Development of Multi-Stage Steam Injector for Feedwater Heaters in Simplified Nuclear Power Plant*

Tadashi NARABAYASHI**,***, Shuichi OHMORI****, Michitsugu MORI****, Yutaka ASANUMA** and Chikako IWAKI**

A steam injector (SI) is a simple, compact and passive pump and also acts as a high-performance direct-contact compact heater to heat up feedwater by using extracted steam from the turbine. To develop high performance compact feedwater heater, it is necessary to quantify the characteristics between physical properties of the flow field. Its performance depends on the phenomena of steam condensation onto the water jet surface and heat transfer in the water jet due to turbulence on to the phase-interface. The analysis was conducted by using CFD code embedded separate two-phase flow models that were confirmed by the experimental data. As the four-stage SI is compact heater, the system is expected to bring about great simplification and materials-saving effects, and high reliability of its operation. Therefore, it is confirmed that the simplification of the power plant by replacing all low-pressure feedwater heaters with the four-stage SI system, having steam extraction pressures equal to those for the existing ABWR system.

Key Words: Jet, Multi-Phase Flow, Nozzle, Pressure Distribution, Turbulent Mixing, Nuclear Reactor, Power Plant, CFD Code, Separate Two-Phase Model, BWR, Steam Injector, Feedwater Heater

1. Introduction

Nuclear power plants have a number of advantages such as they do not produce carbon dioxide, and fuel loaded in a reactor core has a stockpiling effect to be advantageous in terms of Japan’s energy security. On the other side, however, the cost of constructing new nuclear power plants should be decreased to keep ascendancy of power cost over advanced-combined-cycle thermal power plants. In case of a fourth-generation nuclear reactor, capability of mitigating the severe accidents in a reactor design. The high construction costs resulting from the complicatedness of plants and an enormous number of components required, a long period of construction, enormous numbers of systems and equipment to be inspected during periodical inspections, and the increased manpower due to large numbers of replacements involved. At some nuclear power plants, degraded feedwater heaters have been replaced, resulting in power losses of several months. Analysis of this cost classifies into (a) the complicatedness of the turbine condensation and feedwater heating systems in the balance of plant (BOP), and (b) the volume and materials used in such systems. Such being the case, based on the high-performance steam injector technology that has been developed to achieve high performance and extend an application range(1)–(7). By substituting the steam injectors for feedwater, thereby to substantially simplify system and components, achieve material reductions, enhancing the reliability and international price competitiveness of Japanese nuclear power plants(11).

A separate two-phase flow model was developed based on the fundamental test data using a single-stage visualized steam injector that was made of heatproof acrylic resin. The obtained data set was the axial-velocity distribution in the steam phase, and temperature/axial-velocity distribution in a water jet. Axial-velocity flow in the steam phase was measured by using the advanced measuring techniques of LDV method to measure supersonic velocity. In order to enable to analyze steam injector performances, a separate-two-phase flow model was made as
user subroutines in some CFD codes, such as PHONICS and Star-CD. The validity of the model was confirmed by analyzing the fundamental test results. The analysis results showed in good agreement with the set of test results\(^6\).

In this paper, we focused on the merits of simplifying the feedwater system by using a four-stage steam injector, and also focused on improving the performances of the steam injector especially in the 1st-stage, to enhance the plant thermal efficiency.

2. Nomenclature and Abbreviations

- \( A \): area of bubble surface [m\(^2\)]
- \( T \): water temperature
- \( m \): mass flow rate [kg/s]
- \( h \): enthalpy [kJ/kg]
- \( C_{pl} \): specific heat

Subscripts

- “mix” represents mixing flow
- \( l \): liquid phase
- \( g \): vapor phase

Abbreviations

- ABWR: Advanced boiling water reactor
- BOP: Balance of plant (Turbine and feedwater system)
- CFD: Computer fluid dynamics
- LDV: Laser Doppler velocimeter
- SI: Steam injector

3. Development for Simplified Feedwater System

3.1 Simplified feedwater system

Steam injector is a passive jet pump that has no movable part and drives water jet by supersonic steam jet\(^1\)–\(^7\). When water is injected from the water jet nozzle at the axial center in the case of Fig. 1 and steam is supplied to the annular steam nozzle composed of the outside of the water jet nozzle and the mixing nozzle inlet, the steam becomes a supersonic flow in the mixing nozzle and accelerates the water jet, producing a high-speed water flow at the throat.

The steam condensation is completed and the flow changes into a single-phase water flow in a diffuser, with its pressure rising to a high level in accordance with Bernoulli’s principle.

In addition to its function as a pump, steam injector works as a heat exchanger through direct contact between steam and water. This provides steam injector with capability to serve also as a direct-contact feedwater heater that heats up feedwater by using extracted steam from the turbine. For this purpose, we have been developing the multi-stage steam injector system as shown in Fig. 2, composed of the first-stage, second-stage, third-stage steam injectors, and jet deaerator as the final-stage.

As it is compact equipment, steam injector is expected to bring about great simplification and materials-saving effects, while its simple structure ensures high reliability of its operation, thereby greatly contributing to the simplification of the power plant. The high-performance steam injector system with multi-stage parallel operation, having been developed\(^8\)–\(^11\). The high-performance steam injector, because of its wider operating and application ranges from higher through lower steam pressures, compared with conventional steam injectors, which attains higher discharge pressure than the supply steam pressure.

Figure 3 shows BOP system of an ABWR. The low-pressure feedwater heating system has a total of 12 (four-stage \(\times\) three-series) low-pressure feedwater heaters. The size of a low-pressure heater is about 2 m in diameter and 13 m long. The feedwater heating system of ABWR, shown in Fig. 4 (a), can be simplified by the six parallel four-stage SI systems as shown in Fig. 4 (b).

As the low-pressure feedwater heaters of ABWR, which are placed inside the huge condenser as necked heaters as shown in Fig. 5. For the case, by using the four-stage steam injectors, as shown in Fig. 6, the large necked heaters will be removed and the turbine building height can be reduced by \(\sim 3.5\) m.

3.2 Scaled model test for simplified feedwater system

In this study, we aimed at using reduced-scale test-based analytical improvement development. The performance test was carried out with 1/7-scaled tests to confirm the numerical simulation. The multi-stage steam injector test facility is shown in Fig. 7. Then, 1/5-scaled steam injector test model was made geometric-analogy to 1/7-scaled SI model, and also conducted the performance test.

Table 1 shows the test results summary for both a 1/7-scaled and a 1/5-scaled test models with the full-scale target value of the actual steam injectors. Since the ratios of the inner diameter and length are \(\sim 2^{1/2}\), the flow rate of the 1/5 scaled SI is twice of that for the 1/7-scaled test model. The 1/5-scaled SI test model was made analogy to
1/7-scaled SI model. The test results of the outlet temperatures and pressures at each stage by the 1/5-scaled model were almost similar to those of the 1/7-scaled model.

4. Improvement of SI with CDF analysis

4.1 CFD analysis model

In relation to a steam injector improvement, supersonic steam condensation onto a water jet was developed, without relying on full-scale demonstration of operational equipment, with the results of experiments using scaled models. The authors developed the separate-two-phase flow model and wrote a user subroutine compiled with some CFD codes, such as PHONICS and Star-CD. The validity of the model was confirmed by analyzing the fundamental test results. The analysis results showed in good agreement with the set of test results, and also showed little effect on scaling of a steam injector\(^5\).

In this study, analyses of the multi-stage steam injector for feedwater heater were conducted, by using the separate-two-phase flow model in the Star-CD codes. This paper describes the analyses results to improve the steam injector improvement.

The performance improvement of steam injectors will
produce the enhancement of the plant thermal efficiency, on which the performance of the 1st-stage SI, especially, has remarkable impact, since it is worked with the lowest-pressure extracted steam of 0.05 MPa from the turbine. Figure 8 illustrates the 3D-CAD modeling of the multi-stage steam injector from the first through third stages with the large-diameter bell mouth and mixing nozzle. The steam-liquid interface is shown by blue-water jet. Figure 9 shows analysis modeling of extended large inlet bell-mouth with the mesh for numerical simulation and the boundary conditions for analyses. The pressures of the extracted steam as the input set were 0.05 MPa, 0.11 MPa, 0.21 MPa from the first stage to the third stage, respectively. The inlet pressure and temperature of the feedwater flow as the boundary conditions were set to 1.60 MPa and 42°C.

**4.2 Analysis results**

The analyses were parametrically carried out, varying the inner diameter of the inlet bell mouth, and the diameter and the length of the mixing nozzle through the first stage steam injector. The series of the parametric survey was performed to seek for the better configuration of the first-stage SI to increase the outlet temperature.

When the bell mouth was applied for the mixing nozzle adopted in the last design to enlarge the steam nozzle inlet, the outlet temperature of the first-stage SI decreased to 51.7°C, the fact of which showed that the configuration of the mixing nozzle with the bell mouth including the shape of a curve surface affected the SI performance.

The temperature distribution from the 1st-stage to the 3rd-stage SI predicted by analysis is shown in Figs. 10 and
The temperature of the steam flow can be found to be lower than expected in the downstream of the 1st-stage SI, which may cause the performance degradation of the 1st-stage SI and, therefore, the temperature increase at the outlet of the 1st-stage SI could not be attained. The outlet mixed temperature of the 1st stage SI can be determined by:

\[ T_{\text{mix}} = \frac{(m_l h_l + m_g h_g)}{(m_l + m_g) C_{pl}} \]  

where \( m \) is mass flow rate (kg/s), \( h \) is enthalpy (kJ/kg); and \( C_{pl} \) is specific heat, as shown in the nomenclature.

We conducted over 10 cases to improve the performance of the 4-stage steam injector feed-water heaters, especially the 1st-stage. Among ten cases, typical three cases were shown in Table 2. The analysis results for the three cases are described in following order: (a) Original case of test nozzle, (b) Extended large inlet-bell mouth case, and (c) Improved thick mixing nozzle case.

### 4.2.1 Original case

The original case of the analysis result is shown in Figs. 10 and 11. The 1st-stage mixing nozzle used in the test was the same dimensions that was described in section 3.2. As shown in Fig. 10(a), pressure in each stage is almost the same as the supplied steam from the turbine extracted steam port, except in a mixing nozzle in the 1st-stage. The analysis results of the water temperature in Fig. 10 (b) were 67°C. The 1st-stage outlet water temperature calculated Eq. (1) by using the calculated steam flow rate in the 1st-stage mixing nozzle was also 67°C. The value was less than that of the current ABWR’s feedwater heater. As shown in Fig. 10(b), the

<table>
<thead>
<tr>
<th>Case</th>
<th>1st-stage nozzle</th>
<th>1st-stage exit temp. (°C)</th>
<th>4th-stage exit temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Original</td>
<td>Round bell-mouth</td>
<td>67</td>
<td>144</td>
</tr>
<tr>
<td>(b) Extended</td>
<td>Extended bell-mouth</td>
<td>69</td>
<td>144</td>
</tr>
<tr>
<td>(c) Improved</td>
<td>Thick dia. mix. nozzle</td>
<td>72</td>
<td>144</td>
</tr>
<tr>
<td>ABWR</td>
<td>Heat Exchanger</td>
<td>75</td>
<td>139</td>
</tr>
</tbody>
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analysis results of steam temperature distribution curve in the 1st-stage had a valley in the mixing nozzle from 80°C to 70°C at the bottom. The reason why the steam temperature decreased to 70°C was to the steam velocity in the mixing nozzle was too high to decrease static pressure, according to the polytropic expansion line\(^{(4)}\) and steam temperature was also decreased according the saturation temperature of the steam pressure decrease, making some moisture in the two-phase flow area, as shown axial velocity peak in Fig. 11.

4.2.2 Extended large inlet-bell mouth In order to improve the heater efficiency of the 1st stage SI, the extended large inlet-bell mouth at the inlet of the 1st-stage mixing nozzle, which had a longer water jet, was analyzed. As shown in Fig. 12 (a), there were also still the steam axial-velocity peak, the 1st-stage exit temperature increase was only 2°C, from 67°C to 69°C. The predicted exit temperatures and pressures at each stage for the full
scale steam injector by analysis also showed the almost similar results against those of 1/7-scaled and 1/5-scaled test models, which exhibited the applicability of the scale law on analogy in the design of the enlarged multi-stage steam injector.

4.2.3 Improved mixing nozzle of the 1st-stage

As shown in Fig. 12, the axial velocity in the mixing nozzle was too high to decrease the steam temperature in the mixing nozzle of the 1st-stage, an improved mixing nozzle was analyzed as Case (c). Inner diameter of the mixing nozzle was enlarged from 31 to 36.5 mm as shown in Fig. 13. The comparison of the analyses results of case (b) and case (c) are shown in Fig. 14. By using the improved thick-diameter mixing nozzle, the steam axial-velocity peak was decreased to about 260 m/s, and the steam temperature in the 1st-stage mixing nozzle were increased. Thus, the 1st-stage outlet temperature were increased from 69°C to 75°C as shown in Fig. 15 (a) and (b), and the steam flow rate was also increased to heat up water jet in the 1st-stage higher than about 8°C compared with the original case. It was almost compatible steam pressure and exit water temperature at each stage. The 4th-stage of jet deareator exit temperature is saturation temperature of extracted steam of 0.4 MPa. Therefore, exit temperature of 4th-stage steam injector is higher than that of ABWR’s low-pressure heater. Thus, it will be possible to increase the plant thermal-efficiency by using the steam injector feedwater heater system.

5. Effects of Material-Saving Using Steam Injector

In order to demonstrate the merits of applying the multistage steam injector for the feedwater heating system, the comparison was made estimating the volume and weight reduction between ABWR and the simplified feedwater system as shown in bird’s eye view layout design in Fig. 16.

As the diligent tally up working results as shown in Fig. 17, the weight and volume of the feedwater heating system of the simplified plant can be reduced by around one-third, compared with those of ABWR. The high construction costs resulting from the complicatedness of plants and an enormous number of components will be reduced, and a long period of construction and outage days for inspection and replace the heaters will also shortened. The four-stage steam injector is simple devices...
and easy maintenance only changing nozzles in steam injector casings.

In this point of view, the proposed system can contribute greatly to enhance reliability; in addition to economic efficiency and marketability both in domestic and overseas markets by simplified feedwater heater system.

6. Conclusions

Using high-performance SI system technologies that can be as a direct-contact heater for a wide operating range, we have carried out a study on a simplified nuclear power plant design for feedwater heater systems. In order to develop high performance compact feedwater heater, it is necessary to improve the performances of exit temperature. Its performance depends on the axial-steam velocity condensed onto the water jet surface and heat transfer in the water jet due to turbulence in the water jet. The analysis was conducted by using Star-CD code embedded user subroutine of separate two-phase flow models.

It was confirmed by the CFD analysis, the improvement of the outlet water temperature increase to obtain the high-performance direct-contact heaters that were almost compatible steam pressure and exit water temperature at
each stage. The 4th-stage of jet deaerator exit temperature is saturation temperature of extracted steam of 0.4 MPa. Therefore, it was concluded that the four-stage steam injector is suitable for compact feedwater heater and it will be possible to increase the plant thermal-efficiency.

The comparison exhibited the volume and weight reduction between ABWR and the simplified plant by applying the multistage parallel steam injector for the feedwater heating system, the weight and volume of the feedwater heating system of the simplified plant can be reduced by around one-third, compared with those of ABWR. In addition, plant maintenance and operations will be streamlined, and the competitiveness of nuclear power will be enhanced through improvements in techniques for nuclear power plant simplification and materials saving.

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