Study of hydrodynamic processes in a two-phase layer above a submerged perforated sheet

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Abstract. To study the hydrodynamics of a two-phase flow over a submerged perforated sheet (SPS) and the entrainment of water droplets from the water-air interface, a "Bubbler" installation was built. The main observation tool was video recording of the process followed by data analysis. An SPS with two holes was used. Three experiments were performed with different air flow rates. A general picture of air flow was established: the rise of bubbles in the water volume under the SPS, the formation of an air blanket, air bubbling in the layer of water above the SPS, the formation and jump of water drops upward. For each air flow rate, the size of the bubbles in the two-phase layer and the size of the resulting droplets were determined. It was found that with increasing air flow, these parameters increase.

1 Introduction

The main purpose of a horizontal steam generator (SG) installed at nuclear power plants comprising Russian-designed water–water energy reactors (WWERs) is to generate a given amount of saturated steam, which then enters the turbine, where the expanding steam rotates the turbine blades, resulting in the generation of electricity [1]. In this regard, serious requirements are formulated on the moisture of the steam leaving the SG in order to prevent erosive wear of the turbine blades. To ensure the required moisture value in horizontal SGs, a gravitational separation scheme is used [2], based on a noticeable difference in the specific weights of steam and water, which allows a significant number of quiet large drops of water, carried upward by the steam flow from the evaporation surface, to return there again. Only a small number of droplets approach the steam outlet tubes, the mass of which is so small that gravitational forces cannot overcome the dynamic flow of the steam flow. However, in a horizontal SG, steam is generated non-uniformly: near the hot input collector, the amount of generated steam is greatest, and near the cold output collector, it is the least. Such non-uniformness of the steam load on the evaporation surface reduces the efficiency of gravitational separation, since in this case the height of the steam volume required to provide a given value of steam moisture must be determined by the highest steam velocity, which is localized in the area of the hot collector, although for the

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rest of the evaporation surface it is so significant no height needed. Therefore, it is advisable to equalize the steam load on the evaporation surface. For this purpose, a submerged perforated sheet is installed, which is a device with a high coefficient of hydraulic resistance, which helps equalize the steam load.

Currently, semi-empirical correlations developed on the basis of available experimental data are used for practical determination of steam moisture. The first such correlation was proposed by Kruzhilin. [3]. He assumed that drops on the evaporation surface are formed due to the kinetic energy of the steam flow, and, using the similarity laws, he obtained an expression for moisture depending on other parameters; the values of the coefficients in this expression were found by fitting them with experimental data. Sterman [4] used a similar approach, but took into account a larger number of factors, and also used significantly more experimental data on entrainment when developing the correlation. The correlation he obtained remains significant to this day. Kataoka and Ishii [5] developed a set of correlations based on a mechanistic approach, in which they tried to take into account known laws for key separation phenomena (the physics of droplet formation, their distribution of sizes and velocities on the evaporation surface and the movement of droplets in a vapor flow) and to validate the expressions they obtained, they used all experimental data known at that time on moisture entrainment for water-air and steam-water mixtures. It was shown in [6] that the Kataoki-Ishii correlation predicts experimental data on moisture entrainment better than other correlations. We also note the paper [7], in which, based on the analysis of experimental data, an empirical correlation was obtained for moisture entrainment, applicable for various regimes of two-phase flow (from bubble to churn-turbulent flows), for various geometric conditions and in a wide range of superficial steam velocities (from 0. 05 m/s to 5 m/s).

Despite the existence of correlations, to calculate moisture entrainment it is also necessary to develop gravity separation models based on a completely mechanistic approach (“from first principles”). In [8], a separation model was proposed, implemented in the STEG code, but the movement of droplets in the steam volume was modeled in a simplified manner. In [9, 10], the Lagrangian model of droplet motion was introduced into the CFD codes; as a result, the main features of steam flow in the steam volume of a SG were established and the trajectories of droplets of various sizes were determined. However, the main uncertainties in developing a separation model are associated, first of all, with the parameters of the droplets formed on the evaporation surface: the diameter of the droplet and its initial velocity. There are experimental studies (see review [6]) in which these values were determined in one way or another, but directly for the conditions of a two-phase flow in a horizontal SG, when the evaporation surface is preceded by a submerged perforated sheet, which affects the size of the formed bubbles, similar studies was not carried out. This paper presents the results of a study of the dynamics of droplet detachment from the interface surface using an experimental setup simulating the geometry of a horizontal SG.

2 Materials and methods

To study the hydrodynamics of a two-phase flow under and above the SPS, a “Bubbler” installation was built, Figure 1. The test section of this installation has the shape of a parallelepiped with dimensions of 690x300x1000 mm with transparent glass walls. In the lower part of the test section, three distribution boxes with dimensions of 200x200x100 mm are installed for air supply, with varying degrees of perforation. In the middle part, a perforated sheet measuring 600x300 mm with two holes with a diameter of 13 mm was installed. A bead with a depth of 200 mm is attached to the perforated sheet; there is a 45 mm gap between the wall of the test section and the bead.

Compressed air from the air preparation and supply system is supplied to the distribution manifold, then through three pipelines it is supplied to the perforated boxes of the test section.

The measurement system of the “Bubbler” installation includes differential pressure sensors on the SPS (Sapfir-22M-DD-2430) and flow meters for measuring air flow (Mass-Stream D-6270/6250). Photo and video recording was used to record the process.

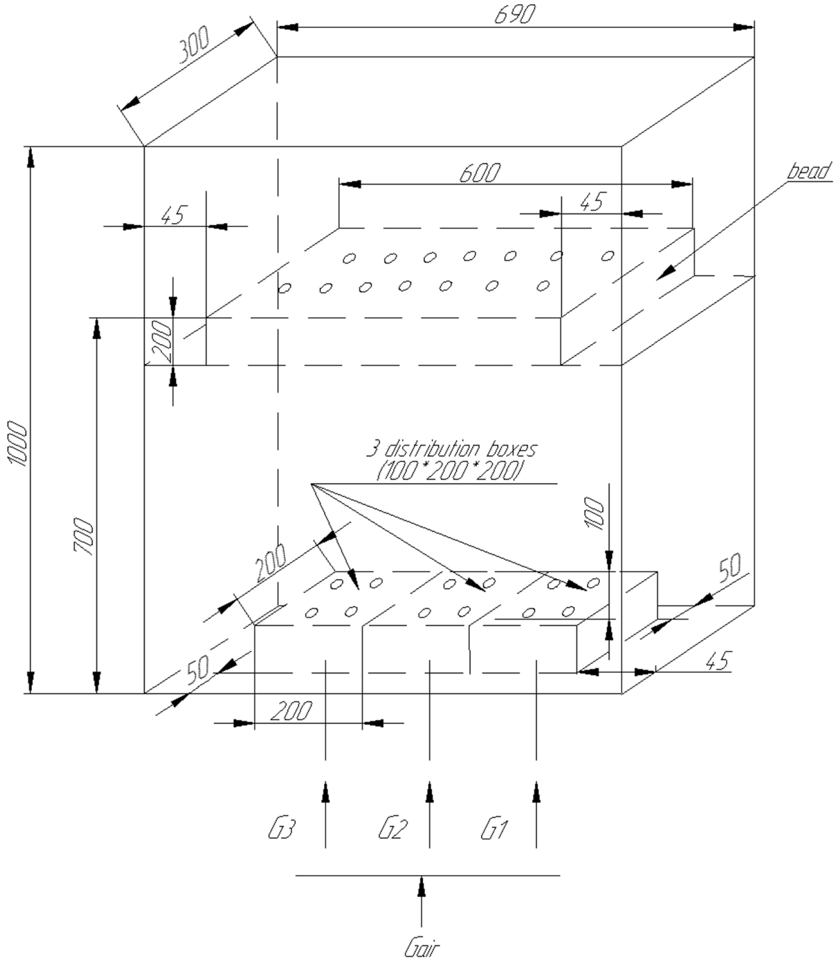

Fig. 1. Test section of the "Bubbler" installation.

3 Results

Three experiments were performed with different air flow rates. The duration of each experiment was about 100 s. The general picture of the process is following. As a result of the supply of air from the distribution boxes, bubbles are formed that flow upward. Having reached the SPS, the air spreads over the lower surface of the sheet, forming an air blanket. Then the air flows upward through the holes of the SPS and again flows in the form of bubbles through the layer of water located above the SPS. And finally, having reached the interface, it rushes up and leaves the test section. In this case, water drops of various sizes are formed on the interface surface, jumping up to a certain height.

The main parameters of the experiments and the obtained experimental data are presented in Table 1. In each experiment, the pressure drop across the SPS was measured. With increasing air flow, the pressure drop across the SPS increases. Also, based on the analysis of video recording of the process, the following characteristics of a two-phase flow were determined: 1) the average thickness of the air blanket under the SPS, 2) the average diameter of bubbles in the two-phase layer above the SPS, 3) the frequency of formation of these bubbles. Since the SPS has two holes that are located symmetrically relative to the middle of the sheet, the obtained values of these parameters are presented in Table 1 for the left and right halves of the SPS, respectively.

Table 1. Experimental parameters and data.

Test	Air flow rate, l/m	Pressure drop across the SPS, kPa	Air blanket thickness, mm	Bubbles diameter, mm	Bubble formation frequency, number/s
1	18.92	0.28	7 / 8	34 / 32	8 / 6
2	55.57	0.32	11 / 12	42 / 43	8 / 6
3	125.56	0.40	23 / 26	45 / 43	8 / 7

With increasing air flow, the thickness of the air blanket and the diameter of the bubbles increase. Of greatest interest are the results on the parameters of the droplets formed at the interface. Figure 2 shows the diameter of water droplets depending on the diameter of air bubbles entering the interface for three experiments, and also shows a straight line generalizing the experimental data and obtained by the least squares method. There is a clear tendency for the average droplet diameter to increase with increasing bubble size, which is consistent with previous observations [11]. However, it should be noted that the spread of experimental data is quite large.

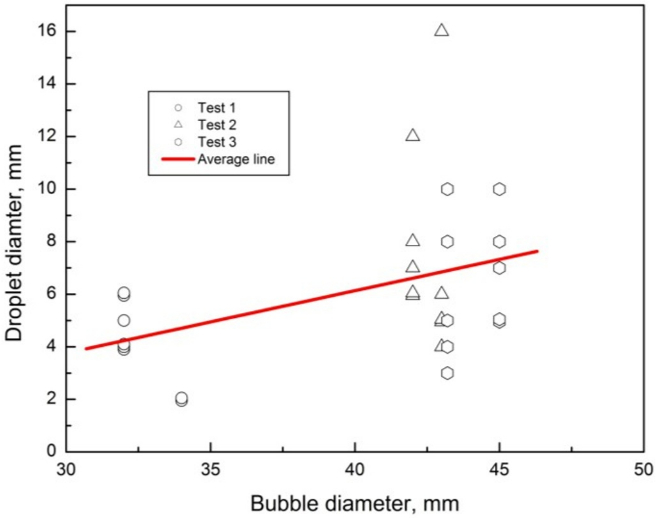

Fig. 2. Diameter of water droplets as a function of bubble diameter.

The initial velocity of droplets rising above the interface was determined by the value of the maximum rising height of the drop, based on the balance of the initial kinetic energy of the drop and the potential energy of the drop at the maximum rising height. Figure 3 shows experimental data on the initial droplet velocity as a function of the size of the bubbles approaching the interface. Also, based on the least squares method, a linear relationship between these parameters was constructed. It can be argued that as the bubble size increases, the initial velocity of the droplets increases.

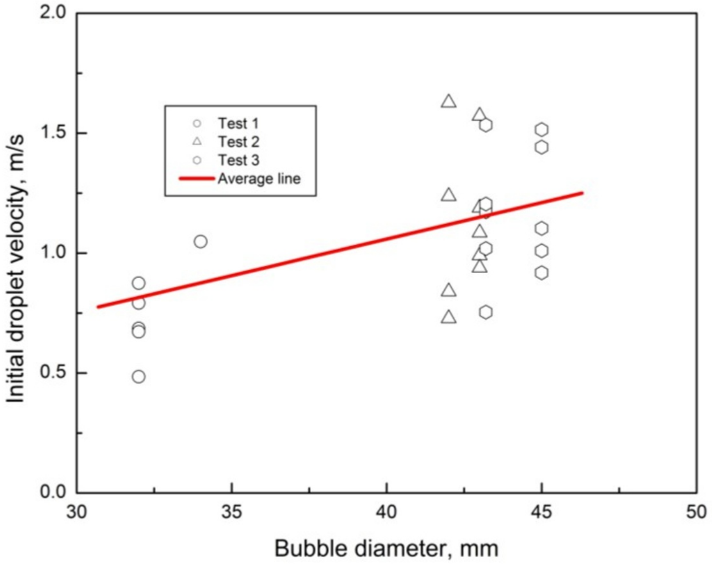

Fig. 3. Initial velocity of water droplets as a function of bubble diameter.

4 Discussion

Let us consider how well the experimental conditions correspond to similar parameters in a full-scale horizontal SG. The steam velocity at the evaporation surface in a steam generator varies from 0.1 m/s (near a cold collector) to 0.7 m/s (near a hot collector). For a degree of perforation of the SPS of 7.8% and a hole diameter of 13 mm, it can be obtained that the steam velocities in the SPS holes are 1.3–9 m/s. In the experiments at the "Bubbler" installation, three air flow rates were used: 18.92, 55.57 and 125.56 l/min. The SPS had two holes with a diameter of 13 mm. The air velocity in the holes, calculated using these parameters, is 1.19, 3.49 and 7.88 m/s, which is comparable to the full-scale parameters.

The height of the rise of water droplets was determined quite well in our experiments. This parameter made it possible to reliably determine the velocity of a water drop at the moment of separation from the water surface. The resulting dependence of the velocity of separation of a water drop on the diameter of the air bubble, presented in Figure 3, depends on many determining physical factors. To identify these dependencies, in the future, using the same experimental setup, it is planned to carry out experiments to study the rate of separation of a water drop depending on the diameter of the hole of the SPS, which significantly affects the dynamics of the process under consideration.

The performed experimental study clearly showed that for a more complete understanding of the processes under study, it is necessary to additionally perform an appropriate theoretical study based on numerical modeling of the dynamics of a two-phase medium with an interface. It is most natural in such a study to use the VOF (Volume Of Fluid) method, which allows numerical modeling of two-phase flows with a phase interface. Such numerical modeling will provide complete information about the hydrodynamics of the separation of a drop from the water surface, caused by the release of air bubbles onto this surface. A comparison of the results obtained in this experimental work on the rate of detachment of water droplets with future results of numerical modeling will allow us to evaluate the accuracy of the models used for numerical calculations.

5 Conclusion

To study the hydrodynamics of a two-phase flow over a submerged perforated sheet and the separation of water droplets from the water-air interface, a “Bubbler” installation was built. The main tool of observation was video recording of the process followed by data analysis. In this study, a two-hole SPS was used and three experiments were performed at different air flow rates. The general picture of the process was as follows. The air supplied from below reached the SPS and spread over the lower surface of the sheet, forming an air blanket. Then the air flowed upward through the holes of the SPS and rose in the form of bubbles through the layer of water located above the SPS. And finally, having reached the interface, he left the test section. At the same time, water drops of various sizes formed on the air-water interface, jumping up to a certain height. In this paper, for each air flow rate, the sizes of bubbles in the two-phase layer and the sizes of the resulting droplets were determined. It was found that with increasing air flow, these parameters increase. The results obtained will be used to develop a model of steam separation in a horizontal SG.

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