Preliminary Study on Steam-Water Circulation System of Marine Small Nuclear Power Plant

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Abstract: Marine small nuclear power plants need to pursue the highest economy by improving the thermal efficiency of the steam-water circulation system. Based on the design concept of the steam-water circulation system of foreign nuclear-powered ships and onshore nuclear power plants, this paper proposes a preliminary heat balance diagram of the steam-water circulation system of marine small nuclear power plants, and comparatively analyzes the effect of initial steam pressure, condenser pressure and steam extraction pressure on thermal efficiency of steam-water circulation system. This study has certain guiding significance for the design of the general scheme of conventional islands in small marine nuclear power plants.

1. Introduction
Marine small nuclear power plants can independently supply power, desalinated water and heating for offshore facilities, such as comprehensive oil extraction supply stations and offshore oil drilling platforms.

Currently, most nuclear power ship steam-water circulation systems in China adopt the simplest heat balance process, so the thermal efficiency of conventional islands is low. Further, the marine small nuclear power plant uses technologies currently available in China. Therefore, we should learn the design concepts of nuclear power ships and nuclear power plant steam-water circulation systems from domestic or foreign research, which can optimize system composition and parameters and improve thermal efficiency.

2. Foreign nuclear power ships' thermal balance diagram of the steam-water circulation system
In terms of the design of the heat balance diagram of the steam-water circulation system of the marine small nuclear power plant, we can refer to the steam-water circulation system of nuclear power ships and onshore nuclear power plants in other countries. For example, the thermal balance diagrams of the Russian "Northern Line" nuclear-powered icebreaker, the American "Savanna" and the Germany "Otto Han" nuclear-powered merchant ships are shown in Figures 1, 2 and 3 [1, 2]. The design parameters of their conventional steam-water circulation system are shown in the table below.

| Table 1. Design parameters of foreign nuclear power ships |
|--------------------------------------------------------|
| ship name | Savanna | Northern Line | Otto Han |
| country/ship type | American/passenger and cargo ship | Russian/nuclear-powered icebreaker | Germany/nuclear-powered merchant ships |
| reactor rated thermal power/MW | 69 | 135 | 38 |
| nuclear power plant efficiency/% | 23.6 | 21.79 | 21.3 |

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the steam parameters /MPa 2.8 (Saturated Vapor)
condenser pressure /kPa 4.9

System Configuration

| the three-level feed water heater | 3.9MPa/290℃ 7.6 |
|----------------------------------|------------------|
| (low-pressure heater, deaerator, high-pressure heater) | the four-level feed water heater (deaerator) |
| the three-level feed water heater | the three-level feed water heater |

| feed water temperature /℃ | 175 | 150–170 | 185 |

Figure 1. The thermal balance diagrams of the Russian "Northern Line" nuclear-powered icebreaker

Figure 2. The thermal balance diagrams of the American "Savanna" passenger and cargo ship

Figure 3. The thermal balance diagrams of the Germany "Otto Han" nuclear-powered merchant ships

The thermal balance process of the steam-water circulation system of the “Northern Line” nuclear-powered icebreaker has three steps. First, the steam parameters at the outlet of the steam generator are 3.92 MPa and 290 ℃. When the steam reaches the steam turbine, the steam parameters become 3.6 MPa, 280 ℃. Second, the steam enters the high-pressure cylinder. After passing through the high-pressure cylinder, the steam enters the intermediate steam-water separator. Third, the steam enters the low-pressure cylinder, and the residual steam of the steam turbine is pumped to the deaerator, distillation device and the first-stage feed water heater. In doing so, the excess steam is discharged to the main condenser and cooling condenser where the pressure is maintained at 0.0076 MPa. Based on the main condensate electric pump, the condensate is pumped to the deaerator after passing through the main ejector, suction ejector, ion exchange filter, and low-pressure feed water heater. The feed water passing through the deaerator has a pressure of 0.13 MPa and a temperature of 106 ℃. The feed water that passes through the high-pressure feed water heater has a temperature of 150 ℃ ~ 170 ℃. The feed water is sent to the steam generator through the main feed water vapour pump.

The backup feed water pump installed can provide feed water of 3.5 MPa from the deaerator to the steam generator. When the device operates or stops, the steam and steam-water mixture generated by the steam generator is received by two auxiliary condensation devices.

The three-stage feed water heating is performed by the steam extraction of the steam turbine unit. (The three-level feed water heater is: low-pressure heater, deaerator, high-pressure heater): the first-level feed water heater (low-pressure heater) is heated by steam with a pressure of 0.083 MPa extracted from the extraction branch of the low-pressure cylinder, and then the generated condensate water is discharged to the hot condensate tank and drained to the main condensation pipe by the drain pump.

The steam pressure of the steam branch of the steam-water separator reaches 0.32 MPa. After passing through the intermediate steam-water separator, the steam and the residual steam generated by the steam turbine feed pump will be supplied to the deaerator, the second-level feed water heater and the distillation device.

The third-level feed water heater uses the extraction steam from the extraction branch of the high-pressure cylinder. The steam extraction pressure is 0.98 MPa. After condensation in the heater, the steam will be discharged to the deaerator.

The nuclear-powered merchant ship "Savanna" and the nuclear-powered ore ship "Otto Han" basically share the same thermal balance diagram of the steam-water circulation system as that of the "Northern Line". The difference is that "Savanna" and "Otto Han" are equipped with two instead of three extraction points, and a three-stage feed water heater (the low-pressure heater of "Otto Han" contains a two-stage hydrophobic regenerator(3)).
The above-mentioned heat balance diagrams share two features in common:
(1) 2~3 steam extraction points and 3~4-level feed water heaters are set on the main steam turbine unit, and the latent heat of vaporization of the steam turbine unit is fully utilized to improve the thermal efficiency of the power plant;
(2) An emergency feed water pump is equipped to meet the water demand of the steam generator in case of failure of the steam turbine feed water pump.

The land-based PWR nuclear power plant is a high-power reactor, and its construction space is not limited, so its initial vapour pressure is large (generally 5~6 MPa), and it will be set at 5~7-level heaters. The biggest difference with nuclear-powered ships is that the onshore pressurized water reactor nuclear power plant is equipped with a steam-water separation reheater (MSR), which is absent in the steam-water circulation system of nuclear-powered ships. Figure 4 is the heat balance diagram of a 900 MW pressurized water reactor nuclear power plant. The initial steam pressure is 5.47 MPa, and MSR is adopted, and a 5-level heater is installed, and the gross efficiency of the power plant is 33.14%.

Figure 4. The thermal balance diagram of 900MW PWR nuclear power plant unit

Actually, increasing the initial steam pressure is beneficial to improving the thermal efficiency of the steam-water circulation system, so some researchers have proposed the use of a once-through steam generator. Table 2 shows the performance comparison between the once-through steam generator (OTSG) and the natural circulation steam generator (SG).

| Advantage | OTSG | SG |
|-----------|------|----|
| Compact structure | Mature technology |
| High thermal efficiency | Good inheritance |
| Fast load response | |

| Disadvantage | OTSG | SG |
|--------------|------|----|
| High requirements for feed water quality indicators | Large size |
| High requirements on nuclear control system | Low thermal efficiency |
| Need to set start and stop system | Slow load response |

The over-current steam generator has not been used in domestic nuclear facilities, and thus no experience in this regard is available in China. Therefore, the reliability and safety of the operation of the once-through steam generator should be explored. The control of water supply coordination, system start and stop and discharge, system monitoring and other aspects will be different if a direct-current steam generator is used. Thereby, how to achieve safe and reliable control is one of the
key issues in the design of steam water circulation systems.

Based on the above analyses, it is advisable to employ natural circulation steam generators, and add MSR based on the existing mature technology, and set 2~3 steam extraction points, and 3~4-level heaters to improve thermal efficiency of steam-water circulation systems in marine small nuclear power plants.

3. Analysis of some factors influencing the thermal efficiency of the steam-water circulation system of a small marine nuclear power plant

According to the mature design experience of nuclear power ships and the partial design of onshore nuclear power plants abroad, it is suggested that China should consider the performance requirements and technical characteristics of small marine nuclear power plants. They should initially utilize a natural steam generator, add MSR, adopt Level 2 steam extraction recuperation and the Level 3 feed water heating scheme.

3.1 The effect of initial steam pressure on the thermal efficiency of the steam-water circulation system

The steam parameters at the outlet of the steam generator have a significant effect on the thermal efficiency of the steam-water circulation system. This paper calculates the thermal efficiency of the steam-water circulation system when the initial steam pressure is 3.0 MPa, 3.5 MPa and 4.0 MPa.

As Figure 6 shows, when initial steam pressure is within a certain range, the thermal efficiency of
steam-water circulation system increases with the increase of initial steam pressure and the maximum efficiency is 27.09%. However, the following problems will be incurred:

1. The steam humidity at the steam turbine outlet would increase. If the steam turbine exhaust humidity rises excessively, erosion will occur on the last few blades of the steam turbine, which not only adversely affects the operation safety of the steam turbine, but also reduces the internal efficiency of the steam turbine;

2. Increasing the operating pressure of the steam generator will require an increase in the head of the feed water pump. As a result, the axial thrust of the impeller of the feed water pump rises, and the power consumption of the feed water pump also increases with regard to the unit mass flow of working fluid;

3. Increasing the initial steam pressure is also subject to the influence of the operating temperature of the coolant on the primary side of the steam generator.

3.2 The effect of condenser pressure on the thermal efficiency of the steam-water circulation system

According to the Carnot cycle thermal efficiency formula, reducing the condenser pressure can promote the thermal efficiency of the steam-water circulation system more effectively. In this study, the steam-water circulation thermal efficiency is calculated when the initial steam pressure is 3.5 MPa and the condenser pressure reaches 5.5 kPa, 6.0 kPa and 6.5 kPa, respectively. The calculation results are shown in Table 3.

Table 3. Calculation result of the effect of condenser pressure on the thermal efficiency of steam-water circulation system

| parameter          | condition | 1   | 2   | 3   |
|--------------------|-----------|-----|-----|-----|
| SG outlet pressure (MPa) | 3.5       | 3.5 | 3.5 |     |
| heat exchange area (m²)    | 1805.72   | 1490.53 | 1274.84 |
| condenser pressure (kPa)  | 5.5       | 6.0 | 6.5 |     |
| the thermal efficiency (%)| 26.81     | 26.64 | 26.50 |

The calculation results show that when the condenser pressure is 5.5 kPa, the thermal efficiency of the steam-water circulation system is the highest, reaching 26.81%, but the heat exchange area of the condenser increases sharply: the heat exchange area in this scenario is 29.4% higher than when the condenser pressure is 6.5 kPa, which has a greater impact on the overall layout and economy of the system.

3.3 The effect of steam extraction pressure on the thermal efficiency of the steam-water circulation system

The steam-water circulation system recycles the latent heat of vaporization of residual steam by providing steam extraction in a high-pressure cylinder. If the steam extraction parameters and the steam extraction position are different, then it also has different impacts on the thermal efficiency of the steam-water circulation system. In terms of the problem, when the initial steam pressure is 3.5 MPa, and the condenser pressure is 6.0 kPa, this paper calculates different extraction schemes with extraction points set at different positions in the high-pressure cylinder stage. The calculation results are shown in Table 4.

Table 4. Calculation result of the effect of steam extraction pressure on the thermal efficiency of steam-water circulation system

| parameter                  | condition | 1   | 2   | 3   |
|----------------------------|-----------|-----|-----|-----|
| SG outlet pressure (MPa)   | 3.5       | 3.5 | 3.5 |     |
| Steam extraction pressure in | 0.60   | 0.76 | 0.98 |

The calculation results show that when the steam extraction pressure is 0.60, the thermal efficiency of the steam-water circulation system is the highest, reaching 26.64%, but the extraction pressure increases sharply: the extraction pressure in this scenario is 29.4% higher than when the extraction pressure is 0.98, which has a greater impact on the overall layout and economy of the system.
The calculation results show that when the heat transfer end difference of the feed water heater is controlled at 8 ~ 15 ℃, the thermal efficiency of the steam-water circulation system is high. When the pressure value is not in this range, the higher the steam extraction pressure of the high-pressure cylinder, and this is not conducive to improving the thermal efficiency of the steam-water circulation system. Therefore, the optimal steam extraction pressure of the steam-water circulation system is closely related to the feed water temperature of the steam generator.

4. Conclusion

The paper researched the design methods of the steam-water circulation system of nuclear-powered ships and nuclear power plants at home and abroad. In addition, we proposed a preliminary heat balance diagram of the steam-water circulation system of marine small-scale nuclear power plants. The paper also analyzed some factors affecting the thermal efficiency of the steam-water circulation system, and the following conclusions are as follows.

By studying the design methods of the steam-water circulation system of nuclear-powered ships and nuclear power plants at home and abroad, this paper proposes a preliminary heat balance diagram of the steam-water circulation system of marine small nuclear power plants and analyzes some factors that affect the thermal efficiency of the steam-water circulation system. Finally, the article concludes some results as follows.

1) The marine small nuclear power plants not only focus on the economy but also are restricted by its weight and size. Therefore, it is recommended to use natural circulation steam generators for the steam-water circulation system and to install MSR dependent upon the basis of mature technology. We still need to set 2~ 3 steam extraction points as well as 3~ 4-level heaters.

2) The thermal efficiency of the steam-water circulation system increases with the increase of initial steam pressure, but it will also result in some problems and be limited by steam initial pressure value provided by the nuclear island.

3) The pressure of the condenser has a great impact on the thermal efficiency of the steam-water circulation system. Although reducing its pressure can improve the thermal efficiency, the heat exchange area of the condenser also increases, which has a greater impact on the overall layout and economy.

4) The optimal steam extraction pressure is closely related to the steam generator feed water temperature, and it is of benefit to the later design of the steam turbine unit.

References

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