Simulation of the two-phase flow across tube bundle

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Abstract. Experiments on two-phase flow across an in-line tube bundle are analyzed with the STEG code, which has been developed for modeling thermal-hydraulic processes in a horizontal steam generator (SG). An adiabatic, vertical two-phase flows of air-water across horizontal in-line, 5 x 20 rod bundles, with a pitch-to-diameter ratio P/D=1.3 are considered, the mass velocity is varied in the range 27 - 818 kg/m$^2$s. The calculated values of void fraction in the tube bundle are compared with the experimental ones measured by a gamma densitometer. A reasonable agreement between the calculations and the experimental data is obtained.

1. Introduction
Nuclear power plants with Russian-designed water-water energy reactors (WWER) are one of the most popular nuclear power plants in the world. The most important equipment of NPP with WWER is a horizontal steam generator (SG), which is designed for heat removal from the coolant of the primary loop and generating dry saturated steam [1]. The operation and efficiency of an NPP essentially depend on the efficiency of the SG. A lot of works have been devoted to the modeling of thermohydraulic processes occurring in a horizontal SG. The degree of reliability of the simulation results is determined, first of all, by the quantity and quality of the calculation code validation against experimental data on hydrodynamic processes occurring in the horizontal SG. The STEG code is designed to simulate thermal-hydraulic processes in horizontal SGs and has been validated in several experiments [1, 2]. The purpose of this work is to validate the STEG code on experiments [3-5] on the two-phase flow of air-water across tube bundle, which is one of the most important thermohydraulic phenomena. The correct description of this phenomenon requires adequate correlations for pressure losses of two-phase flow and interfacial drag resistance.

2. Brief description of the STEG code
The STEG (STEam Generator) code [1] is developed at the Department of Nuclear Power Plants of National Research University “Moscow Power Engineering Institute” for modeling hydrodynamic processes in a horizontal SG. This code is based on a 3D two-fluid model. According to this model, each phase uses its own velocity components, enthalpy, volume fraction, and density to describe the flow of water and the flow of steam. The mass, momentum, and energy balances are formulated for each phase. To close the system of equations, relations for interfacial friction force and interfacial drag each phase with tube bundle and wall are used. The SG tubes are considered as porous medium. The interfacial drag resistance as well as the shear coefficients of water and steam with tube bundle is described by semi-empirical correlations.
The two-phase flow considered in this study is adiabatic when the phase temperatures are at the saturation line. The interfacial heat transfer could therefore be neglected. For brevity, the energy equations and terms related to phase change as well as the correlations for heat transfer are not provided herein.

2.1. Conservation equations

Mass conservation:

Water

$$\frac{\partial \alpha_1 \rho_1}{\partial t} + div(\alpha_1 \rho_1 \vec{V}_1) = M_{s1}$$  \hspace{1cm} (1)

Steam

$$\frac{\partial \alpha_2 \rho_2}{\partial t} + div(\alpha_2 \rho_2 \vec{V}_2) = M_{s2}$$  \hspace{1cm} (2)

Momentum conservation:

Water

$$\alpha_1 \frac{d \rho}{dz} = -\alpha_1 \rho_1 g + F_{21} - F_{31}$$  \hspace{1cm} (3)

Steam

$$\alpha_2 \frac{d \rho}{dz} = -\alpha_2 \rho_2 g - F_{21} - F_{32}$$  \hspace{1cm} (4)

Here $p$ – pressure, $\alpha_1$ and $\alpha_2$ are the volume fractions of the liquid and gas phases, $\rho_1$ and $\rho_2$ are the densities of the liquid and gas phases, $g$ is the acceleration of gravity, $F_{21}$ – gas-liquid interfacial friction force, $F_{31}$ – liquid-tubes flow resistance, $F_{32}$ – gas-tubes flow resistance, $M_{s1}$ and $M_{s2}$ - mass source terms of water and steam.

2.2. Interfacial drag

In order to calculate the interfacial drag in this work, we used the Simovich method [6].

In this method, a set of two-phase interfacial drag correlations was proposed for application to gas-liquid flows across tube bundles.

The interfacial drag force per unit volume is calculated from the following equation:

$$\vec{F}_{12} = \frac{3}{4} \alpha_2 \rho_1 \frac{C_D}{D_p} \Big| \vec{V}_2 - \vec{V}_1 \Big| (\vec{V}_2 - \vec{V}_1)$$  \hspace{1cm} (5)

Where $C_D$ – interfacial drag coefficient, $D_p$ - dispersed bubble diameter, $V_1$ - liquid velocity and $V_2$ – gas velocity,

The coefficient $C_D$ is related to the coefficient $C_{12}$ as follows:

$$C_{12} = \frac{3}{4} \alpha_2 \rho_1 \frac{C_D}{D_p}$$  \hspace{1cm} (6)

In the above equation, the coefficient $C_{12}$ is interfacial shear coefficient.

The Simovich model, to calculate the ratio of the interfacial drag coefficient $C_D$ to the dispersed bubble diameter $D_p$, is considering two types of flow:

For void fractions $\varphi \leq 0.3$, which correspond to bubbly flow:
\[
\frac{C_D}{D_p} = 0.267 \cdot k(\alpha_{\text{tubes}}) \left( \frac{g \Delta \rho}{\sigma} \right)^{1/2} \left( \frac{1 + 17.67f(\varphi)^{6/7}}{18.67f(\varphi)} \right)^2
\]

Where

\[
f(\varphi) = (1 - \varphi)^{1.5}
\]

\[
k(\alpha_{\text{tubes}}) = \begin{cases} 
1.0 & \text{if } \alpha_{\text{tubes}} \geq 0.1 \\
2.5 & \text{if } \alpha_{\text{tubes}} < 0.1
\end{cases}
\]

For void fractions \(\varphi > 0.3\), which correspond to churn-turbulent flow:

\[
\frac{C_D}{D_p} = 1.487 \cdot k(\alpha_{\text{tubes}}) \left( \frac{g \Delta \rho}{\sigma} \right)^{1/2} (1 - \varphi)^3 (1 - 0.75\varphi)^2
\]

The gas-phase void fraction is as follows:

\[
\varphi = \frac{\alpha_2}{\alpha_1 + \alpha_2}
\]

### 2.3. Tube bundle pressure drop

A correlation based on the Chisholm-Laird equation with the Lockhart-Martinelli parameter is used to calculate the total pressure drop of a two-phase flow across a tube bundle.

The frictional two-phase pressure drop:

\[
\Delta P_{\varphi} = \Delta P_l \cdot \varphi_l^2
\]

\[
\varphi_l^2 = 1 + \frac{C}{x_{tt}} + \frac{1}{x_{tt}^2}
\]

\[
\Delta P_l = \xi_0 \rho_l \frac{W_{\text{omax}}^2}{2}
\]

\[
x_{tt} = \left( \frac{1 - X}{X} \right)^{1.8} \left( \frac{\rho_d}{\rho_l} \right) \left( \frac{\mu_l}{\mu_g} \right)^{0.2}
\]

Here \(\varphi_l^2\) – two-phase friction multiplier, \(X\) – quality, \(x_{tt}\) – the Lockhart – Martinelli parameter, \(\Delta P_l\) – the pressure drop for the liquid phase, and \(\xi_0\) is single-phase loss coefficient of tube bundle.

Coefficient \(C\) depends on the geometry of the tube bundle and flow parameters. Coefficient \(C\) for in-line arrangement tube bundle and \(P/D = 1.3\) is obtained from the following equation:

\[
\begin{cases} 
\text{if: } G \geq 200 \frac{kg}{m^2s} \rightarrow C = 8 \\
\text{if: } G \leq 100 \frac{kg}{m^2s} \rightarrow C = 70 \\
\text{if: } 100 < G < 200 \frac{kg}{m^2s} \rightarrow C = \text{determined by interpolation}
\end{cases}
\]

### 2.4. Tube bundle arrangement

The tube bundle is modeled using its proportion in the control volumes where the tubes are placed.

Volume fraction balance:
\[ \alpha_1 + \alpha_2 + \alpha_{\text{tubes}} = 1 \] (17)

Where \( \alpha_{\text{tubes}} \) is tubes volume fraction.

3. Description of the test section and input parameters:

The test section and the tube bundle model schematic are shown in Figure 1 [3]. Water enters the channel from below and air enters the channel through the nozzle on the right. The mixture of water and steam enters homogeneously to the tube bundle after passing through the flow straightener plates. The tube bundle has an in-line arrangement of 20×5.

![Figure 1. Test section and the tube bundle model schematic](image)

The range of input parameters is presented in Table 1.

| Parameter                          | Value       | Unit       |
|------------------------------------|-------------|------------|
| Pitch tube bundle                  | 24.7        | mm         |
| Diameter of pipes                  | 19          | mm         |
| Mass velocity based on minimum flow area | 27-818  | kg/m².s   |
| Pressure                           | 101-180     | kPa        |
| Quality                            | 0-0.33      | -          |
| Water density                      | 998.26      | kg/m³      |
| Air density                        | 1.25        | kg/m³      |
| Channel flow area                  | 0.00988     | m²         |
4. Results and discussion
As mentioned, calculations were performed for two-phase adiabatic flow. The average gas-phase void fraction was performed for different values of mass velocity and quality. The deviations of the calculated values from the experimental values were determined by the mean absolute deviation (MAD), which is defined as follows:

\[
\text{MAD} = \frac{1}{N} \sum_{i=1}^{N} |\varphi_{\text{exp},i} - \varphi_{\text{calc},i}| \times 100
\]  

(18)

All MADs are presented in Table 2.

Table 2. Mean absolute deviations of void fractions

| Mass velocity based on minimum flow area | MAD % |
|----------------------------------------|-------|
| kg/m².s                                 |       |
| 27                                      | 2.084 |
| 77                                      | 3.225 |
| 96                                      | 2.449 |
| 151                                     | 2.030 |
| 262                                     | 2.292 |
| 348                                     | 2.043 |
| 503                                     | 3.877 |
| 599                                     | 3.775 |
| 696                                     | 3.981 |
| 818                                     | 4.124 |

For low mass velocities (G ≤ 348 kg/m².s), there is a good match between the calculated and experimental values of void fraction. MADs are about 2-3%. Characteristic dependences of void fraction relative to quality in this range of mass velocities are shown in Figure 2, a, b. With an increase in the mass velocity (348 kg/m².s < G ≤ 818 kg/m².s), the coincidence between the calculated and experimental values decreases slightly, and MADs are around 4%. As shown in Figure 2 c, d in this range of mass velocities at low values of steam quality (<0.001), the STEG code underpredicts experimental values, and here local deviations reach 8-11%.

![Graph a) G=27 kg/m².s](image1.png)

b) G=348 kg/m².s
c) $G=503 \text{ kg/m}^2\text{s}$

d) $G=818 \text{ kg/m}^2\text{s}$

**Figure 2.** Void fraction data and quality for different values of mass velocity

It should be noted that the accuracy of prediction of void fraction using the Simovich correlation was estimated by the authors [6] as ± 8%. However, in Figure 3 of [6], it can be seen that in the range of experimental values of the void fraction 0.2-0.3, the Simovich correlation for the in-line tube bundle gives a prediction error of 10-12%, which is consistent with our results. Taking into account the error in the experimental determination of the void fraction, which according to [3-5] is ± 5%, it can be concluded, that the STEG code simulates experiments [3-5] rather well. However, in the future, it is necessary to improve the description of interfacial friction in the range of high mass velocities and low vapor qualities.

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