

# Design of a Novel Fracturing Flowback Fluid Separation Device

Shuai Zhao, Hangxin Wei and Kuancheng Lei

School of Mechanical Engineering, Xi'an Shiyou University, Xi'an Shaanxi, 710065, China

## Abstract

To address the problems associated with traditional fracturing flowback fluid separation devices, such as reliance on manual operation and low separation efficiency, this paper presents the design of a novel automatic separation device based on a combination of gravity settling and multi stage filtration. The device adopts a multi chamber structure to successively achieve sand settling, filtration, and oil water separation, with automatic discharge of oil, water, and sand achieved through level sensors and gate control systems, enabling continuous operation. The internal flow field was simulated using ANSYS Fluent with a multiphase flow model to verify the feasibility and effectiveness of the separation process. The results indicate that the device can effectively improve separation efficiency, reduce manual intervention and operating costs, and shows promising engineering application prospects.

## Keywords

Fracturing Flowback Fluid; Oil-water-sand Separation; Gravity Settling; Automatic Control.

## 1. Introduction

Since the wave of industrialization swept across the world, human productive forces have advanced rapidly. With the continuous expansion in scope and intensification in degree of various industrial activities [1], the consumption of traditional energy sources such as coal, oil, and natural gas has grown exponentially [2]. In view of insufficient energy production, scientists have developed a technology that can effectively increase the productivity of oil and gas fields—hydraulic fracturing [3], which plays an irreplaceable role especially in the development of shale gas, shale oil, tight oil, and low-permeability reservoirs [4]. China's oil and gas development is currently confronted with a compound dilemma summarized as "two deep, one unconventional, and one old." On the one hand, major eastern oilfields represented by Daqing and Shengli have generally entered a late development stage characterized by "two highs" (high water cut and high recovery degree). The decline in conventional resource output has become difficult to reverse [5]. On the other hand, unconventional oil and gas resources serving as strategic successors (such as shale gas and tight oil), as well as low-permeability reservoirs, are generally hosted in deep or tight formations with complex geological conditions and poor physical properties [6]. Meanwhile, during oil and gas production—particularly after fracturing operations—the flowback waste fluid from wells often contains high concentrations of hazardous components such as formaldehyde, fine sand, petroleum residues, and various chemical additives [7].

Since the 1970s, researchers in the United States, the former Soviet Union, Canada, and China have focused on the treatment of drilling wastewater, dedicating substantial effort and resources to this field. They have proposed a series of innovative treatment methods and designed and manufactured various types of equipment specifically for fracturing wastewater treatment. Over time, water treatment technologies and their supporting equipment have undergone continuous technological innovation, and technologies for treating fracturing flowback fluid have accordingly achieved significant improvements and advancements [8].

Among the physical methods for treating flowback fluid, cyclonic separation and gravity settling are the main technical routes. Based on an investigation of oil and gas fields and considering the production status of the high-water-cut gas zones in the Changqing Oilfield—where small gas production is accompanied by large water output (“small gas, large water”)—it was found that flowback fluid features an extremely high water content, with relatively small proportions of oil and sand, and gas can be almost neglected. Under such operating conditions, this study designs an oil–water–sand separation device based on the mechanism of gravity settling. Traditional gravity-type flowback fluid separators offer advantages such as simple structure, convenient operation, and low operating cost. However, their separation efficiency is limited, and they are unable to achieve automatic three-phase separation of oil, water, and sand. Manual intervention is typically required, including periodic water discharge, skimming of floating oil, and sand removal. On the basis of the structure of conventional gravity separators, the product designed in this paper introduces innovative optimizations. By incorporating features of filtration-type separators, a novel fracturing flowback fluid separation device is developed. This device not only enables periodic sand removal, but also realizes automatic discharge of the oil and water phases after gravity settling, thereby enabling continuous operation, reducing labor costs, and enhancing economic efficiency.

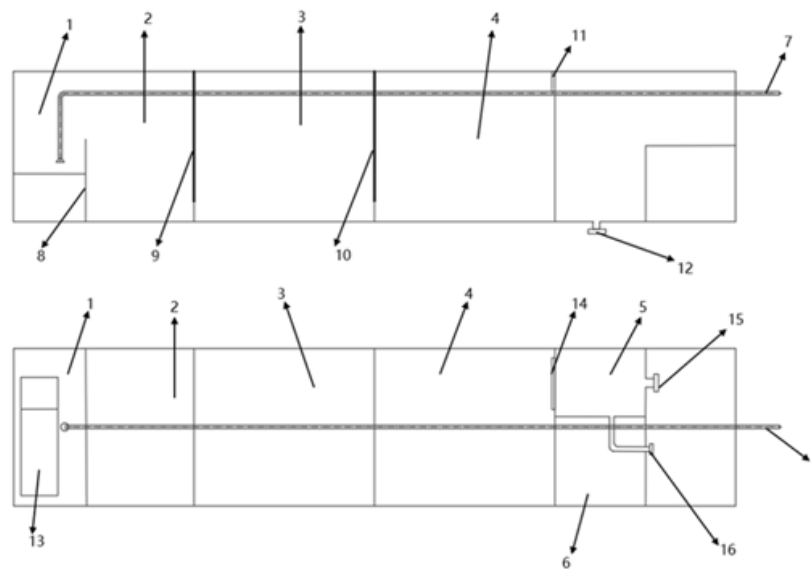
## 2. Structural Design of the Fracturing Flowback Fluid Separation Device

In industrial production, separators serve as key unit equipment and can be classified according to their separation mechanisms into three main types: gravity-type, cyclone-type, and filtration-type [9]. Gravity-type separators exploit density differences between phases to achieve phase separation through natural settling under a gravitational field. Although they come in various structural forms, the core separation mechanism is the same. Cyclone separators employ a characteristic conical structure and induce a strong swirling flow through tangential inlets. Under centrifugal force, they efficiently achieve solid–liquid, gas–liquid, or gas–solid separation and exhibit excellent separation performance. Filtration-type separators, on the other hand, rely on internally packed multi-stage filter media and achieve precise classification and separation of different materials via a combined mechanism of surface interception and depth filtration. The internal configurations of gravity-type separators share basic similarities. They typically consist of an outer shell, mixture inlets, outlets for each phase, liquid-level monitoring devices, internal baffles, and other key components, forming a complete separation unit [10]. Considering current operating requirements, a vertical gravity-type flowback fluid separator was ultimately selected as the research target. An oil–water–sand separator was then designed in accordance with these requirements.

### 2.1. Working Principle of the Separation Device

As shown in **Figure 1**, the working principle of the fracturing flowback fluid separation device is as follows: Flowback fluid enters the first sand-settling chamber (1) through the flowback fluid inlet pipe (7), where a portion of large-diameter sand particles and fine sand settle out. The remaining mixture flows into the second sand-settling chamber (2) via the baffle (8). When the liquid level in the oil–water storage chamber (4) reaches a predetermined height, the sand-discharge component (13) in the first sand-settling chamber (1) starts to operate, discharging the settled solids from the chamber. After primary settling, the flowback mixture enters the second sand-settling chamber (2), where it is further filtered by the coarse filter screen (9) to remove particles of relatively larger size. The remaining flowback fluid then enters the silt-settling chamber (3). A fine filter screen (10) is installed between the silt-settling chamber (3) and the oil–water storage chamber (4) to further remove solid particles. In the oil–water storage chamber (4), oil and water undergo further gravity settling and phase separation. At the bottom between the oil–water storage chamber (4) and the clean-water storage chamber

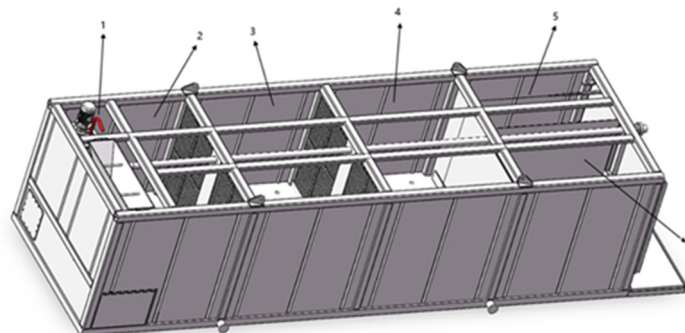
(5), there is a gate opening equipped with a gate-valve actuating device (14). When the liquid level in the oil-water storage chamber (4) reaches a specified height, the gate-valve actuating device (14) opens, allowing the water phase that has settled at the bottom to flow through the gate into the clean-water storage chamber (5), from which it is discharged via the water outlet (15). When the liquid level in the oil-water storage chamber (4) drops to a lower threshold, the gate closes to prevent oil from entering. To ensure that the liquid level in the clean-water storage chamber (5) remains relatively high, a makeup-water inlet (16) is connected at its lower outer side. At the top between the oil-water storage chamber (4) and the waste-oil storage chamber (6), an oil window (11) is installed. After settling separation in the oil-water storage chamber (4), the oil phase accumulates on the upper layer of the mixture. When the liquid level in the oil-water storage chamber (4) rises to a high level, the oil phase flows through the oil window (11) into the waste-oil storage chamber (6) and is then discharged from the device through the oil outlet (12).



1.First sand-settling chamber 2.Second sand-settling chamber 3.Silt-settling chamber 4.Oil-water storage chamber 5.Clean-water storage chamber 6.Waste-oil storage chamber 7.Flowback fluid inlet pipe 8.Baffle 9.Coarse filter screen 10.Fine filter screen 11.Oil window 12.Oil outlet 13.Sand-discharge component 14.Gate-valve actuating device 15.Water outlet 16.Makeup-water inlet

**Figure 1.** Schematic of the Flowback Fluid Separation Device

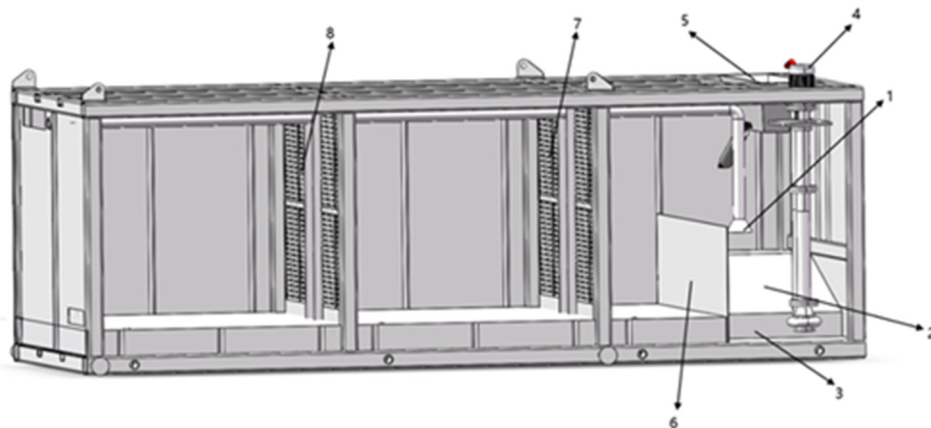
## 2.2. Structural Design of the Separation Device



1.First sand-settling chamber 2.Second sand-settling chamber 3.Silt-settling chamber 4.Oil-water storage chamber 5.Clean-water storage chamber 6.Waste-oil storage chamber

**Figure 2.** Three-dimensional Model of the Flowback Fluid Separation Device

As shown in **Figure 2**, the separation device consists of six functional chambers mounted on a skid: the first sand-settling chamber (1), second sand-settling chamber (2), silt-settling chamber (3), oil-water storage chamber (4), clean-water storage chamber (5), and waste-oil storage chamber (6).



1.Flowback fluid collection inlet 2.Splash guard 3.Sand collection pit 4.Vertical sand-discharge pump 5.Reversible sand-dumping mechanism 6.Baffle 7.Coarse filter screen 8.Fine filter screen

**Figure 3.** Structural Diagram of the Main Separation Body

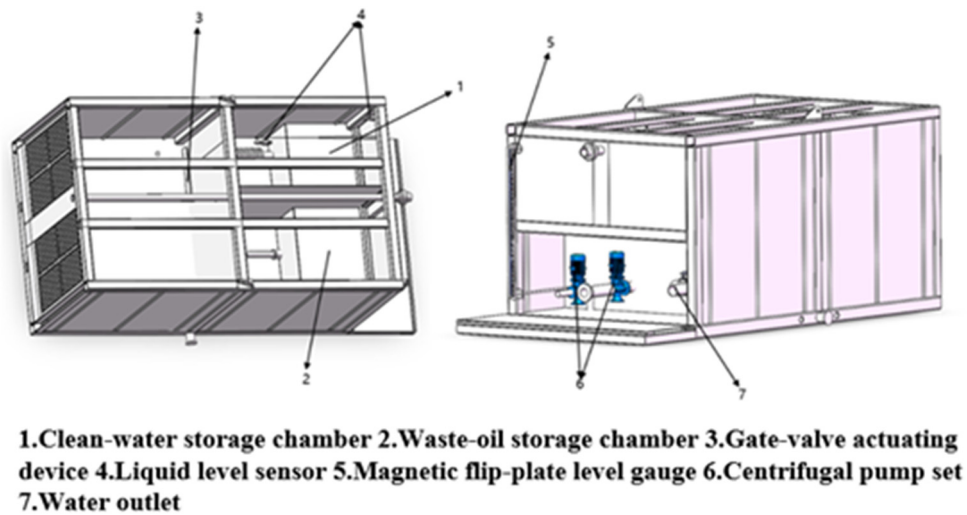
**Figure 3.** illustrates the internal structure of the main separation body.

The first sand-settling chamber is the direct flowback collection chamber, equipped with a splash guard (2), a sand collection pit (3), a vertical sand-discharge pump (4), and a reversible sand-dumping mechanism (5). The reversible sand-dumping mechanism (5) consists of a sand-dumping bucket and a lifting device. The second sand-settling chamber functions as the sedimentation and flow chamber for sand particles and the oil-water mixture. A baffle (6) is located between the two chambers. When flowback fluid enters the first sand-settling chamber via the flowback fluid collection inlet (1), the splash guard (2) and sand collection pit (3) are used to concentrate part of the large-diameter gravel and some fine sand. As the liquid level rises, the remaining mixture flows into the second sand-settling chamber through the baffle (6). When the liquid level in the tank reaches a specified height, the vertical sand-discharge pump (4) starts and pumps the mixture from the first sand-settling chamber into the sand-dumping bucket, where solid particles are filtered out. After a period of operation, the vertical sand-discharge pump (4) is shut down, and the reversible sand-dumping mechanism (5) tilts the sand-dumping bucket to discharge the solid particles from the tank.

The silt-settling chamber is a fine-filtration and settling chamber, separated from the second sand-settling chamber by a replaceable filter screen. After the mixture flows into the second sand-settling chamber, it passes through the coarse filter screen (7), which further removes larger solid particles. The residual impurities after coarse filtration are of size  $\leq 0.25$  mm. The oil-water storage chamber is primarily used for further settling and separation of oil and water. A replaceable fine filter screen (8) is installed between the silt-settling chamber and the oil-water storage chamber, yielding a residual impurity size after filtration of  $\leq 0.15$  mm.

**Figure 4.** shows the structure of the automatic liquid-discharge assembly. It consists of the clean-water storage chamber (1), waste-oil storage chamber (2), gate-valve actuating device (3), liquid level sensor (4), magnetic flip-plate level gauge (5), centrifugal pump set (6), and water outlet (7). The centrifugal pump set (6) comprises a sludge/oily-water discharge pump

for waste oil and a makeup pump for liquid replenishment. When the device starts operating, the liquid level sensor (4) detects the liquid level in the clean-water storage chamber (1) and activates the makeup pump to replenish liquid. The magnetic flip-plate level gauge (5) measures the liquid level in the oil-water storage chamber. When the level reaches a specified threshold, the control system opens the gate valve, allowing the water located at the lower part of the chamber to pass through the gate channel into the clean-water storage chamber (1), from which it is discharged through the water outlet (7). When the liquid level drops to a lower limit, the gate valve is closed to prevent waste oil from entering. When the liquid level rises to a higher set point, oil flows into the waste-oil storage chamber (2), and the waste-oil discharge pump is switched on to discharge the waste oil from the tank. In this way, automatic liquid discharge is realized. At the same time, the liquid level in the oil-water storage chamber also controls the start/stop of the sand-discharge pump and the reversible sand-dumping mechanism; the control sequence has been described previously.



**Figure 4.** Structural Diagram of the Automatic Liquid-Discharge Assembly

### 3. Multiphase Flow Model and Flow-Field Simulation Analysis within the Separation Device

#### 3.1. Multiphase Flow Models

##### 1. Gravity Settling Model

The gravity settling model is used to describe the settling process of solid particles or liquid droplets under a gravitational field. The model is based on the density difference between the particles and the fluid, as well as the effect of fluid viscosity. In the device, solid-phase separation in the flowback fluid is mainly governed by gravity settling:

$$v_s = \sqrt{\frac{4gd_p(\rho_p - \rho_f)}{3C_D\rho_f}} \quad (1)$$

Where  $v_s$  is the settling velocity of particles (m/s),  $g$  is the gravitational acceleration (9.81 m/s<sup>2</sup>),  $d_p$  is the particle diameter (m),  $\rho_p$  is the particle density (kg/m<sup>3</sup>),  $\rho_f$  is the fluid density (kg/m<sup>3</sup>),  $\mu$  is the dynamic viscosity of the fluid (Pa·s), and  $C_D$  is the drag coefficient, which is a function of the Reynolds number.

##### 2. Filtration Model

The filtration model describes the interception behavior of solid particles as they pass through a filter screen. It is based on the relationship between particle size and filter pore size, and on filtration efficiency:

$$\frac{\Delta P}{L} = \frac{150\mu(1-\epsilon)^2v}{\epsilon^3d_p^2} + \frac{1.75\rho_f(1-\epsilon)v^2}{\epsilon^3d_p} \quad (2)$$

Where  $\Delta P$  is the pressure drop (Pa),  $L$  is the filter layer thickness (m),  $\epsilon$  is the porosity of the filter layer, and  $v$  is the superficial fluid velocity (m/s).

### 3. Eulerian Multiphase Flow Model

The Eulerian multiphase model is more complex yet more powerful. Each phase is treated as an interpenetrating continuum, and a full set of momentum and continuity equations is solved for each phase. Coupling between phases is achieved through interphase exchange coefficients.

#### a. Volume Fraction Equation

This equation describes the spatial distribution of each phase:

$$\frac{\partial}{\partial t}(\alpha_k\rho_k) + \nabla \cdot (\alpha_k\rho_k\vec{v}_k) = 0 \quad (3)$$

Where  $\alpha_k$  is the volume fraction of phase  $k$ , satisfying  $\sum\alpha_k = 1$ ;  $\rho_k$  is the density of phase  $k$  (kg/m<sup>3</sup>);  $\vec{v}_k$  is the velocity vector of phase  $k$  (m/s), and  $t$  is time (s). This is essentially the mass conservation equation for each phase.

#### b. Momentum Equation

This equation describes the motion of each phase and is the core of the model. Each phase has its own momentum equation and is coupled to the others via interphase forces  $\vec{R}_{kl}$ .

For phase  $k$ :

$$\frac{\partial}{\partial t}(\alpha_k\rho_k\vec{v}_k) + \nabla \cdot (\alpha_k\rho_k\vec{v}_k\vec{v}_k) = -\alpha_k\nabla p + \nabla \cdot \vec{\tau}_k + \alpha_k\rho_k\vec{g} + \sum_{l=1, l \neq k}^n \vec{R}_{kl} \quad (4)$$

Where  $p$  is the shared pressure field (Pa), identical for all phases;  $\vec{g}$  is the gravitational acceleration vector (m/s<sup>2</sup>);  $\vec{\tau}_k$  is the stress-strain tensor of phase  $k$  (Pa), typically written as:

$$\vec{\tau}_k = \alpha_k\mu_k(\nabla\vec{v}_k + \nabla\vec{v}_k^T) \quad (5)$$

Where  $\mu_k$  is the molecular viscosity of phase  $k$  (Pa·s); and  $\vec{R}_{kl}$  is the interphase momentum exchange term (N/m<sup>3</sup>), which is crucial in determining how different phases interact.

#### c. Interphase Forces

The interphase force  $\vec{R}_{kl}$  is predominantly in the form of drag force. A general form is:

$$\vec{R}_{kl} = K_{kl}(\vec{v}_l - \vec{v}_k) \quad (6)$$

Where  $K_{kl}$  is the interphase momentum exchange coefficient between phases  $k$  and  $l$  (kg/(m<sup>3</sup>·s)).

## 3.2. Internal Flow-Field Simulation Analysis

ANSYS Fluent was used to perform flow-field simulations of the separator. Because the separation tank has a large volume, a very large number of computational cells would be required to resolve all flow details. To balance accuracy and computational cost, a very fine mesh was used in critical regions, such as near the inlet and in the expected oil-water interface region, while a coarser mesh was employed in other regions. This strategy ensures sufficient accuracy while controlling the total mesh count.

Given that the water phase accounts for the overwhelming majority of the fracturing flowback fluid, the water phase was set as the primary phase in the calculation, while solid particles of different sizes and the oil phase were treated as secondary phases. Initially, the separator was assumed to be filled with air. The Eulerian multiphase flow model was activated, and

appropriate interphase forces were specified between phases, including surface tension models between the oil and water phases. The turbulence model adopted was the k-ε model.

Boundary conditions were set as follows: at the velocity inlet, the velocities and volume fractions of each phase were specified; at the pressure outlet, the backflow volume fraction of air was set to 1. The porous-media model was used to represent the interception behavior of the coarse and fine filter screens, incorporating their respective flow resistance characteristics. Based on the volume of fluid method, a cross-sectional plane along the X-direction was taken within the fluid domain to visualize the contour plots of phase volume fractions. This approach was employed to observe the settling behavior of sand particles inside the chamber as well as the separation process between oil and water phases. When the simulation reached approximately 3100 seconds, the contour plots are presented in the figure below.

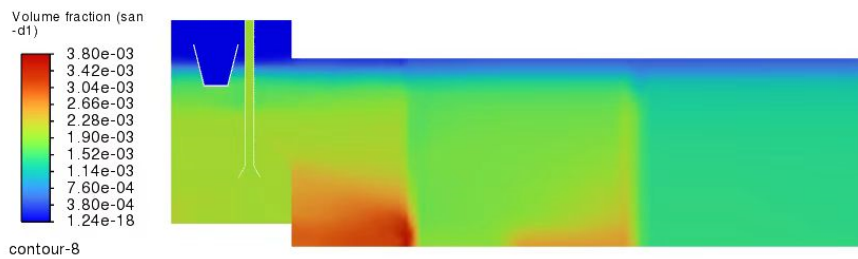


Figure 5. Contour plot of the volume fraction for Sand 1

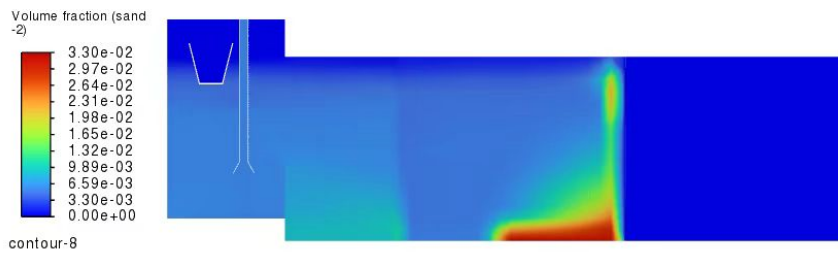


Figure 6. Contour plot of the volume fraction for Sand 2

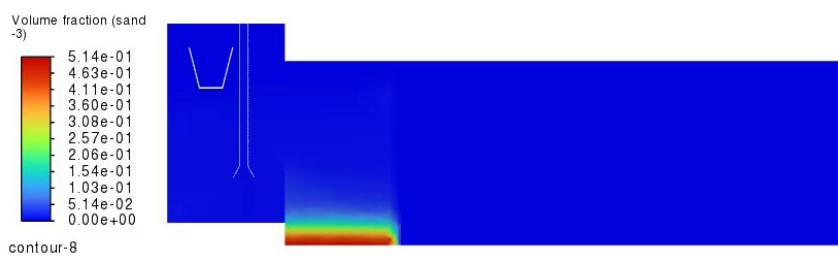


Figure 7. Contour plot of the volume fraction for Sand 3

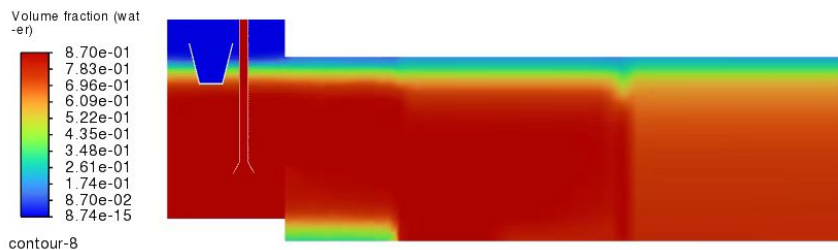


Figure 8. Contour plot of the volume fraction of water

**Figure 5.** shows the contour plot of the volume fraction for the smallest-sized sand particles (Sand 1). Analysis of this figure indicates that Sand 1 is undergoing a settling process; however, due to its minimal particle diameter, this sedimentation occurs relatively slowly. **Figure 6.** presents the contour plot of the volume fraction for Sand 2. From this figure, it can be observed that these particles are intercepted and have deposited on the fine screen. **Figure 7.** displays the contour plot of the volume fraction for Sand 3. This figure clearly demonstrates that the sand particles are intercepted by the coarse screen and, owing to their largest diameter, exhibit the fastest deposition rate. **Figure 8.** illustrates the contour plot of the volume fraction of water. Analysis of this figure reveals that the separation between oil and water is in progress; however, due to the low oil content, this separation process also proceeds at a relatively slow rate.

## 4. Conclusion

In this study, an innovative flowback fluid separation device was designed to overcome the limitations of traditional separators, which can only discharge liquid and sand manually. Based on a gravity-type separator structure and incorporating features of filtration-type separators, the proposed device introduces an automatic liquid-discharge assembly that uses liquid level as the control signal to start and stop connected components and pump sets, thereby achieving automatic liquid and sand discharge. CFD simulations of the internal flow field verified the effectiveness of the design.

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