Investigation of the equalization capability of submerged perforated sheets for WWER-1500 horizontal steam generator

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Abstract. Non-uniform heat transfer occurs at the steam generator secondary side, thus inducing a non-uniform steam generation and a non-uniform steam flow rate along the evaporation surface. In order to equalize the steam flow rate, submerged perforated sheet is installed in the horizontal SGs. An analysis of the equalization of the non-uniform steam load in the WWER-1500 horizontal steam generator is performed using the STEG calculation code. Variant calculations of various options for the perforation of sheets allowed us to determine the design of submerged perforated sheet, which very well equalizes the initially non-uniform steam load.

1. Introduction

Horizontal steam generators (SGs) are employed in nuclear power plants with Russian-designed water-water energy reactors (WWERs) [1]. A horizontal SG is equipped with horizontal U-tubes, which are mounted between vertical inlet (hot) and outlet (cold) collectors. These collectors are positioned at a short distance relative to the horizontal extensions of the U-tube. As a result, non-uniform heat transfer occurs at the SG secondary side, thus inducing a non-uniform steam generation in the SG and a non-uniform steam flow rate along the evaporation surface. In order to equalize the steam flow rate, submerged perforated sheet (SPS) with an equal degree of perforation of the entire area is installed in the horizontal SGs of VVER-1000. In the new designed more powerful WWER-1500 SGs, the non-uniformity of the steam load increases. The efficiency of the steam load equalization of WWER-1500 SGs was supposed to have been increased using SPS plates of various perforation degrees, which provides equalization of the steam load owing to the flow of the steam–water mixture below the SPS from high load zones to low load zones [2].

To experimentally investigate the possibility of improving the equalization of the non-uniform steam load using a variable perforation SPS, a test facility PGV, which is a model of the horizontal SG, was developed at Electrogorsk Research and Development Center (EREC, Russia). The PGV test facility consists of a submerged perforated sheet, tube bundle, and system for the supply of a non-uniform steam flow rate.

The experimental data obtained at the PGV test facility and the first results of the STEG code validation were presented in [3, 4]. A detailed validation of the STEG code was performed by Le et al. [5] based on all PGV experimental data as well additional data of the regimes comprising a strong non-uniform steam supply.
The results indicated the generally good predictive ability of the STEG code. Tests that comprised the most similar conditions to those of the SG provided fairly good predictions in terms of the standard deviations of the calculated void fractions and pressure drops from the measured data, which were less than 10% and 30%, respectively.

In [6] the study of equalization of non-uniform steam flow using a SPS comprising the same perforation (5.7%) and a SPS comprising variable perforation (on the hot side the degree of perforation is 4.1%, on the cold side it is 8.3%) was carried out for experimental conditions of the PGV test facility. One of the main findings of the STEG code calculations for the SPS comprising variable perforation is the presence of a large flow of steam in the central part of the SPS, where the low degree of perforation (4.1%) on the hot side changes to a large degree of perforation (8.3%), and the steam moving under the SPS from the hot side to the cold side is able to flow up. This phenomenon affects the equalization capability of the SPS. The SPS perforation degrees that improve the equalization of the non-uniform steam load are determined using the STEG code. The use of the SPS comprising a smooth change in degree of perforation made it possible to improve the equalization of the steam load.

In this paper, we analyze the equalization capability of SPSs comprising variable perforation for the WWER-1500 horizontal SG using the STEG code. The optimal distribution of SPS perforation is determined, which provides a good equalization of the non-uniform steam load and reducing the moisture of the steam.

2. Main parameters of WWER-1500 horizontal SG

The WWER-1500 horizontal SG consists of a cylindrical shell in which U-shaped heat transfer tubes arranged in horizontal rows are connected to tubular vertical collectors for the supply (hot collector) and discharge (cold collector) of the heating coolant of the primary loop as shown in figure 1. Main parameters of SG are presented in Table 1 [7].
Figure 1. WWER-1500 horizontal SG: (a) side view, (b) cross-section view. 1 – tube bundle, 2 - submerged perforated sheet, 3 – distribution perforated sheet, 4 – steam collector, 5 - cold collector, 6 - hot collector, 7 -feed water collector, 8 - tube support plates.

Table 1. Steam generator design data.

| Description                                      | Value     |
|--------------------------------------------------|-----------|
| Nominal thermal power (MW)                       | 1062.5    |
| Mass flow rate of steam (t/h)                    | 2151      |
| Steam temperature at SG outlet (°C)              | 289       |
| Inlet coolant temperature to SG (°C)             | 330       |
| Outlet coolant temperature from SG (°C)          | 297.6     |
| Steam pressure at SG outlet (MPa)                | 7.34      |
| Feed water temperature (°C)                      | 230       |
| Steam quality at SG outlet (%)                   | < 0.2     |
| Heat transfer tube parameters:                  |           |
| total number                                     | 15261     |
| outer diameter (OD) (mm)                         | 16        |
| wall thickness (mm)                              | 1.5       |
| arranged type                                    | in-line   |
| distance between axes of rows (mm)              | 22        |
| distance between tubes axes in a row (mm)       | 24        |
| Total heat transfer area (secondary side) (m²)   | 9490      |
| Tubular collector OD (mm)                        | 1455      |
| Geometry parameters of SG shell:                |           |
| inside diameter (mm)                             | 4800      |
| length (mm)                                      | 15620     |
3. Brief description of the STEG code and the interfacial drag model

The STEG (STEam Genarator) code is developed at the Department of NPP of National Research University “Moscow Power Engineering Institute” for modeling hydrodynamic processes in a horizontal SG. The mathematical model of the STEG code is based on a 3D two-fluid model as two inter-penetrating continua, each having its own velocity components, enthalpy, volume fraction, and density at each point in the space domain under consideration. The mathematical model consists of a system of mass and momentum conservation equations for the water and steam phases. In order to close the system of conservative equations, the laws of the interface momentum transfer, tube bundle, and SPS flow resistance are defined. The porous medium concept is used in the simulation of the two-phase flow within the SG tubes. A detailed description of the mathematical model is presented in [5, 6].

4. Result and discussion

To simulate the WWER-1500 SG, a nodalization scheme is developed, as shown in figure 2. Along the longitudinal, transverse and vertical directions, 70, 43 and 47 cells are used, respectively. The typical cell sizes are 4–13 cm. The nodalization is performed with a maximum consideration of the SG’s geometric features.

![Figure 2](image)

**Figure 2.** Nodalization scheme: a) cross-section view, b) top view.
Two options of SPS perforation distribution are analyzed. SPS-1 was proposed in [2] based on an approximate calculation method. SPS-2 is proposed in the present study. We performed variant calculations using different distributions of SPS perforation degree, and as a result, SPS-2 was the best. The arrangement of plates with various degrees of perforation for these two variants of SPS is shown in figure 3.

Figure 3. Distribution of SPS perforation degree: a) SPS-1, b) SPS-2

Figure 4 shows the vertical velocity distribution at the evaporation surface for two SPSs. For SPS-1, on the hot side of the steam generator, a significant region of sufficiently high steam velocities of 0.5–0.7 m/s is observed. On the cold side, in the case of SPS-1, velocities are noticeably lower and do not exceed 0.3 m/s. SPS-1 gives a steam moisture at the SG outlet of 0.13%. It can be seen that the SPS-2 provides a more uniform steam output at the evaporation surface compared with SPS-1. As a result of this, for the case of using the SPS-2, the moisture value at the SG outlet is obtained three times less compared to SPS-1.

Thus, in this paper, an analysis of the equalization of the non-uniform steam load in the WWER-1500 horizontal SG was performed using the STEG calculation code. First, the SPS proposed in [2] was considered. It provides the required steam moisture at the outlet of the SG (0.13%). However, variant calculations of various options for the perforation of SPSs allowed us to determine the design of SPS, which significantly better evens the initially non-uniform steam load. In this case (SPS-2) the steam moisture at the SG outlet is 0.42%, which is almost 5 times less than the limiting value of 0.2%.
**Figure 4.** Distribution of the steam vertical velocity at the evaporation surface: a) SPS-1, b) SPS-2.

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