Determination of void fraction in a bed of solid particles by the method of flow cutoff

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Abstract. The paper presents a new method for determining the void fraction of two-phase flow with a condensable vapor phase. This method relies on the known technique of blocking the flow and allows measuring void fraction in the pore space of solid particle packings. The paper presents the results of experiments with packed beds of steel balls with diameters of 2 mm and 4 mm, 250 mm high. A comparison with some techniques for calculation of void fraction for empty vertical pipes is made.

1. Introduction
The void fraction and the pressure drop of the two-phase vapor-liquid flow are its main parameters in the description of the characteristics in the calculations of thermal and nuclear energy devices, oil and gas technologies, and chemical reactors. There are many methods developed to measure the void fraction of a two-phase flow, which are based on the use of various physical principles. Some of them are applied to study flows in porous media. These include the weight method [1], the methods involving capacitance probe [2], X-ray transmission [3], and neutron flux transmission [4]. All of these methods have advantages and disadvantages. For example, the weight method, despite its simplicity and high accuracy, cannot be directly applied to pressure flows. Exposure to neutron or x-ray radiation allows making measurements in the flow but the equipment is very expensive and bulky.

In our research, the flow cutoff method [5] is employed to measure the average void fraction. This method is based on the known method of blocking the flow and is a type of weight method.

2. Experimental setup
The testing rig is part of the experimental high-temperature circuit plant. Figure 1 shows a diagram of the experimental rig. The working channel is a vertical section of a stainless steel pipe with an inner diameter of 39 mm. Along the channel length, there are sampling points for measuring pressure at various heights. A steam-water mixture, formed by isenthalpic throttling of preheated water, is fed to the channel inlet. The TV valve acts as a throttle plate. A 210 mm long section of the channel with an internal volume of 255 ml is highlighted. This section is cut off by two ball-type high-temperature valves CV-1 and CV-2 with pneumatic drives, which are synchronized by a metal rod. The internal volume of the section can be filled with a packed bed under study. In our case, it is steel balls with diameters of 2 mm and 4 mm. An incut is made in the cutoff area. It is used to connect the tap to the pressure sensor, and the LV valve is used to connect a measuring beaker. After the CV-1 and CV-2 valves are closed, the steam-water mixture bypasses the section through the opened BV valve. The entire volume of the
vertical channel up to CV-1 is filled with steel balls of 3-4 mm in diameter, which significantly stabilizes the flow at high void fraction. Pressure sensors PD-100 manufactured by the OWEN company, L-type thermocouples, a PT100-type thermometer, Bonomi WAVER high-temperature ball valves for working medium temperatures up to 198 °C, and Valbia pneumatic actuators, which provide a blocking time of about 200ms, were employed in the experimental rig.

Figure 1. A scheme of the experimental setup.

For the experiment, we set the necessary mass flow rate and inlet flow quality. The mass flow rate was measured by the volumetric method after the condensation unit. The flow quality was set based on the values of pressure and temperature sensors before the TV valve. After all the parameters were set, the CV-1 and CV-2 valves were simultaneously closed, and immediately after that, the BV valve was opened. Next, the cut-off section was cooled with pressure control. When the pressure in the cut-off section decreased to the atmospheric level, the LV valve was opened. With a further decrease in pressure, water from the measuring beaker entered the cut-off section. Cooling was carried out to a temperature of about 60 °C. After that, the volume of the delivered water was determined according to the level decrease.

The void fraction was calculated by the formula:

$$\phi = \frac{V_1}{V_0 \left(1 + \frac{\rho'}{\rho''} \right)},$$  \hspace{1cm} (1)

where $V_1$ is the amount of water that came from the measuring beaker, $V_0$ is the total volume of voids in the cutoff section, $\rho'$, $\rho''$ are densities of water and vapor, respectively. The total volume of voids takes into account the formation of no-flow areas and is determined by the formula [6]:

$$V_0 = V_0 \left(1 - 0.107 \right),$$  \hspace{1cm} (2)

where $V$ is a void volume of the cutoff section, $\varepsilon$ is the porosity of the packed bed.
The two-phase flow in the packed beds of highly thermally conductive particles at a velocity which is substantially lower than the critical flow velocity is a thermodynamically equilibrium flow. This made it possible, based on the measurement data, to calculate the slip parameter between the liquid and vapor phases in the flow according to the formula:

\[ s = \left( \frac{1}{\varphi} - 1 \right) \frac{x \rho'}{(1-x) \rho''}, \]  

where \( x \) is the flow quality, \( s \) is the slip parameter: the ratio of the vapor phase velocity to the liquid phase velocity.

The parameters of the steam-water mixture at the packed bed outlet differ from the inlet parameters. In the experiments, the flow quality was calculated at the inlet and outlet of the packed bed. The average flow quality was calculated by the formula

\[ x_{av} = \frac{x_1 + x_2}{2}, \]  

where \( x_1, x_2 \) are flow quality at the packed bed inlet and outlet, respectively.

3. Flow conditions

Series of experiments were carried out to determine the void fraction of a two-phase flow during its vertical movement through a granular layer of spherical particles with a diameter of 2 mm and 4 mm. The experiments were made with the following parameters: pressure was 0.3 MPa and 0.6 MPa; mass flow rates reduced to average porosity were 100 kg/m\(^2\)s and 200 kg/m\(^2\)s, the inlet flow quality varied from 0.005 to 0.08.

4. Results.

The experimental relationships between the value of the mixture void fraction and a change in the flow quality at fixed values of mass velocity and pressure in the system have been obtained. The data for four different flow parameters are shown in Figure 2. Additional experiments were carried out to measure the void fraction in a pipe with and without a pebble bed at the same specific mass velocity of the mixture. The measurement results have shown a high degree of coincidence between the void fraction values in the presence and absence of packing of spherical particles in the pipe. In this regard, we considered the possibilities of describing the obtained experimental data using the already known recommendations for calculation of void fraction in pipes. The well-known formulas from the research by Miropolsky [7], Fedorov [8], and Premoli [9] were taken as the main ones. Experimental and calculated relationships between the void fraction and flow quality were established.
Figure 2. Relationships between the void fraction $\phi$ and average flow quality $x_{av}$. a – $P=0.3$ MPa $\rho_w=100$ kg/m$^2$/s; b – $P=0.3$ MPa $\rho_w=200$ kg/m$^2$/s; c – $P=0.6$ MPa $\rho_w=100$ kg/m$^2$/s; d – $P=0.6$ MPa $\rho_w=200$ kg/m$^2$/s. Packed bed of balls with a diameter of 2 mm — ×, 4 mm — ●, without packed bed — □, — — Miropolsky[7], — —— Fedorov[8], ——— Premoli[9].

The measured values are located in the region bounded from below by the relationships of Miropolsky and Fedorov, and in the region bounded from above - by the relationships of Premoli. It is worth noting that the presented calculation methods are recommended for higher pressures of the steam-water mixture: Fedorov [8] and Premoli [9] for pressure starting with 0.5 MPa, and Miropolsky [7] for pressure starting with 2 MPa. There was no noticeable effect of the diameter of the balls in a bed on the measured value of the void fraction.
**Figure 3.** The relationship between the slip ratio \( s \) and the average flow quality \( \chi_{av} \), \( P=0.6 \, \text{MPa} \). 

\[ + — d=2 \, \text{mm}, \rho_w=100 \, \text{kg/m}^2\text{s}; \circ — d=2 \, \text{mm}, \rho_w=200 \, \text{kg/m}^2\text{s}; \times — d=4 \, \text{mm}, \rho_w=100 \, \text{kg/m}^2\text{s}; \square — d=4 \, \text{mm}, \rho_w=200 \, \text{kg/m}^2\text{s}. \]

**Figure 3** shows the effect of the specific mass flow rate and the diameter of the packed bed ball on the resulting value of the slip ratio. An increase in the mass flow rate from 100 kg/m\(^2\)s to 200 kg/m\(^2\)s reduces slip, on average, from 5 to 3.

**5. Conclusion**

The improved method of flow cutoff has been applied to measure the void fraction of a steam-water flow through the random packed bed of single-size balls with the diameters of either 2 mm or 4 mm and in an empty channel. The experiments have shown that the void fraction in the packed bed lies in a range of values characteristic of empty pipes and does not depend much on the ball diameter.

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