Analysis of experimental data on the hydrodynamics in a horizontal steam generator using the STEG code

Thanh Tung Le, V I Melikhov, O I Melikhov and A A Nerovnov
National Research University “Moscow Power Engineering Institute”,
Krasnokazarmennaya 14, Moscow 111250, Russia
Email: vladimir.melikhov@erec.ru

Abstract. The new model of interfacial drag is proposed and implemented in the STEG code based on the 3D two-fluid model is presented. Experimental data obtained at the PGV test facility is used for validation of the modified STEG code. The PGV test facility comprises a model of the horizontal steam generator used for Russian type water-water energetic reactors. A quantitative comparison with experimental values of void fractions has been performed. It can be argued that the results generally indicate the relatively good predictive ability of the modified STEG code.

1. Introduction
The most important equipment of nuclear power plants with Russian-designed water-water energy reactors (WWERs) are horizontal steam generators (SGs) designed for heat removal from the coolant of the primary loop and generating dry saturated steam. The operation of a nuclear power plant largely depends on the efficiency of the SG. One of the main factors in determining the acceptability of the SG’s characteristics is the quality of the generated steam. The deterioration of steam quality, i.e. the increase in its moisture content and the increase in the quantity of impurity, leads to the erosion of turbine blades. The quality of the generated steam depends on several factors, but primarily on the design features of the SG and its separation devices.

The peculiarity of the horizontal SG is the presence of hot and cold sides of the heat-exchange tube bundle, which causes a non-uniformity of the steam load at the evaporation surface. A submerged perforated sheet (SPS) is employed to equalize the steam load in the WWER-1000 SG in order to facilitate the use of a gravitational separation scheme. The SPS is an equalizing distribution device with a high coefficient of hydraulic resistance that is determined by its degree of perforation. SPS plates with an equal degree of perforation of the entire area are employed in the WWER-1000 SG. In the new designed more powerful WWER-1200/1500 SGs, the non-uniformity of the steam load increases. The efficiency of the steam load equalization of WWER-1200/1500 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 [1]. 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) [2, 3].

Attempts to numerically simulate experiments at the PGV test facility using the 3D thermal-hydraulic code STEG (a description of the code is given below) showed that the results significantly
depend on the models of interfacial drag force. In this paper, we propose a new model of interfacial drag force for the STEG code, which allows us to achieve good agreement with the experimental data on the hydrodynamics of a horizontal steam generator obtained at the PGV test facility.

2. Brief description of the STEG code and the interfacial drag model

The STEG (STEnn Generator) code [4] 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]. The key to the correct description of the hydrodynamics of the 3D flow of the steam-water mixture in the SG volume is the interfacial drag model. Existing models do not allow for satisfactory agreement with available experimental data.

Analysis of experimental data on hydrodynamics in a horizontal SG allows us to identify the following characteristic regions.

Region I: Tube bundle. In tube bundles, the steam void fraction varies from 0 to 0.7-0.8. Bubbly, churn-turbulent and annular-mist (liquid film at tube surface) flows are observed.

Region II: Corridors. Experimental data show that the values of a void fraction in the corridors are less than 0.5. The bubbly flow dominates in this region, and the size of the bubbles varies greatly (10-40 time).

Region III: The region from the top of the tube bundle to the SPS. In this region, the values of the steam void fraction are in the range of 0.5–1.0, which corresponds to the churn-turbulent and mist flow regimes.

Region IV: The bubbling layer above the SPS and steam region. At the initial section of the bubbling layer the steam jets flowing out of the SPS holes are fragmented into bubbles of various sizes. These bubbles are then bubbled upwards in a stabilized middle section of the bubbling layer, where the values of a void fraction are in the range of 0.3–0.5, and the bubble size varies quite significantly. After the bubbling layer, at the evaporation surface the steam leaves the bubbling layer, capturing droplets of moisture and enters the steam region. The water droplets settle down under the influence of gravity.

In this paper, we propose the interfacial drag model based on the characteristics of the steam-water mixture flow in spatial regions described above.

The interfacial drag force per unit volume $M_{id}(N/m^3)$ is given by:

$$M_{id} = 0.75 \frac{C_D}{D_p} \cdot \rho_c \alpha_d \cdot \left| \vec{V}_r - \vec{V}_c \right|,$$

(1)

here $C_D$ – drag coefficient, $D_p$ – particle diameter (m), $\rho_c$ – density of continuous phase (kg/m$^3$), $\alpha_d$ – void fraction of dispersed phase, $\vec{V}_r = \vec{V}_d - \vec{V}_c$ – relative velocity (m/s), $\vec{V}_d$ – velocity of dispersed phase (m/s), $\vec{V}_c$ – velocity of continuous phase (m/s).

For the two-phase mixture flow across the tube bundle, the interfacial drag correlation developed in [7] is used. This correlation is confirmed by experimental data in a wide range of parameters. Flow map consists of bubbly (0$\leq\alpha\leq$0.3) and churn-turbulent (0.3$<\alpha<1$) flows. The drag coefficient of the bubbly flow is given by the modified Ishii and Zuber correlation:

$$C_D = 0.267 \cdot \left( \frac{g \Delta \rho}{\sigma} \right)^{0.5} \left( \frac{1+17.67 f(\alpha)/6}{18.67 f(\alpha)} \right)^2,$$

(2)
where \( g \) - gravity (m/s²), \( \Delta \rho \) - density difference (kg/m³), \( \sigma \) - interfacial tension (N/m²), \( f(\alpha) = (1 - \alpha)^{1.5} \).

For describing the drag coefficient of churn-turbulent flow, a new correlation is used with the same functional form, as the CATHARE code (France).

\[
\frac{C_d}{\rho_p} = 1.487 \left( \frac{g \Delta \rho}{\sigma} \right)^{0.5} (1 - \alpha)^3 (1 - 0.75\alpha)^2
\]

(3)

In other regions not occupied by tubing, the new interfacial drag model is proposed, generally based on the Ishii-Zuber approach [8], but having a specificity related to consideration of the cap bubbly flow.

Assume that for the void fraction values \( 0 \leq \alpha \leq 0.5 \) the dispersed phase is bubbles, as well as small bubbles (distorted bubbles – Group-1) and large bubbles (cap bubbles – Group-2).

The Group-1 and Group-2 void fractions are given by model developed in [9].

\[
\alpha_{g1} = \begin{cases} 
\frac{\alpha}{0.5 - \alpha} & \text{if } \alpha \leq 0.25 \\
0.5 - \alpha & \text{if } 0.25 < \alpha \leq 0.5 
\end{cases}
\]

(4)

\[
\alpha_{g2} = \alpha - \alpha_{g1}
\]

(5)

According to these formulae, for the void fraction \( 0 \leq \alpha \leq 0.25 \) there are only small bubbles of the Group-1, and for the void fraction \( 0.25 \leq \alpha \leq 0.5 \) the Group-1 void fraction linearly decreases to 0, at \( \alpha = 0.5 \) there are only the Group-2 bubbles.

In the region of the low void fractions (\( \alpha \leq 0.2 \)) the shape of bubbles is assumed to be spherical, the average diameter of the spherical bubbles is given by the capillary length (\( R_p = La, La = \sqrt{\sigma/\left(\Delta \rho \cdot g\right)} \)) and the drag coefficient should be given as function of Reynolds number (viscous regime):

\[
\frac{C_{d1}}{\rho_p} = \frac{24}{Re_p} (1 + 0.15 \cdot Re_p^{0.67})
\]

(6)

where \( Re_p = \rho_f D_p |V_r|/\mu_f \) - Reynolds number, \( D_p = 2R_p \) - bubble diameter, \( \mu_f \) - viscosity of liquid (Pa·s).

As the void fraction increases, owing to coalescence the size of the Group-1 bubble is increased and the bubbles become distorted shape. In this regime (distorted-particle regime), the drag coefficient depends on the diameter of the bubbles, the properties of the medium, but is independent of velocity and viscosity

\[
\frac{C_d}{\rho_p} = \frac{2}{3} \left( \frac{g \Delta \rho}{\sigma} \right)^{0.5} \left( 1 + 17.67 \cdot (1 - \alpha_{g1})^{1.3} \right)^2
\]

(7)

It is assumed that the large bubbles of the Group-2 have an average diameter \( D_p = 40La \), and the drag coefficient is determined by the following formula:

\[
\frac{C_d}{\rho_p} = \frac{8}{3} (1 - \alpha)^2
\]

(8)

The interfacial drag force between the Group-1 bubbles, Group-2 bubbles and liquid per unit volume, \( M_{id} \) (H/m³), is determined as follows:

\[
M_{di} = 0.75 \left( \frac{C_{d1}}{\rho_p} \right)^{(1)} \rho_f \alpha_{g1} V_{r1}^2 + 0.75 \left( \frac{C_{d2}}{\rho_p} \right)^{(2)} \rho_f \alpha_{g2} V_{r2}^2,
\]

(9)

where \( \rho_f \) - density of liquid, \( V_{r1} = V_{g1} - V_f \) - relative velocity of the Group-1 bubbles, \( V_{r2} = V_{g2} - V_f \) - relative velocity of the Group-2 bubbles.

In the range of the void fraction values from 0.5 to 0.7, the churn-turbulent flow is implemented. For this regime, the drag coefficient and the average churn bubble diameter is defined as:

\[
\frac{C_d}{\rho_p} = \frac{8}{3} (1 - \alpha)^2, \quad D_p = 4La
\]

(10)
The dispersed flow is observed in the range of high void fractions ($\alpha \geq \alpha_c = 0.8 \div 0.9$). The average droplet diameter should be given by [10]

$$D_p = 1.67 \cdot L_a \left( \frac{j_{ge}^2 \rho_g \Delta \rho}{\sigma} \right)^{0.42} \cdot \left( \frac{\rho_g}{\rho_f} \right)^{0.29},$$

(11)

where $j_{ge}$ - steam superficial velocity at the evaporation surface (m/s).

If the diameter of droplets exceeds a critical value

$$D_p > D_{crit},$$

(12)

so the droplets have distorted shape, accordingly, the drag coefficient is defined as

$$\frac{C_D}{D_p} = \frac{2}{3} \left( \frac{g \Delta \rho}{\sigma} \right)^{0.5} \left( \frac{1 + 17.67 \cdot (1 - \alpha_g)_{1.13}}{18.67 \cdot (1 - \alpha_g)_{1.15}} \right)^2$$

(13)

For this case, the critical void fraction ($\alpha_c$) is equal 0.8.

When the diameter of droplets is less than the critical value

$$D_p < D_{crit},$$

(14)

the droplets become to spherical particles and there is a viscous flow regime.

$$C_D = \frac{24}{Re_p} \left( 1 + 0.1 \cdot Re_p^{0.75} \right), Re_p = \frac{\rho_g \rho_d |V_r|}{\mu_m}, \mu_m = \frac{\mu_g}{(1 - \alpha_f)}$$

(15)

For this regime: $\alpha_c = 0.9$.

Here the critical diameter is given by

$$D_{crit} = 69.3 \left( \frac{\rho_g \Delta \rho}{\mu_g^2} \right)^{-1/3}$$

(16)

3. PGV test facility

The PGV test facility is a two-dimensional slice of the WWER-100 horizontal SG; it is placed in a 1670-mm diameter high-pressure vessel, as shown in figure 1. The length and width of the lower part of the test facility are 2450 and 100 mm, respectively. The vertical dimensions of the test facility are taken as full-scale. The main technical characteristics of the test facility: pressure – 7 MPa; the mass flow rate of the steam – 4-8 t/h.

The separation scheme of the test facility consists of the submerged perforated sheet (SPS) installed in the lower part of the test facility, and a distribution perforated sheet (DPS) installed at the top of the test facility, which has a perforation degree of 4.5%. Two variants of the SPS were used: 1) with a uniform degree of perforation (5.7%) and 2) with a non-uniform degree of perforation (left side 4.1%; right side 8.3%).

The two-phase hydrodynamics in the upper part of the SG is simulated at the test section, starting from the upper rows of the tube bundle to the distribution perforated sheet. The heat exchange from the coolant of the primary loop to the boiler water of the secondary loop is not modeled, i.e., the steam is not generated at the surface of the tube bundle. The steam generation is simulated by the steam supply into the lower part of the test section via the steam collector. The steam supply collector is partitioned into two parts with a separate supply of heating steam in order to simulate the non-uniform distribution of mass steam flow rate along the cross-section of the test facility. In the lower part of the test facility, a tube bundle simulator consisting of three rows of tubes with an outer diameter of 16-mm, is installed.

The void fractions below and above the SPS ($\varphi_1-\varphi_4$), behind the bead ($\varphi_5$), as well as the pressure drop along the SPS at four locations ($\Delta \varphi_1, \Delta \varphi_2, \Delta \varphi_3, \Delta \varphi_4$), are measured.

The operation of the test facility is summarized as follows. At a given water level, the supplied steam is introduced to the steam collector located at the bottom of the facility. The steam from the
steam collector passes through the tube bundle and enters the space under the SPS. In the space under the SPS, the steam spreads because of hydraulic resistance of SPS. It spreads through the holes to the water layer above the SPS and thereafter into the steam volume of the model. In the steam volume, the steam is separated and then enters through the holes of the distribution perforated sheet into the outlet collector. Water is drained from the SPS in the right end through the gap between the facility wall and the 100-mm wide bead.

![Figure 1. Test section.](image)

### 4. Result and discussion

The calculations of four series of experiments were performed: 1) series "1:1" (uniform steam supply along the length of the test facility, steam flow rate was varied in the range of 4–8 t/h; 2) series "3:1" (non-uniform steam supply: 5.3 t/h on the hot side and 1.8 t/h on the cold side); 3) series "2:0" (very non-uniform steam supply: 4 t/h on the hot side, and 0 on the cold side); 4) series "0:2" (very non-uniform steam supply: 0 on the hot side and 4 t/h on the cold side). The calculations were performed using different interfacial drag models: 1) TRACE [11], 2) Simovic et al. [7] and 3) the «STEG2020» model. As an example, figure 2 shows the prediction of the void fractions below the SPS for the test P2.1 with a uniform steam supply and the uniform perforation degree of the SPS (5.7%). It is clearly seen that the new correlation «STEG2020» provides results very close to the experimental data.

Figure 3 shows a comparison of the experimental and predicted void fractions for all of the tests. The use of the new correlation «STEG2020» in the STEG code significantly improves the quality of experimental simulations. The standard deviations from the experimental data of the STEG code calculations using different interfacial drag models are: 34% (TRACE), 17% (Simovic et al.) And 8% (correlation «STEG2020»).

Thus, in this paper, the new model of interfacial drag is proposed and implemented in the STEG code. Experimental data obtained at the PGV test facility is used for validation of the modified STEG code. The PGV test facility comprises a model of the horizontal steam generator used for Russian type water-water energetic reactors. A quantitative comparison with experimental values of void fractions has been performed. It can be argued that the results generally indicate the relatively good predictive ability of the modified STEG code.
Figure 2. Void fraction below the SPS in the locations of the sensors $\phi_1$, $\phi_2$, $\phi_5$.

Figure 3. Void fraction prediction.

Acknowledgments
The reported study was funded by the Russian Foundation for Basic Research (RFBR), project number 18-08-01159.
References

[1] Trunov N B, Sotskov V V, Ageev A G and Vasilieva R V 2006 Approximate method for calculating the variable perforation of a submerged perforated sheet of a horizontal steam generator Voprosy atomnoy nauki i tekhniki (Issues of Nucl. Sci. and Technol.) 15 pp 89–99 [In Russian]

[2] Blinkov V N, Elkin I V, Emelianov D A, Melikhov V I, Melikhov O I, Nikonov S M, Parfenov Yu V and Nerovnov A A 2015 The influence of void fraction on the submerged perforated sheet hydraulic friction factor Therm. Eng. 62 484–9

[3] Blinkov V N, Elkin I V, Emelianov D A, Melikhov V I, Melikhov O I, Nikonov S M, Parfenov Yu V and Nerovnov A A 2016 Influence of non-uniformity of the submerged perforated sheet on steam demand leveling on the evaporation surface of a WWER steam generator Therm. Eng. 63 51–5

[4] Melikhov V I, Melikhov O I, Nigmatulin B I 1995 Numerical modeling of secondary side thermal hydraulics of horizontal SG Proc. of 3rd Int. Seminar on Horizontal Steam Generators vol 2 (Lappeenranta, Finland) pp 249–70

[5] Melikhov V I, Melikhov O I, Parfenov Yu V and Nerovnov A A 2011 Simulation of the thermal-hydraulic processes in the horizontal steam generator with the use of the different interfacial friction correlations Sci. Technol. Nucl. Install. 2011 Article ID 181393

[6] Le T T, Melikhov V I, Melikhov O I, Nerovnov A A and Nikonov S M 2020 Validation of the STEG code using PGV experiments on hydrodynamics of horizontal steam generator Nucl. Eng. Des. 356 110380

[7] Simovic Z R, Ocoljic S and Stefanovic V D 2007 Interfacial friction correlations for the two-phase flow across tube bundles Int. J. Multiphase Flow 33 217–26

[8] Ishii M and Zuber N 1979 Drag coefficient and relative velocity in bubbly, droplet or particulate flows AIChE J. 25 843–55

[9] Ozar B, Dixit A, Chen S W, Hibiki T and Ishii M 2012 Interfacial area concentration in gas–liquid bubbly to churn-turbulent flow regime Int. J. Heat Fluid Flow 38 168–79

[10] Ageev A G, Belov V I and Vasilyeva R V 1988 Experimental and analytical study of limit loads under gravitational separation Thermo-hydrodynamic processes in the elements of power equipment of power plants, Collection of scientific papers ENIN (Moscow) 41–5 [In Russian]

[11] TRACE V5.0 2007 Theory Manual. Field Equations, Solution Methods and Physical Models (U.S. Nuclear Regulation Commission, Washington)