Comparative evaluation of air-water mixers operating with flotation plants

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Abstract. The article deals with theoretical and experimental studies of oily industrial wastewater flotation treatment using a saturator and vortex mixing devices (VMD) for preparing a water-air mixture. The use of VMD allows, in comparison with the saturator, to improve the efficiency of oil product removal on the flotator by 5-7% due to the greater gas saturation of the flotation volume. The energy consumption for preparing the water-air mixture in vortex mixers was on 8–10% lower than in flotation plants using a saturator.

Key words: industrial wastewater, oil-containing impurities, suspended substances, reagent flotation purification, vortex mixing devices.

1. Introduction

One of the most efficient methods for cleaning industrial oil-containing wastewater is the pressure flotation method, using apparatus and plants having various designs [1-7]. An essential factor influencing the flotation treatment degree is the method of gas-liquid mixture preparation. In pressure flotation, high-pressure air is introduced into the saturator and dissolved in water. When a supersaturated aqueous solution enters the flotator, air is released from the water in the form of bubbles. The disadvantage of pressure flotation is the insignificant gas content of the supersaturated solution (not greater than 4-4.5%), with the increase of which air bubbles coalesce and the quality of purification deteriorates. The development of a new type mixers that would create a finely dispersed water-air mixture with high gas saturation without preliminary dissolution of air in water is an urgent task.

Tubular compact vortex mixing devices (VMDs) can be used as such mixers; their constructions was discussed in sufficient detail in [8]. The first-stage VMD (I VMD) is a vortex ejector, whereas the second-stage VMD (II VMD) is a coaxial "pipe-in-pipe" system with a rotational-translational motion of the water-air mixture. Such a system allows to increase quantity of bubbles contacts with pipe walls at high values of tangential stresses generated by the velocity gradient of the gas-liquid mixture, which intensifies the water-air mixture dispersion [9].

To determine the effect of the energy dissipation degree in a tubular mixer on the average diameter of dispersible air bubbles, formula [10] is used

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where \( \varepsilon_0 \) is the average value of the power dissipated in the unit mass of the mixed medium, W/kg or m\(^3\)/s\(^3\); \( \rho_l \) is density of the liquid phase, kg/m\(^3\); \( \sigma \) is surface tension at the air-liquid interface, n/m.

The value \( \varepsilon_0 \) is related to the velocity gradient \( G, \text{s}^{-1} \) in the mixer by the relation [11]

\[
\varepsilon_0 = G^2 \cdot \nu_m,
\]

(2)

where \( \nu_m \) is the kinematic coefficient of viscosity of water-air mixture, m\(^2\)/s.

The velocity gradient \( G, \text{s}^{-1} \), is determined by the formula

\[
G = \left( \frac{E}{t_m \cdot V_m \cdot \rho_m \cdot \nu_m} \right)^{0.5},
\]

(3)

where \( E \) is the energy expended on mixing, J; \( t_m \) is the mixing time, s; \( V_m \) is the volume of the mixer, m\(^3\); \( \rho_m \) is density of water-air mixture, kg/m\(^3\).

The energy value for tubular mixers is found from expression

\[
E = Q_m \cdot \Delta \rho \cdot t_m,
\]

(4)

where \( \Delta \rho \) is pressure losses in the mixer, Pa; \( Q_m \) is the flow rate of the water-air mixture, m\(^3\)/s.

Taking into account (2) and (4), the formula (1) for determining the mean diameter of air bubbles in the hydraulic fluid will have the following form:

\[
d_b = 0.43 \left( \frac{\sigma}{\rho_l} \right)^{0.6} \cdot \left( G^2 \cdot \nu_m \right)^{-0.4} = 0.43 \left( \frac{\sigma}{\rho_l} \right)^{0.6} \cdot \left( \frac{\Delta \rho}{\rho_l} \right)^{-0.4} \cdot \varepsilon^{-0.4}.
\]

(5)

The value \( \rho_m \) can be determined with sufficient accuracy by the formula

\[
\rho_m = \rho_l \left( 1 - \phi / 100 \right),
\]

(6)

where \( \phi \) is volumetric gas content in the mixture, %.

Thus, by setting the structural dimensions of stage II tubular mixer and the technological parameters of treating the water-air mixture, it is possible to determine the degree of dispersion of the air bubbles obtained in a certain range. In this article, the task was set of determining the average size of air bubbles in the flotator and comparing the efficiency of flotation treatment of oily wastewater using water-air mixtures obtained in the VMD and in the saturator.

2. Materials and methods

The object of research was the industrial wastewater of a machine-building plant entering, after an oil separator, the flotation treatment plant. Industrial wastewater was characterized by the following composition:

- oil products \( C_{oo} = 12 - 31 \) mg/l;
- suspended substances \( C_{so} = 28 - 55 \) mg/l;
- pH 6.8 - 7.1.

In the experiments on flotation treatment of effluents, polyaluminum chloride (PAC) was used as a coagulant with an active part content of 18%, used in industrial flothers as the main treating agent. To enhance the effect of removing contaminants, 4-5 mg/l of K-555 cationic flocculant is dosed to the wastewater after adding coagulant.

The oil-containing wastewater flotation treatment plant was installed at the industrial effluents treatment plant of the machine-building plant.

The experimental flotation plant (figure 1) consisted of a flotation column 1 with a total height of 2.2 m, a saturator 2 with a capacity of 0.017 m\(^3\), first 3 and second 4 stage vortex mixing devices (VMDs), a receiving tank 5, a centrifugal pump 6, a compressor 8, coagulant dosing pumps 17 and
flocculant 18. The installation also comprised pipelines, instrumentation and shut-off valves, auxiliary tanks.

![Diagram of laboratory flotation plant](image)

**Figure 1.** Layout of laboratory flotation plant: 1 – flotation column, 2 – saturator, 3, 4 – stage I and II VMDs, 5 – receiving tanks, 6 – pump, 7 – bypass line, 8 – compressor, 9, 9’ – pressure pipes of the original effluent, 10, 10’ – compressed air pipelines, 11 – air-water mixture pipeline, 12 – clarified water draw-off pipe, 13 – flotation sludge discharge pipeline, 14, 15, 16 – pressure gauges, 17 – coagulant dosing pump, 18 – flocculant dosing pump, 19 – air-water mixture discharge pipe, 20 – air vent, 21, 21’ – flow meters.

The initial wastewater was drawn off to the receiving tank 5 from the pipeline supplying oily wastewater to industrial flotators. The wastewater was then fed by pump 6 to the water-air mixture preparation devices – saturator 2 or VMDs 3 and 4. These devices worked alternately by closing the valves on the pressure pipes 9 and 9’. The flow rate of wastewater supplied to the saturator 2, was 0.1 m³/hr due to the opening of the valve on the bypass line 7 and the circulation of most of the flow. Simultaneously, from compressor 8 through pipeline 10’ air was supplied at a pressure of 4.5 – 4.6·10⁵ Pa to saturator 2. The time of saturation of water with air was within 5 - 6 minutes. Excess compressed air was removed through valve 20, the pressure in the saturator was monitored by pressure gauge 16. The water-air mixture was throttled by a valve installed on pipeline 11 in the immediate vicinity of flotation column 1. The degree of water aeration (gas saturation) \( \varphi \) was 3.8 – 4%. The coagulant solution was fed by the dosing pump 17 to the original effluent feed pipe upstream of the water-air mixture preparation devices.

During the examination of the VMDs operation, a gate valve was opened on pipeline 9 and with the gate valve on the bypass line 7 closed, the sewage water from the pump 6 was fed to stage 3. The compressed air from compressor 8 through pipeline 10 was also entered there. The (gas) air saturation was from 6% to 8% and was controlled by flow meters 21 and 21’. After the primary mixing, the water-air mixture was fed to stage II VMD 4 and then flowed through the pipeline 11 to the flotation column. Excess of the air-water mixture flow leaving the VMD was discharged into the sewage system through the branch pipe 19. The pressure differential across VMD was maintained within 3.3 – 4.2·10⁵ Pa due to the valves installed on the pipelines 9, 11 and was monitored by manometers 14 and 15. The height of the barrel of stage II VMD H in the experiments varied from 1.5 to 2.0 m. The wastewater-air mixing time in the VMD was under 2 s. The general view of the VMD is shown in figure 2.
The water-air mixture, obtained in the saturator or the VMD, was mixed immediately upstream the flotation column with the flocculant K-555 solution, fed by dosing pump 18 (see figure 1). The flotation time was 15–20 min. The flow rate reduced to the flotator’s separation surface was 5.6 – 5.7 m³/m²·hr. The sludge formed during the operation of column 1 through the branch pipe 13 was discharged to the sewer, the clarified water through the branch pipe 12 was drawn off for chemical analysis.

Figure 2. General view of vortex mixing devices (VMD): 1– recycle pump, 2 – first stage VMD (I VMD), 3 – second stage VMD (II VMD), 4 – compressed air supply.

The experimental program provided for the addition of a coagulant solution into the original water, water aeration in the saturator or in stage I and II VMDs, treatment of the water-air mixture with flocculant at a constant dose of 5 mg/l, and flotation purification of water from contamination in the laboratory column. In each experiment, purified water samples were taken to determine residual concentrations of pollutants. The average size of the air bubbles in the flotation column was determined from the rate of the collective ascent of the bubbles in accordance with the recommendations [3, 12].

3. Results and discussion

The results of experiments to determine the average diameters of air bubbles in a flotation column are shown in figure 3.

The average size of the air bubbles \(d_b\) in the flotation column downstream of the saturator was 70-75 µm (Diagram 1, figure 3). The diameter of the air bubbles depended on the height of the VMD’s barrel of in the flotation column downstream of the VMD and air saturation of wastewater. At \(H = 1.5\) m and \(\varphi = 6\%\), the average bubble diameter was 120-125 µm, and at \(\varphi = 8\%\) the bubble size varied from 150 to 155 µm (diagram 2, figure 3). The pressure losses \(\Delta p\) in the VMD’s barrel for \(H=1.5\) m varied from 3.6·10⁵ to 3.8·10⁵ Pa. At \(H = 2.0\) m and \(\varphi = 8\%\), the average bubble diameter \(d_b\) was 95-100 µm, and at \(\varphi = 6\%\) it was equal to \(d_b = 80 - 85\) µm (diagram 3, figure 3). The pressure losses \(\Delta p\) in the VMD’s barrel for \(H=2.0\) m varied from 4.0·10⁵ to 4.2·10⁵ Pa. It should be noted that the power consumption for the pump and compressor during water aeration using the VMDs were 8-20% lower than those when a saturator was used.
Figure 3. Diagrams of average diameters of dispersed air bubbles in the flotator downstream saturator (1), downstream second stage VMD with \( H = 1.5 \) m (2), downstream second stage VMD with \( H = 2.0 \) m (3) – at \( \phi = 6\% \); – at \( \phi = 8\% \).

The dependences of residual concentrations of oil products and suspended substances on the doses of the PAC coagulant following a 20 min flotation treatment using the water-air mixture having gas saturation of 3.8 - 4% obtained in the saturator are shown in figure 4. The dose of the K-555 flocculant in all the experiments was \( D_f = 5 \) mg/l. The purification efficiency was determined by the formula

\[
E = \frac{C_{wo}(C_{so}) - C_{so}(C_{si})}{C_{so}(C_{so})} \cdot 100\%.
\]  

(7)

where \( C_{wo} \) (\( C_{so} \)) and \( C_{so} \) (\( C_{si} \)) are the concentrations of contaminants, mg/l, in the original and purified effluent respectively.

Figure 4. The dependences of residual concentrations of oil products \( C_o \) and suspended substances \( C_s \) in the effluents on the coagulant doses \( D_c \) after flotation with water-air mixture obtained in the saturator at initial concentrations \( C_{wo} = 15 \) mg/l (1), \( C_{wo} = 30 \) mg/l (2), \( C_{wo} = 30 \) mg/l (1'), \( C_{wo} = 50 \) mg/l (2'),

- - - - - - oil products; - - - - - suspended substances.

The results of experiments on flotation treatment of effluent using a water-air mixture obtained in the VMD with a barrel height of \( H = 1.5 \) m are shown in figures 5 and 6.
Figure 5. The dependences of residual concentrations of oil products $C_o$ on the coagulant doses $D_c$ after flotation with water-air mixture obtained in the VMD with a barrel height of $H=1.5$ m at initial concentrations $C_{i0}=15$ mg/l (1, 1'), $C_{i0}=30$ mg/l (2, 2')

- - - - - - at $\phi=6\%$;

- - - - - - at $\phi=8\%$.

Figure 6. The dependences of residual concentrations of suspended substances $C_s$ on the coagulant doses $D_c$ after flotation with water-air mixture obtained in the VMD with a barrel height of $H=1.5$ m at initial concentrations $C_{i0}=30$ mg/l (1, 1'), $C_{i0}=50$ mg/l (2, 2')

- - - - - - at $\phi=6\%$; at $\phi=8\%$.

A comparative analysis of the graphs in Fig. 4-6 showed that the efficiency of flotation treatment of wastewater from oil products and suspended substances with the use of the air-water mixture produced downstream the VMD with the barrel height $H = 1.5$ m was somewhat lower than the treatment efficiency using a saturator.

The results of experiments with the use of a water-air mixture produced in the VMD with a barrel height $H=2.0$ m for flotation treatment of wastewater are shown in figures 7-8.
Figure 7. The dependences of residual concentrations of oil products $C_o$ on the coagulant doses $D_c$ after flotation with the water-air mixture obtained in the VMD with a barrel height of $H=2.0$ m at initial concentrations $C_{wo}=15$ mg/l (1, 1'), $C_{wo}=30$ mg/l (2, 2')

- - - - - at $\varphi=6$ %;  
- - - - - at $\varphi=8$ %.

Figure 8. The dependences of residual concentrations of suspended substances $C_s$ on the coagulant doses $D_c$ after flotation with water-air mixture obtained in the VMD with a barrel height of $H=2.0$ m at initial concentrations $C_{ws}=30$ mg/l (1, 1'), $C_{ws}=50$ mg/l (2, 2')

- - - - - at $\varphi=6$ %;  
- - - - - at $\varphi=8$ %.

Analysis of the graphs in figures 4, 7 and 8 showed that due to the higher gas saturation of the water-air mixture in the flotation column with the use of the VMD (barrel height $H=2.0$ m and in-barrel pressure losses $\Delta p=(4 \div 4.2) \cdot 10^3$ Pa) a higher cleaning effect on oil products and suspended solids was achieved in comparison with the experiments in which a saturator was used, with lower power consumption (by 8-10%). The effect of purification of industrial effluents with the use of water-
air mixture from the saturator with the PAC doses of $D_c=40$ mg/l was the same as in the case of using in the flotation column of water-air mixture obtained downstream of the VMD (H=2.0 m) with coagulant doses of $D_c=18-22$ mg/l at $\phi=6$ % and $D_c=16-20$ mg/l at $\phi=8$ %. The effect of purification of industrial effluents from suspended substances with the use of water-air mixture from the saturator with the PAC doses of $D_c=40$ mg/l was equal to the effect of purification with the use in the floater of water-air mixture obtained downstream of the VMD with coagulant doses of $D_c=33-35$ mg/l at $\phi=6$ % and $D_c=30-33$ mg/l at $\phi=8$ %.

4. Conclusions
1. The time required for retention of wastewater in the VMD’s barrel for obtaining a highly disperse water-air mixture is reduced by more than 150 times compared with the water aeration time in the saturator. The pump and the compressor power common consumption during water aeration using VMDs was 8-10% lower than those using the saturator.
2. With the increase in gas saturation in the VMDs from 6 % to 8 % an increase of the average size of the air bubbles is observed from 120–125 $\mu$m to 150 - 155 $\mu$m with the height of the stage II VMD H=1.5 m and c 80–85 $\mu$m to 95–100 $\mu$m at H=2.0 m. The pressure losses in the VMDs are $(3.6 \div 3.8) \cdot 10^4$ Pa and $(4.0 \div 4.2) \cdot 10^4$ Pa respectively.
3. Vortex mixing devices (VMD), by providing a higher gas saturation of the air-water mixture in comparison with the saturator allow for a 5-7% increase on average in the efficiency of flotation treatment of wastewater from oil products and suspended substances at lower power consumption and coagulant doses.

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