The experimental and numerical study of the vertical gas movement in the cylindrical channel

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Abstract. The detailed experimental and theoretical studies of the vertical gas movement through a layer of liquid (water, molten tin) placed in a cylindrical channel (10 cm diameter) were performed. It was shown that during the gas passage through a single opening (the diameter of 8 mm) its movement at a small flow takes place as single bubbles, whose diameter becomes greater as they move towards the free surface of the liquid. Increase in the diameter at identical gas and liquid temperatures is explained by the decreasing liquid pressure in the upstream direction. If the gas temperature is lower than the liquid temperature, the diameter of bubbles increases also due to gas heating, thus resulting in the increase of its pressure in the bubble. As the gas flow increases, the number of bubbles which then merge into the uniform mass in the upper part of the channel without reducing their diameter, becomes greater. When passing the gas though the diaphragm with a high number of openings (80 openings of 1 mm in diameter), the amount of bubbles becomes higher, however their diameter in the upper part of the channel practically does not increase. When using multiple strainer diaphragms arranged at small distances from each other along the channel height, the diameters of bubbles become considerably reduced, which is connected with their periodic fragmentation when passing through each subsequent strainer. Furthermore, the bubbles get the smallest diameter when they pass through the last strainer, after which the liquid and the gas make a uniform gas and liquid emulsion in the form of a mist. The analysis of the results of air passage thought the molten tin (at a temperature of 300°C) allows concluding on considerable increase in the bubble diameter as compared to the experiments with water, which is explained by gas heating in the bubbles due to a sufficiently high temperature of tin and, as a result, the increase of pressure in them. Experimental studies applicable to small-diameter cylindrical channel (2 cm) were also performed. Their analysis allows concluding about a considerable divergence of the obtained results as compared to the greater diameter channel (10 cm) at the same gas flow. For the small-diameter channel, numerical calculations were also performed (e.g. tin) in a vertical cylindrical channel (reactor) [5 – 8]. The amount of hydrogen obtained at the reactor outlet depends on the intensity of methane heating to the pyrolysis temperature. It is known that methane passes through the molten tin in the form of bubbles, whose diameter increases as they move towards the upper part of the reactor, which is connected with the reduction of upstream pressure of liquid metal as well as the increase of gas pressure in bubbles resulted from its heating. The increase in the bubble diameter makes it heating to the pyrolysis temperature difficult as a result of low heat conductivity of methane. In this regard, measures should be taken to decrease their diameter.
1. Experimental study
The experimental studies performed directly at the reactor due to impermeability of its walls and of molten tin, are impossible. Therefore, this work describes the detailed studies of air passage through water in a transparent cylindrical channel on two customized sets (figures 1 – 6), which have different cylindrical channel diameters. One of them has the diameter of 10 cm (figures 1 – 5), and the diameter of the second one is 2 cm (figure 6). The sets comprise the following components: a transparent cylindrical channel; air supply compressor; tube; air flow control valve, liquid (water), air bubbles.

The following variants of studies were made with the sets:
1) Air supply through a single tube with a diameter of 8 mm in a cylindrical set with a diameter of 10 cm (figure 1 – 2);
2) Air supply through the diaphragm (strainer) containing 80 holes 1 mm in diameter (figure 3);
3) Air passage through multiple strainers arranged at a small distance from each other along the height (figure 4);
4) Air passage through the horizontal nozzle located in the near-wall area of the reactor to perform liquid twirling around the vertical axis.
5) Air supply through a single tube with a diameter of 3 mm in a cylindrical set with a diameter of 2 cm (figure 6);
6) Repeating all the listed research variants with the air passage through the heated water (80°C).

The results of experimental studies using the set with a large diameter of cylindrical channel at a liquid temperature equal to the gas temperature are given in fig. 1–5. Their analysis allows concluding that with small gas flow, its movement in liquid takes the form of single bubbles (figure 1). The diameter of bubbles increases as they approach the free surface as a result of a decrease in the upstream water pressure. As the gas flow increases, the number of bubbles grows (figure 2).

When passing the gas though the diaphragm with a high number of small-diameter openings (80 openings of 1 mm diameter), the amount of bubbles becomes higher and their diameter in the upper part of the channel increases 2 to 3 times (figure 3).

When using multiple strainer diaphragms located at a distance from each other along the channel height, gas bubbles, upon passage through each strainer, become fragmented. Furthermore, their diameters at this moment are small due to a small inter-strainer distance. As a result of periodic fragmenting of bubbles, they have the smallest diameter after passing the last strainer while making a uniform gas and liquid emulsion in the form of a foam.

At the set with cylindrical channel of a greater diameter (d = 10 cm) the studies were also performed at water temperature of 80°C and air temperature of 20°C. Their analysis allows concluding about the increase of the diameter of bubbles as a result of the pressure increase in them due to gas heating during the upward movement.

As applied to the reactor with a greater cylinder diameter (d = 10 cm) the studies were also made for the horizontal arrangement of the nozzle in the near-wall area for the liquid twirling around the vertical axis (figure 5). Their analysis allows concluding that with a small gas flows, the gas after leaving the nozzle, becomes slightly twirled but in its main bulk it raises up as a gas column in the near-wall area of the gas reactor. In the rest of the reactor there are only separate gas bubbles moving both in the vertical and horizontal directions.

The results of studies for the set with a small diameter of cylindrical channel (d = 2 cm) are given in figure 6. Their analysis allows concluding on a considerable dissimilarity in the nature of their flow as compared to the channel of a greater diameter. And, in particular, with high gas flow, the stream takes the form of a non-continuous vertically deflecting cord. The results of studies at the set using the molten tin are given in figure 7. The tin layer height in the cylindrical channel with a diameter of 10 cm amounted to 4 cm. The tin temperature amounted to 300°C the temperature of passed air was 20°C. From the analysis of the research results it may be inferred that with small air consumption single bubbles occur inside the tin, reaching the diameter of 1 – 2 cm at the surface. As the flow grows, the amount of bubbles and their diameter on the tin surface increases. A considerable increase in the diameter of air bubbles (up to 3 – 5
cm) should be noted. It is explained, firstly, by their heating, and as a result, the increase of pressure in a bubble, and secondly, by greater density (6 times higher than that of water) and viscosity (20% higher than for water), which directly proportionally influence the size of bubbles.

2. Numerical study

The forms of a gas flow through small-diameter channels qualitatively confirm the results of numeric calculations (figure 8). For visualisation of the hydrodynamic nature of a vertical flat thin (0.5 mm) stream of methane to the reservoir with tin, a computational experiment is performed. The geometry of the reactor filled with a heat carrier, represents a rectangular area with a height of 1300 and a width of 40 mm, having a slit with the size of 0.5 mm in the central part of the lower base of the area for methane supply (figure 8). The geometry and rectangular strainer (with a volume of 0.25 million of cells) filling the inner area of the reactor are built in the grid construction software ICEM [9].

Simulation was made using the Mixter mixture model implemented in the Ansys Fluent software complex [10]. For the side and bottom walls of the reactor, the no-slip and non-penetration conditions of the mixture were set: a constant velocity of methane flow of 0.1 m/s for the slit boundary and constant statical pressure conditions at the outlet (the upper reactor boundary). Thermophysical properties are set to be constant (corresponding to the temperature at 500 °C: tin density $\rho_{\text{tin}} = 6810 \, \text{kg/m}^3$, tin dynamic viscosity $\mu_{\text{tin}} = 1.18 \times 10^{-3} \, \text{kg/(s}\cdot\text{m})$; methane density $\rho_{\text{m}} = 0.253 \, \text{kg/m}^3$, and methane dynamic viscosity $\mu_{\text{m}} = 2.3 \times 10^{-5} \, \text{kg/(s}\cdot\text{m})$. The calculation is made for 3 days with the use of the computational cluster having the following specifications: 96 cores/24 IntelXeon 2.7 GHz processors /6 nodes with 120 Gb RAM and 836 Gb disc memory per node. It can be concluded from the figure 8 that: the process hydrodynamics is quasiperiodic, the stream from a particular moment of time takes a swinging nature, the transversal pressure gradient occurs and small particles (bubbles) come off the stream which move in the upstream direction along the flow in a chequerboard pattern. The analysis of the obtained data allows concluding on their qualitative coincidence with the experimental data given in figure 6.

Figure 1. General view of a small gas in the set with a diameter of $d = 10 \, \text{cm}$.  
Figure 2. General view of the increasing gas flow in the set 2 with the cylindrical channel diameter of $d = 10 \, \text{cm}$. 
Figure 3. General view of the high gas flow through the diaphragm: \( n = 80 \) – number of holes; hole diameter \( d_h = 1 \text{ mm} \).

Figure 4. General view of the high gas flow through the multiple strainer diaphragm.

Figure 5. Horizontal arrangement of the nozzle at the near-wall part of the set.

Figure 6. Gas flow through liquid in the the set with a small-diameter cylindrical channel.
Conclusions

1. Multioptional experimental and theoretical studies of the gas (air) movement through a liquid layer (water, molten tin) placed in a vertical cylindrical channel have been performed. The studies for air passage through water were performed for two options of cylindrical channel diameters ($d = 10 \text{ cm}$ and $d = 2 \text{ cm}$), and air passage through the molten tin was studied only for one option of $d = 5 \text{ cm}$. Air flow from the compressor was controlled using the gate valve. The studies for air passage through water were performed for the water temperature of $20 ^\circ \text{C}$ and $80 ^\circ \text{C}$. Air temperature in both cases was equal to $20 ^\circ \text{C}$.

2. The studies of gas passage through water in the channel with a diameter $d = 10 \text{ cm}$ were made for the following designs of air supply components: a nozzle with a diameter $d = 0.8 \text{ cm}$ arranged vertically in the lower part of the channel along its central axis; the diaphragm (grid) containing 80 openings with a diameter of $1 \text{ mm}$; four diaphragms in the form of strainers arranged vertically at a distance of $10 \text{ cm}$ from each other; and a nozzle with a diameter $d = 0.8 \text{ cm}$ located horizontally in the near-wall area of the channel. From the results for all the mentioned options of air supply structures, it can be concluded that the air flow is characterized by the occurrence of single bubbles with the diameter increasing with the upward movement. The increasing diameter of air bubbles is explained by the decrease of hydrostatic water pressure in the upper part of the channel by the value of the liquid column height as compared to the lower part. In case when the liquid temperature is higher than the gas temperature, the diameter of bubbles also increases as a result of gas heating inside the bubble, which is accompanied by the increase of its growth. If the liquid tin is used, the temperature factor of the diameter increase is determinant.

3. The analysis of results of the studies using the set with a small-diameter cylindrical channel ($2 \text{ cm}$) allows concluding about substantial qualitative difference of the flow nature as
compared to the channel of a greater diameter (10 cm). Thus, the diameter of bubbles in the upper part of the channels becomes equal to the diameter of a cylindrical channel, which considerably impedes gas heating in a bubble.

4. For the reduction of the diameter of bubbles, a cascade of strainers vertically arranged at a slight distance from each other, is the most efficient. In this case, upon passage through each strainer, the bubbles get fragmented with forming a steam and liquid mix in the form of a mist at the channel outlet.

5. The studies of the gas flow have been performed for the coaxial nozzle (in the area adjoining the channel wall). The purpose of this research consisted in the gas and liquid twirling around the vertical axis. The results of studies allow concluding that with small gas flows the twirling effect of the gas and water flow is insignificant. However, at a high gas flow, there is the stream change combined with the increasing diameter of bubbles and, as a result, more intensive gas and liquid mixing.

6. The study analysis of the gas flow through the molten tin allows concluding on a considerable (as compared to water) increase of bubble diameter at the same gas flow. This fact is explained by more intensive gas heating in bubbles from the molten tin with a temperature of approximately 300°C.

7. The mathematical simulation has been made for the evolution of methane stream flowing to the reservoir with tin within the mix model implemented in the Ansys Fluent software. The quasiperiodic nature of methane bubbles coming off the flowing stream has been recorded.

8. The analysis of the obtained data allows concluding on their qualitative agreement with the data of the real-life experiment. The obtained data are the basis for further computational experiments.

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