The simulation of water-oil emulsion separation process in a settling tank with corrugated plates

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Abstract. This research paper deals with the problem of increasing the efficiency of water-oil emulsion separation. In order to intensify the process of its stratification, the internal baffles with orientation of corrugations at an angle of 45° were studied. The numerical simulation of emulsion separation process inside the apparatus was conducted by means of ANSYS Fluent software package. In the course of studies, three models of apparatus of different geometrical dimensions were considered. Each subsequent design was by 50% larger than the previous one. The results of studies allowed to make a conclusion that the separation efficiency of water-oil emulsion is on average equal to 73.7%. At the same time, a peak range was determined, corresponding to the rates from 0.05 to 0.17 m/s, at which the separation efficiency is on average equal to 77.7%. The maximum separation efficiency of at least 80%, regardless of dimensions of apparatus, is achieved at the emulsion rate equal to 0.11 m/s and rates close to this value. The emulsion movement rate, the size and density of oil globules are the key indicators that affect the change in the efficiency of water-oil emulsion separation into components.

1. Introduction
As of today, an important task for the petrochemical industry is to improve the efficiency of water-oil emulsion separation, i.e. a mixture of two insoluble liquids – water and oil, separation. In the course of operation of oil field wells, the percentage of stratum water in oil is increased that leads to a more complex technological process and takes much more time for emulsion separation into components. On average, oil water cut during its production increases up to 80-90% that leads to deterioration of its quality, rapid contamination and corrosion of process equipment. It should be noted that during the development of oil fields, there is an intensive mixing of stratum water and oil. As a result of this process, stable oil-water emulsions are formed. The main characteristics of oil emulsions include the destruction degree within a certain period of time, the effective viscosity, and the average surface-volume diameter of emulsified drops of water phase. Together, these parameters show the intensity of oil emulsification, its physical and chemical properties, and the emulsifier's adsorption capability. The difference in density values for water and oil can also indicate the intensity of water-oil emulsion destruction. It should be noted that in oil production wells, equipped with electric centrifugal pumps, the formation of water-oil emulsions occurs more intensively. The average surface-volume diameter of drops is equal to 3–8 μm. It should be noted that a certain dependency of drop typical size on the pump dimensions is not determined. In the viscous oil fields the diameter of emulsified drops is slightly
larger. When oil is extracted by means of rod well pumps, a very strong emulsification takes place within the valve units of pumps [1–7].

Currently, there are various methods for separating the water-oil emulsions into components: mechanical, thermochemical, and electrochemical. The simplest method is mechanical, which is based on gravitational settling of emulsion. As a rule, mechanical methods are used for the emulsion with high liquid content. The most widely-used devices based on the mechanical method of water-oil emulsion separation are the settling tanks of periodic continuous action and various designs. The raw material tanks are usually used as settling tanks of periodic action. When they are filled with crude oil, water is deposited to the bottom part of them. The devices within which water-oil emulsion is separated due to its continuous inside movement are used as settling tanks of continuous action. The water-oil emulsion in the settling tanks moves in the prevailing direction vertically or horizontally depending on the design and location of separation devices [8–10].

Thermochemical methods include the use of various demulsifiers that destroy the protective solvate shell around water globules, with the deposition of coalesced water drops. It should be noted that the widely used methods of water-oil emulsion separation include thermal methods. It means that the emulsion is heated up to 45–80°C. During the process of water-oil emulsion heating, the strength of emulsifier layers on the surface of drops decreases, which makes it easier for them to merge. Also, when the temperature of water-oil emulsion increases, then the viscosity of mixture components decreases. This leads to a more clear difference in the density of water and oil as well as to the rapid separation of emulsion. As a rule, heating of water-oil emulsion is carried out in tanks, heat exchangers and tube furnaces. When applying the electrochemical methods, water-oil emulsion is passed through electric field which allows to destroy the protective film of oil globules and to deform their forms that increases the collision and enlargement of them. Among the electrochemical methods of water-oil emulsion separation the simplest are electric methods. It should be noted that devices that separate water-oil emulsions by electric methods are widely used due to the comparative simplicity of units, required for this purpose, as well as applicability for most emulsions and sufficient reliability in operation. The electric method of emulsion destruction is used at oil refinery plants for desalting oil at electric treatment units, as well as for cleaning oil products from water solutions of alkalis and acids. These two methods are based on a high-voltage electric field that affects the suspended water particles, and they merge into larger ones. Subsequently, enlarged water particles settle to the bottom of apparatus under the gravity force [11–13]. As a rule, petrochemical facilities apply several of these methods as a step-by-step technological line for oil purification from water. One of most promising ways to improve the operation efficiency of oil treatment process pipeline is to improve and modernize mechanical methods, since they require lower operating costs compared to the other methods. As noted earlier, the most versatile and common apparatuses for separating the water-oil emulsions are the settling tanks. In these tanks emulsions are separated due to the difference in density of two liquids. The main disadvantage of settling tanks is their low throughput capacity [14–18]. Therefore, the development of technical solutions to improve the emulsion separation efficiency in the settling tanks and to increase their throughput capacity is a relevant task.

2. Purpose of study
The purpose of this research paper is to study a technical solution for the settling tanks that can increase the efficiency of separating the emulsion into the components and increase the throughput capacity of apparatus.

The authors proposed to use the separation elements in the form of corrugated plates with orientation of corrugations at an angle of 45°, which are inserted into the settling tank (figure 1). It was hypothesized that the use of corrugated plates in the settling tanks will increase the efficiency of water-oil emulsion separation and throughput capacity of apparatus due to intensification of flocculation of oil drops with further coagulation of them. The intensification of these processes is caused by the formation of a large number of vortex points near the corrugations, which allow to
create a wave structure of flow inside the settling tank that increases the number of processes of oil drops sticking and combining [19–21].

**Figure 1.** Three-dimensional model of settling tank with a cross-section: 1, 2 – input areas for water and oil drops, 3 – corrugated baffles with orientation of corrugations, located at an angle of 45°, 4 – intersectional baffle, 5 – outlet nozzle for output of light phase, 6 – outlet nozzle for output of heavy phase, 7 – housing of settling tank.

In order to test the adequacy of hypothesis, a three-dimensional model of settling tank with separation elements in the form of corrugated plates at an angle of 45° was created. The numerical simulation of emulsion separation process inside the apparatus was conducted by means of ANSYS Fluent software package. This software package is designed for simulating complex flows of liquids and gases with a wide range of changes in thermal properties by providing various modeling parameters and using multigrid methods with improved convergence. The program uses the finite element method, i.e. a grid-based method. The differential equations with partial derivatives are defined depending on the chosen turbulence model. They are supplemented with the set boundary conditions. The description of turbulent flows of viscous liquids in this software package is carried out by solving the Navier-Stokes equations. It should be noted that the solution of non-stationary Navier-Stokes equations makes it possible to describe real turbulent flows, but practical study of them by direct numerical simulation methods with the Navier-Stokes equation system is currently difficult due to high computational costs. In this regard, in order to reduce the requirements for computation power when simulating various hydrodynamic processes, a method, based on the use of time-averaged values, is used. For this purpose, first of all, a virtual three-dimensional model of device with separation elements in the AutoCAD software package (figure 1) was created, and then exported to ANSYS Workbench. The three-dimensional model was calculated based on the k-ε RNG turbulence model. This can be explained by the fact that the accuracy of this model in comparison with the others in ANSYS Fluent is the most preferable for solving the problem. It has required accuracy to solve the problem of separating water-oil emulsions and is not too demanding on computer resources.

A three-dimensional model of settling tank with corrugated plates had the following geometrical dimensions: the height, width and depth of housing – 105, 365 and 20 mm, respectively, the height and width of water inlet area – 100 and 5 mm, respectively, the height and width of corrugated plates – 100 and 300 mm, respectively, the diameter of corrugations – 8 mm, the distance between 2 corrugated plates – 10 mm, the height of intersectional baffle – 50 mm. Simulation of water-oil
emulsion separation process can be described as follows (figure 1): at the inlet areas of settling tanks 1, 2 the mass flow rate of water and oil globules, the diameter $a$ of which varied from 5 to 200 µm, was set; the initial emulsion moved in parallel to two corrugated plates 3, which caused the formation of wave structure of flow movement; then the oil particles moved to the upper part of settling tank, due to lower density in comparison with water; the remaining liquid moved to the bottom part of settling tank. The output of light phase was carried out through the outlet nozzle 5, and the heavy phase – through the nozzle 6. It should be noted that the intersectional baffle 4 allowed to increase the overall efficiency of water-oil emulsion separation, since the part of oil particles remained at the average level of settling tank and thus the baffle changed the direction of movement towards the outlet nozzle 5 (figure 1).

In the course of numerical simulation, the following constant values were taken: ambient temperature 20ºC, the number of oil particles, fed into the settling tank $n = 1000$, density of water 998.2 kg/m$^3$ and oil 920 kg/m$^3$. In order to obtain more extensive data in the course of numerical studies, a three-dimensional model of apparatus was enlarged by 1.5 and 2 times.

The efficiency of emulsion separation in the settling tank was determined by the following formula:

$$ E = 1 - \frac{n_6}{1000}, $$

where $n_6$ – the number of oil particles at the outlet nozzle 6 for the output of heavy phase.

In the previous research papers, the authors considered other types of separation elements: baffles and inserts, made of highly porous cellular material (figure 2). According to the study of these elements, when the oil concentration in the original mixture was equal to 25%, the efficiency of water-oil emulsion separation was on average equal to 74.6, 69.8 and 62.2% when using a settling tank without separation elements, but with inserts, made of highly porous cellular material and baffles as well.

![Figure 2. Models of separation elements: a – baffle, b – insert, made of highly porous cellular material.](image)

In this paper, the authors also compare the effectiveness of corrugated plates and previously studied separation elements [13].

3. Results and discussion

The results of conducted studies are shown graphically in figures 3–5. The use of corrugated baffles with orientation of corrugations, located at an angle of 45° in the settling tank, allows to separate the water-oil emulsions with an average efficiency of 73.7%. In the course of studies, the peak rate of water-oil emulsion movement was determined as a range of 0.05-0.17 m/s, at which the maximum separation efficiency of 77.7% is achieved. When the rate of emulsion movement is within this range, an optimal flow structure is created when flowing around the corrugated elements with moderate size and force of vortexes. The key factor for effective separation of water-oil emulsions into components is that at taken rates the maximum difference between the processes of stratification and mixing at the vortex points is achieved. It should be noted that the emulsion separation process, in addition to the size and force of vortexes, is particularly affected by
the size of oil globules, since the ratio of opposite processes – stratification and mixing – is also changed. An increase in the size of oil globules from 5 to 200 µm reduces the separation efficiency of water-oil emulsion on average from 74.5% to 71.9% at its movement rate within the range of 0.05-0.17 m/s (figure 3).

When the dimensions of settling tank and all its constituent elements are increased by 1.5 and 2 times, the separation efficiency increases on average up to 78.1% and 79.2%, respectively (figures 4, 5). This fact confirms that the use of large-size gravity apparatuses allows to increase the emulsion separation efficiency due to natural stratification, based on the difference in the densities of water and oil components.

The efficiency of water-oil emulsion separation at its movement rate inside the settling tank within the range of 0.02–0.22 m/s into components is on average equal to 74.5, 74.1, 74.2, 74.1, 73.3 and 71.9% with the size of oil globules of 5, 20, 50, 100 and 200 µm, respectively. It is worth noting that the maximum efficiency of emulsion stratification, equal to 82.1%, was recorded at its movement rate of 0.11 m/s and the size of oil globules of 20 µm. Also, at this rate, the highest efficiency of emulsion
separation in comparison with the other rates within the range of 0.02–0.22 m/s is observed, which is on average equal to 80.4%. When the emulsion movement rate is within the range of 0.02–0.05 m/s, there is an increase in the emulsion separation efficiency on average by 11.8%. This is due to the fact that the emulsion stratification processes start to prevail over the mixing processes. The opposite situation is observed when the emulsion moves in the settling tank with rate of more than 0.17 m/s. In this interval, the efficiency of emulsion separation decreases on average by of 7.1% (figure 3).

When the dimensions of apparatus are increased by 1.5 times, the emulsion separation efficiency with the dispersion of dispersed oil globules of 5–200 µm was on average equal to 71.1, 77.8, 82.6, 82.6 and 76.7% with its movement rate in the settling tank equal to 0.03, 0.06, 0.09, 0.12 and 0.15 m/s, respectively. Regardless of increase in dimensions of settling tank, the most effective rates for separating the water-oil emulsion, the same as for the previous case (figure 3), were close to 0.11 m/s. In this case, these rates are equal to 0.09 and 0.12 m/s. An increase in the size of oil globules, as a rule, led to an increase in the emulsion separation efficiency, which was increased on average by 3% with an increase in the size of oil globules for every 50 µm. It should be noted that at the rate of emulsion movement equal to 0.15 m/s, an increase in the size of oil globules led to a decrease in the efficiency of its separation, due to the throwing of drops to the surfaces of corrugated elements, where mixing took place (figure 4).

The demulsification efficiency of water-oil emulsion with a diameter of oil globules dispersed in it of 5–200 microns on average was equal to 66.2, 78.1, 80.4, 75.1 and 68.9% with its movement rate of 0.02, 0.06, 0.11, 0.17 and 0.22 m/s, respectively. An increase in the diameter of oil globules from 5 to 200 µm led to a change in the efficiency of demulsification of water-oil emulsion to a greater or less side by not more than 3%. It should be noted that for the range of changes in the diameter of oil globules of 5-50 µm, the change in the demulsification efficiency was equal to not more than 1–2% (figure 5).

![Figure 5](image)

For the range of 50-200 µm, the efficiency change was equal to not more than 2-3% (figure 5).

When the dimensions of apparatus are increased by 2 times, the emulsion separation efficiency with the dispersion of dispersed oil globules of 5–200 µm was on average equal to 77.5, 78.9, 83.1, 80.9 and 75.8% with its movement rate in the settling tank equal to 0.05, 0.07, 0.09, 0.1 and 0.12 m/s, respectively (figure 3).

As can be seen, the most effective rates of water-oil emulsion are 0.09 and 0.1 m/s, which are closest to the previously set rate of 0.11 m/s in figure 3 and figure 4. When the emulsion rate is equal
to 0.12 m/s and the size of oil globules is more than 100 µm, the separation efficiency decreases, due to the predominance of mixing process over the stratification process (figure 6).

![Figure 6. The dependency of water-oil emulsion separation efficiency in a settling tank with corrugated plates on the size of oil globules, depending on the rate of its movement, m/s: 1 – 0.05, 2 – 0.07, 3 – 0.09, 4 – 0.1, 5 – 0.12. The results were obtained by increasing the dimensions of settling tank by 2 times.](image)

Thus, in the course of studies, it was found that the emulsion movement rates, close to 0.11 m/s, when using the corrugated baffles in the settling tank, allow it to be divided into components with the maximum possible efficiency (figures 3–6).

4. Conclusion
The conducted studies show that the use of separation elements in the form of corrugated plates with the orientation of corrugations, located at an angle of 45°, allow to improve the efficiency of water-oil emulsion separation into components due to the formation of wave flow structure and multiple vortex points relative to the length of plates. However, different characteristics of vortex points i.e. strength and size, are the reason for increasing and decreasing the efficiency of emulsion separation, due to reverse processes – stratification and mixing. In the course of studies, it was found that the efficiency of emulsion separation is on average equal to 73.7%. The peak range was determined, corresponding to the rates from 0.05 to 0.17 m/s, at which the maximum separation efficiency of 77.7% is achieved. High efficiency is caused by the fact that for the rate range of 0.05-0.17 m/s, the emulsion stratification processes prevail over the emulsion mixing processes. The maximum separation efficiency of at least 80%, regardless of dimensions of apparatus, is achieved at the emulsion rate equal to 0.11 m/s and rates close to this value. When the size of oil globules was increased for every 50 µm, an increase in the separation efficiency on average by 3% was observed. Thus, the emulsion movement rate, the size and density of oil globules are the key indicators that affect the change in the efficiency of water-oil emulsion separation into components. The efficiency of separation elements, i.e. the corrugated plates with orientation of corrugations, located at an angle of 45°, is on average by 11.2% higher than for the baffles and inserts, made of highly porous cellular material, which were previously studied. The studied corrugated plates are of practical significance for the petroleum industry, since the process of water-oil emulsion demulsification in most of settling tanks is several times slower.

5. References
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