generation, improvements to adapt to higher temperatures and pressures, and changes in operation method, BFPs have been improving and advancing. We believe that, in making efforts to meet the increasing demand for power and to reduce the environmental load, thermal power generation will play an increasingly important role. It is expected that in Japan, the load-adjusting operation will be more flexible through combined use of renewable energy, and in oil-producing countries more technologies will be introduced, for example, of controlling carbon dioxide emissions based on carbon capture and storage (CCS). It is required that while responding to the changes in the market environment, we should make further efforts to develop technologies for further increasing the efficiency and reliability of BFPs and reduce their manufacturing costs.

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