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Sizing of Low Pressure Feedwater Heaters for the AM600

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1. Introduction

This paper investigates the design configuration and sizing of the Low-Pressure (LP) FeedWater Heaters (FWHs) for the Advanced Modern 600 (AM600) turbine cycle [1], a Turbine Island design to be coupled with a medium sized nuclear reactor plant in the range of 1800~2000 MWt.

The AM600 is unique to Pressurized Water Reactor (PWR) plants in a way that it is designed for a medium sized reactor but has a single LP turbine rotor. This in turn dictates a single string of FWHs, similar to designs for small to medium sized fossil units.

The number of LP FWH strings is determined by the number of LP turbine cylinders. Until now, for nuclear units, this has resulted in either two (2) or three (3) strings of LP FWHs. In these designs, for a LP FWH Out-Of-Service (OOS) condition (e.g., tube failure), the entire string associated with that FWH is isolated, and the unit then operates with partial bypass flow around the remaining string(s). Under this abnormal operating condition, the remaining string(s) is typically designed to operate with 120% to 150% of the normal tubeside flow. However, in practice, the actual flow is limited as the reactor operates with reduced power until the FWH OOS is returned to service.

For the AM600, the four (4) LP FWHs are all to be located in the condenser neck (Fig. 1), placing a constraint on the sizing of the heaters. The purpose for the current study is to determine optimal LP FWH size which balances maximum allowed power levels with an individual LP FWH OOS with constraints associated with FWH size (diameter), which is determined by the dimensions of the tube bundle coupled with shell side clearance to the bundle.

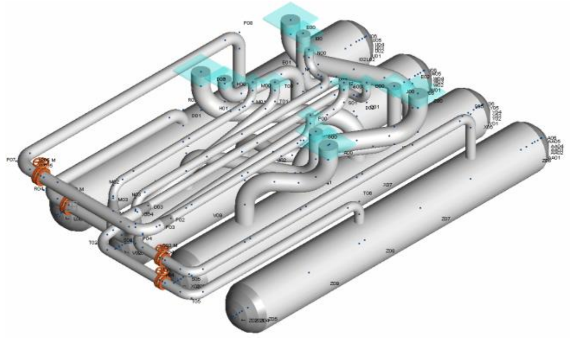

Fig. 1. LP FWH Arrangement in the Condenser Neck

2. Method and Approach

Overall, LP FWH sizing analysis is performed as follows:

1) VWO Operations - Heat balance operating service conditions are determined for normal operation at the Valves Wide Opened (VWO) condition.
2) OOS Operations - Heat balance equipment Out-of-Service (OOS) operating conditions are determined for isolation of individual LP FWHs at the rated power condition.
3) Materials and Tubing Size - LP FWH tube material and size are then based on standard industry practice.
4) Tube Bundle Sizing - The tube bundle is then sized based on VWO flows and industry standards (HEI).
5) Shell Side Nozzle Dimensions - The number and diameter of shell nozzles is then determined using VWO flows and industry standards (HEI).
6) Shell Diameter - The shell-to-bundle clearance is then based on industry standards (HEI) to determine the shell diameter.
7) Steam Velocities - Finally, shell side steam velocities are then checked for the equipment OOS conditions.

Details for the analysis approach are provided in the following sections.

2.1 Heat Balance Analysis

Tubeside - Unlike conventional designs, the limiting flow for the design of the AM600 LP FWH tube side occurs with all FWHs in service. The maximum volumetric flow rates through the tube side of the AM600 LP FWHs occur at full power with maximum Final Feedwater Temperature (FFT) (i.e., minimum enthalpy rise in the Steam Generators (S/Gs)). The volumetric flow rates are then based on the VWO heat balance mass flow rates, pressures, and enthalpies.

With an LP FWH OSS, heat transfer surface area will be removed from service, impairing overall regenerative heating of the condensate and feedwater, slightly reducing the FFT. Fig. 2 shows the bypass arrangement for the case with FWH No. 3 in bypass.

For such bypass conditions, the enthalpy rise in the secondary side of the S/Gs will increase, and the mass and volumetric flow rates will decrease (with or without bypass). Thus the total tube flow area can be based on the VWO condition.

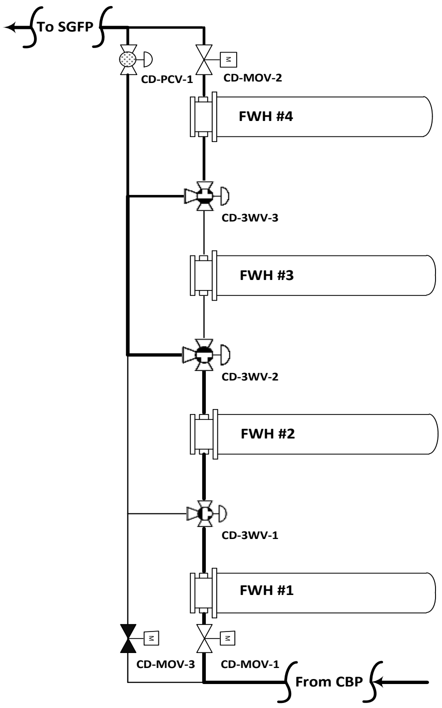

Fig. 2. AM600 LP FWH Bypass Arrangement

Shellside - On the other hand, at full power, shell side steam flow will tend to increase with isolation of the LP FHW OOS. To determine the shell side flow of Extraction Steam (ES), the PEPSE® heat balance software was used to simulate the required operational and design parameters. The analysis reported here aims at establishing the limiting operating power levels of heater out of service (OOS) given the constraints on LP FWH sizing within the condenser neck.

The PEPSE® AM600 Valves Wide Opened (VWO) model for was used as the base model for the evaluation and modified to simulate plant operating and design parameters for an LP FWH OSS. The bypass fraction and operating power level were then parametrically modelled to determine the limiting conditions which could be accommodated within the physical envelope of the condenser neck. The following LP FWH OOS cases were considered in the analysis here.

Table 1. LP FWH OOS Operating Conditions

LP FWH OOS	Operating Power (% Rated)	% Bypass Flow (vs. Rated)
1	100%	30%
2	100%	30%
3	100%	30%
4	100%	30%

2.2 Material Selection

Within the nuclear industry, a consensus has emerged on material selection for FWH tubing. Specifically, ASTM A688 TP304, Dual Rated stainless steel is specified giving a good balance of strength, corrosion resistance, and ductility. This material is also easily inspected using conventional eddy current probes. This is the material specification applied for the design of the AM600 LP FWH tube bundles.

Note that particular attention is required to obtain quality tubing which meets the expectations, above but which goes beyond the explicit requirements of the ASTM specification. A good set of guidelines is provided elsewhere [2].

On the shell side, a combination of Flow Accelerated Corrosion (FAC) resistant carbon steel (0.2% min Cr), Cr-Mo steel, and stainless steels is specified, but this specification is not germane to the considerations here (i.e., the LP FWH dimensions).

2.3 Design Parameters

The design pressure for AM600 LP FWH tubing is established in the hydraulic analysis as 50 bar-g (~720 psig). The industry standard specification of 3/4-in tubing, with a wall thickness of 20 BWG meets the required duty considered here while allowing longer tube support and baffle plate spacing than required for thinner tubing.

Tube side and shell side flows, pressures, enthalpies, and specific volumes for entering and leaving fluids are based on the PEPSE® analysis for the specified bypass flows and operating power level.

2.4 Tube Bundle Arrangement

Fig. 3 illustrates the conventional triangular pitch tube pattern used in virtually all FWHs. Tube layout is defined by the characteristic angle and the corresponding definition of the tube pitch. The 30°, 45°, and 90° layouts are commonly employed but the 60° layout is not considered because its produces lower effectiveness in pressure drop to heat transfer conversion for single phase flow applications and is not generally recommended. The 30° staggered layout has the highest tube density, a very high shell side (condensing) heat transfer coefficient, and a high effectiveness of pressure drop to heat transfer conversion. Therefore, the tube layout for AM600 was selected as the 30º triangular pitch.

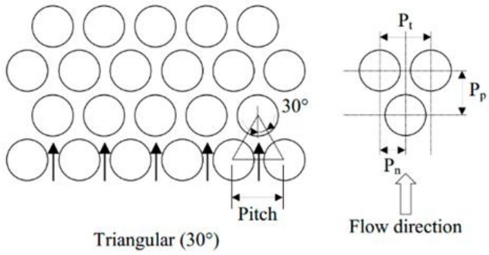

Fig. 3. Tubesheet Standard Pattern

Given the selection of tube diameter above, the standard industry practice to use a pitch-to-diameter ratio of 1.25 is used here.

The flow area for the tube side is based on the limiting tube velocity given by HEI as 10 fps (3 m/s) based on the average density of entering and leaving flow. The volumetric flow for design is based on the VWO heat balance. Finally, a tube plugging allowance of ~5% is applied to the calculated number of tubes from above.

2.5 Shell Dimensions

ES inlet nozzle velocity limits are provided by the Heat Exchange Institute [3]. LP FWH ES inlet nozzles are sized to meet the HEI criterion on velocity (stated using British units) given as:

$$V < 250 / (\text{psia})^{.09} \text{ ft/sec}$$

The shell-to-tube bundle clearance should ensure that the steam distribution dome velocity does not exceed the ES inlet nozzle velocity. This is ensured by requiring the escape velocity into the dome, defined as flow through a flow area for a 45° conical segment between the nozzle penetration point and the impingement plate, not exceed the nozzle velocity. Finally, a minimum distance of 1/4 of the inlet nozzle diameter is set as an overriding criterion. For all LP FHWs, the shell-to impingement plate distance was controlled by the '1/4' criterion.

Once the inner shell diameter is established as described above, additional allowance is included for the shell thickness and for insulation. With application of these dimensions, the outer diameter of the shell for each LP FWH is established.

3. Results and Discussion

3.1 Tubing and Nozzle Calculations

Using the criteria above, the following parameters were established for VWO flows:

Table 2. LP FWH Sizing Parameters

LP FWH	No. 3/4" Tubes (20 BWG)	No. of ES Nozzles	ES Nozzle Size (NPS)
1	1685	4	36
2	1716	2	36
3	1754	2	24
4	1803	1	24

Per typical industry practice, a minimum bend radius of 2-in is used. This permits adequate space for eddy current inspections adjacent to the pass partition plate while limiting wall thinning during the bending process. With the required number of tubes and minimum bend radius, the diameter of the tube bundle can then be determined.

3.2 Shell Diameter

Using the following data: (i) number of tubes per bundle, (ii) tubesheet area per tube, (iii) minimum bend radius, (iv) shell-to-impingement plate distance, (v) shell thickness, and (vi) insulation thickness, the following outer diameter for the LP FWHs was determined:

Table 3. LP FWH Shell Diameter[1] (mm)

LP FWH	Tube Bundle Diameter	Bundle to Shell Clearance (Top)	Shell Diameter
1	~1554	224	2001
2	~1567	224	2017
3	~1583	148	1959
4	~1604	148	1981

1) With allowance for center spacing.

Using these dimensions, the layout of the condenser can now be completed, including layout of the condenser neck area.

3.3 Steam Velocity for LP FWH OOS

Next, the shell side steam velocity for the OOS service condition is checked. It is considered that with FAC resistant materials specified for the ES piping and nozzles, the nozzle velocity criterion can be exceeded for short operating periods. On the other hand, the escape velocity into the steam dome can affect tube vibration, so a check of the escape velocity into the dome is required. Using the PEPSE® results, the escape velocity as a percentage of the recommended velocity is presented below.

Table 4. Escape Velocity vs. Recommended

Escape Velocity[1]	LP FWH OOS			
	1	2	3	4
1	N/A	90%	85%	75%
2	52%	N/A	100%	87%
3	21%	43%	N/A	68%
4	63%	53%	70%	N/A

1) Percent of HEI criterion.

From this result, all cases with LP FWH OOS meet the escape velocity criteria. Final determination ('fine tuning') of operating power levels and bypass fractions must await the final design, but results here indicate that short-term operation is possible for the considered operating conditions.

3.4 LP FWH Length

As the LP FWHs are expected to extend out of both ends of the condenser neck, heater length is not a constraint as related to condenser design. Upfront calculations indicate that overall tube length, and thus overall heat exchanger length for this u-tube configuration is reasonable for purpose and will not be controlling for turbine building dimensioning.

4. Conclusions

The analysis reported here provides a basis for final design of the main condenser for the AM600 turbine island. LP FWH diameters and lengths are reasonable based on past industry experience. With a dimeter of ~2000 mm for each of the four (4) LP FWHs, it is expected that a configuration within the condenser neck can be designed using acceptable engineering practice.

Final determination of limiting operating conditions for OOS operations (i.e., operating power level, and bypass fraction) must await detailed consultation with the LP FWH vendor, but initial estimates provide a basis to expect that high-power levels with an LP FWH OOS can be achieved.

5. References

[1] Field, R. M., *AM600: A New Look at the Nuclear Steam Cycle*, Nuclear Engineering and Technology 49 (2017), pp 621-631.

[2] Pennwell, *Stainless Steel Feedwater and Condenser Tubing – Expectations, Results, and Choices*, Power Generation University, www.powergenu.com.

[3] HEI, *Standards for Closed Feedwater Heaters*, 8th Edition, Heat Exchange Institute, Cleveland, OH, 2009.