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Статья / Article

Proppant Transport in the Low-Flow Oil Wells

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Транспортировка проппанта в скважинах с низким дебитом нефти

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The efficiency of low-flow oil wells after hydraulic fracturing is frequently compromised by residual proppant and early-phase proppant production, which can penetrate pumps and severely diminish their lifespan. Proppant management in such wells remains a persistent challenge, particularly due to the inadequate understanding of how proppant travels from the wellbore bottom to the pump intake. This study bridges that critical knowledge gap by introducing pioneering experimental findings on proppant behavior in low-flow conditions—the first to clarify the primary mechanisms at play. Using advanced laboratory simulations replicating post-fracturing environments, we observe that proppant consistently reaches the pump intake via an unnoticed process: immiscible hydrocarbon fluid droplets encapsulate and transport proppant particles upward. Key results include the revelation that the viscosity of the immiscible phase (e.g., oil or kerosene) does not significantly affect droplet transport capacity. Furthermore, proppant concentration during transport shows no correlation with well flow rates, overturning conventional assumptions. A groundbreaking insight is the role of free gas bubbles: they increase the likelihood of proppant being captured by hydrocarbon droplets, with higher gas volumes directly linked to elevated proppant levels in the flow. These conclusions are substantiated by field data from wells exhibiting high free gas content near the bottomhole, where shorter pump operational periods coincided with the proposed mechanism. By identifying this transport process, the research lays the groundwork for tailored proppant management solutions, paving the way for improved pump durability and operational performance in low-flow oil wells.

Ключевые слова:
проппант, управление проппантом, борьба с пескопроявлением, вынос песка, произвлдство проппанта, нефтяная скважина.

Эффективность работы нефтяных скважин с низким дебитом после гидроразрыва пласта часто снижается из-за остаточного проппанта и его выноса на ранней стадии, что может привести к его проникновению в насосы и значительному сокращению срока их службы. Регулирование выноса проппанта в таких скважинах остается актуальной проблемой, особенно из-за недостаточного понимания того, как проппант перемещается от забоя скважины к приему насоса. Данное исследование устраняет этот важный пробел в знаниях, представляя новаторские экспериментальные данные о поведении проппанта в условиях низкого дебита – первые данные, проливающие свет на основные механизмы. Используя современные лабораторные модели, воспроизводящие условия после гидроразрыва пласта, мы наблюдаем, что проппант стабильно достигает приема насоса посредством незаметного процесса: несмешивающиеся капли углеводородной жидкости инкапсулируют и транспортируют частицы проппанта вверх. Ключевые результаты включают в себя открытие того, что вязкость несмешивающейся фазы (например, нефти или керосина) не оказывает существенного влияния на транспортную способность капель. Более того, концентрация проппанта во время транспортировки не коррелирует с дебитом скважины, что опровергает общепринятые предположения. Новаторским открытием является роль пузырьков свободного газа: они увеличивают вероятность захвата проппанта каплями углеводородов, причем более высокие объемы газа напрямую связаны с повышенным содержанием проппанта в потоке. Эти выводы подтверждаются промысловыми данными по скважинам с высоким содержанием свободного газа вблизи забоя, где более короткие периоды работы насоса совпадали с предложенным механизмом. Выявив этот процесс транспортировки, исследование закладывает основу для разработки индивидуальных решений по управлению проппантом, открывая путь к повышению долговечности и эксплуатационных характеристик насосов в низкодебитных нефтяных скважинах.

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Introduction

Proppant hydraulic fracturing is increasingly being carried out in old oil fields with hard-to-recover residual reserves, such as the oil fields of the Perm region, which have been developed since the first half of the 20th century [1–3]. At such fields, hydraulic fracturing is vital to maintaining the economic efficiency of oil production [4–8]. At the same time, hydraulic fracturing is an expensive operation and it is necessary to reduce the cost of its implementation and well operation after hydraulic fracturing. Well operation after hydraulic fracturing is complicated by proppant production, which requires well cleaning and additional interventions, which causes losses in the form of unproduced oil, additional equipment and well intervention costs [9–12]. One possible way to reduce costs at low-flow wells is to avoid additional interventions to clean wells of residual proppant and proppant produced in the wells during the initial period of production after hydraulic fracturing. The problem with this approach is that proppant can get into the pump and reduce the service life of oil well pumps [13, 14]. Early attempts to use this method in the Perm region fields were extremely unsuccessful. The analysis showed that with an unreasonable well operating mode, pumps can wear out in less than a month of operation in wells after hydraulic fracturing due to wear and seizure. Because of this, the economic efficiency of oil well operation decreases due to additional costs for new equipment and interventions. However, despite the failures, the operator company does not stop trying to reduce costs and minimize additional well interventions to clean wells from proppant, which requires the use of additional proppant management techniques or calculation of accident-free well operation and flow rates, in which proppant transport will be unlikely, and the service life of the pumps will increase.

A method for extending the operating time of pumps after hydraulic fracturing is the use of solids management techniques. In some works [15, 16] complex solutions to the problem of solids production are proposed, which include determining the geomechanical parameters of the productive formation and critical operating modes in which the flow does not carry solids into the well [17–20]. However, these methods are poorly applicable to wells after hydraulic fracturing, since they are extremely difficult to implement, and residual proppant is always present in wells after hydraulic fracturing. Other works are aimed at studying methods to prevent the transport of carried out solids to the pump intake. In reviews [21, 22] the authors conclude that the best way of solids management in oil and gas wells, and providing greater flow capacity, is the use of pre-packed gravel screens, which are quite expensive. Despite the large number of equipment and techniques for preventing solids from entering the pump intake, not all of them are effective, and this problem remains relevant and has not been fully resolved [23,24]. Failures in solids management in oil wells are caused by improper selection of equipment, overfilling of containers, blocking, corrosion and erosion of filters, and a decrease in their flow capacity [25, 26]. Also, the use of additional equipment is associated with costs, which is especially critical in low-flow wells.

The choice of relatively expensive solid management equipment in low-flow wells for the operator company requires additional justification of the probability of proppant transport to the pump intake, which requires an understanding of the proppant transport mechanism in a multiphase flow [27]. The review showed that calculations of critical flow rates in pipes require knowledge of the influence of fluid flow modes, pipe inclination angle, particle size, viscosity and density of the fluid, solid density and their shape, as well as the presence of immiscible phases on solid transport [28]. Factors such as density, viscosity and particle size are combined in the Stoke's equation and are suitable for calculating the settling velocity of solids in vertical pipes [29–31]. The influence of other parameters on the transport of solids, including proppant, in wells is a subject of open discussion.

The angle of the well usually worsens the transport of solids, as they are more prone to settling on the lower wall of the pipe. In the work [32] an experimental study and numerical modeling of sand transport in a single-phase flow were carried out; it was established that gravitational separation causes the sedimentation and movement of sand in the lower part and its transport requires a higher flow velocity than in a vertical pipe. The transport of solids is also influenced by their shape [33–35], in work [36] it has been shown experimentally that particles with a more regular spherical shape have a lower tendency to be transported due to their lower coefficient of hydraulic friction. The sphericity of the proppant reduces the drag force acting on the particles, as a result of which the proppant is transported at higher flow rates.

The influence of multiphase flow on the transport of solids have been studied by various authors [37–41]. The presence of immiscible phases in the flow leads to flow disturbance and local eddies, intensifying the transport of solids. In works [39, 42] experimental studies of the effect of gas on sand transport in inclined wells have been conducted, but the effect of the presence of oil on sand transport has not been studied. In works [40] the mechanism of solids transport in a horizontal pipe with a flow of three phases - solids and two immiscible liquids (water and oil) was investigated, it was found that solids transport is improved by flow perturbation with an increase in the content of a lighter phase (oil) and a decrease in the intermediate (water), due to a local increase in flow velocity. However, in all these studies of solids transport, firstly, sand is considered as a solid, and secondly, high flow rates are considered, which are not typical for low-flow oil wells in the Perm region [43, 44].

Thus, based on the review, it was established that the proppant transport mechanism from the wellbore to the pump intake has not been sufficiently studied and requires additional research to improve the proppant management technique in low-flow oil wells [45–47]. In addition, according to the results of field trials, the data obtained do not correlate with the theoretical ones, for example, according to the Stoke's equation, the settling rate of 16/20 proppant (850–1180 μm) is equivalent to the flow rate of pure oil with a viscosity of 15 mPa·s of about 50 m^3 /day, which is a very high value for the Perm region fields. However, field trials have shown that even in low-flow wells (4–12 m^3/day) proppant is transported to the pump, causing it to fail. As part of the field trials of well operation after hydraulic fracturing without cleaning the bottomhole from proppant, it was found that the pumps quickly fail due to proppant getting into them. The pump operating time is on average 125 days (from 2 to 227 days) for sucker rod pumps and 238 days (from 165 to 406) for ESP. Wells with sucker rod pumps and gravity solid separators had almost twice the pump operating time - 140 days compared to 86 days for pumps without separators. However, the effect of gravity separators is insufficient and unstable, some wells with gravity separators operated from 2 to 10 days. However, according to theoretical calculations of the proppant settling rate using the Stoke's equation (1), it was found that the deposition rate is higher than the actual rate of liquid rise:

$$\vartheta = \frac{gd^2(\rho_p - \rho_f)}{18\mu_f}. \quad (1)$$

An analysis of existing studies has revealed a clear trend towards studying erosion processes in the bottomhole formation zone [48, 49], caused by both mechanical destruction of rock under stress and a decrease in reservoir pressure in combination with high-speed flows [50–52]. However, the studies reviewed lack a systematic analysis of the mechanisms of transport of mechanical particles in the wellbore, and do not disclose the patterns of formation of sand and proppant plugs [53, 54]. Key factors, namely the lack of experiments using four-phase liquid-liquid-gas-solid systems, have not been sufficiently studied. This gap in research requires a detailed consideration of the dynamics of sedimentation-transport processes in relation to the operating conditions of wells with a high content of mechanical impurities. Analysis of hydrodynamic conditions in the wellbore, taking into account the multiphase nature of the flow of oil-gas-water mixtures, makes it possible to substantiate the hypothesis of the involvement of proppant particles in floating oil droplets. The key factors of this process are:

- The difference in densities, which determines the relative rate of ascent of oil droplets in an aqueous medium;
- The effects of interfacial surface tension at the oil-water interface, which promote the adhesion of solid particles to the surface of the droplets;
- The presence of a fluidized layer of proppant in the bottomhole zone, which provides a constant source of particles for transport;
- The turbulent flow, which promotes the interaction of dispersed phases.

The relevance of this study is due to the need to optimize the operation of low-flow wells in order to increase their economic profitability. A critical aspect in this case is ensuring long-term uninterrupted operation of production wells with a minimum of interventions. Of particular importance is the reduction of repair operations associated with the replacement of failed pumping equipment, since they cause significant production downtime and significant capital costs. The solution to this problem requires an integrated approach that takes into account both the technological parameters of operation and the physicochemical processes in the bottomhole formation zone and the wellbore.

1. Methodology

During well operation, regardless of water cut, the fluid flow along the wellbore from the perforation interval to the pump has a droplet-bubble structure, with an external phase of water and oil droplets and gas bubbles floating in it. In this paper, a hypothesis is put forward that oil droplets, due to interfacial tension forces, are capable of picking up and carrying away proppant particles when floating in the water flow from the well bottom to the pump intake. To confirm the hypothesis, experimental studies were conducted on a setup simulating an oil producing well. The paper also presents the dependences of proppant transport intensity on well operating modes, flow rate, and gas factor.

For experimental studies of proppant transport from the bottomhole to the pump intake in the well, a physical model of the well consisting of a plexiglass pipe was used (Fig. 1). In the lower part of the model, there are tubes simulating perforations through which water, oil/kerosene and air, simulating formation fluids, are supplied to the model. Fluids pass through the solids layer and rise to the top in the form of drops and bubbles into the drainage system simulating the pump intake. The effluent is collected in a drainage tank, where water, oil/kerosene and solids are separated. The effect of well operating modes on the intensity of solids transport is determined by the dry mass of the removed solids. The plexiglass pipe can be tilted in 15-degree increments to assess the effect of the well zenith angle on the proppant transport intensity. In this work, the proppant transport intensity was studied at zenith angles of 0, 15, 30, 45, 60 and 75 degrees. Fluids and gas were fed into the pipe model using a peristaltic pump with flow rates from 40 to 320 ml/min, which corresponds to oil well fluid flow rates of up to 12 m^3/day. A relatively small range of well flow rates was chosen to understand the causes of proppant clogging of pumping equipment under the condition that the proppant settling velocity exceeds the velocity of the ascending fluid flow based on the Stoke's equation.

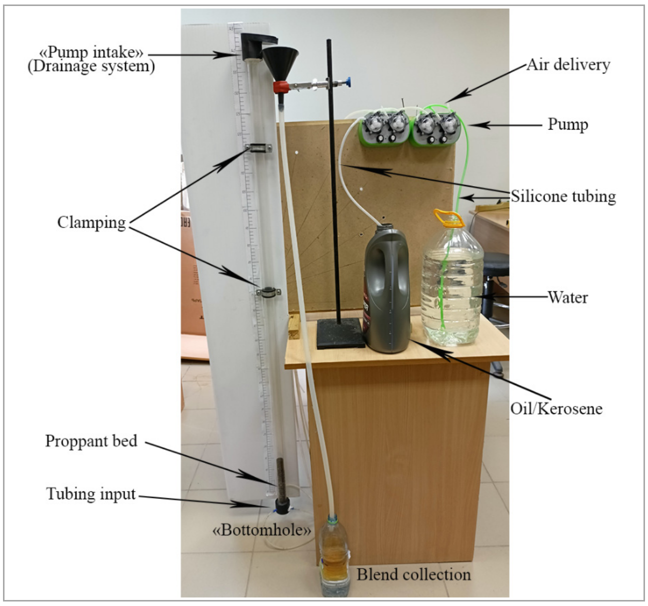


Fig. 1. Experimental setup

In the study, fresh water with a density of 1000 kg/m^3, oil with a density of 850 kg/m^3 and kerosene with a density of 850 kg/m^3 were used as fluids. The viscosities of oil and kerosene under the experimental conditions are 1.49 and 192.3 mPa·s, respectively; such a wide range of viscosities covers all oils in the Perm region. Regardless of the fluid flow rates, a bubbling mode was set in the pipe – oil/kerosene and air floated up in the form of drops and bubbles in water (Fig. 1). Quartz sand with an average grain size of 100 μm, a mineral density of 2700 kg/m^3 and proppant with a fraction of 16/20 (850–1180 μm) and a mineral density of 3080 kg/m^3 were used as solids.

2. Results and discussion

2.1. Solids bed fluidizing

Transport of solids to the pump intake depends on how the particles are carried into the well and interact with the flow. For more accurate physical modeling of well processes of solids transport, it is necessary to find out how solids are produced, and to assess whether solids can accumulate, block the well bottom and prevent the flow of new solids. To do this, it is necessary to assess whether the solids bed in the well is in a stable or fluidized state. A stable solids bed is a mechanical barrier and prevents the production of particles into the well. A fluidized bed slightly impedes the flow of liquid due to relatively constant hydraulic resistance, but does not prevent the production of solids, since the bed is mobile and does not serve as a mechanical barrier.

Fluidization is a physical and mechanical process of transforming a static bulk material into a dynamic state that imitates the behavior of a liquid. Unlike classical liquefaction, in which the gas passes into the liquid phase, fluidization affects dispersed systems that can exhibit fluidity under certain conditions.

The main mechanism of fluidization is realized during the ascending movement of the gas or liquid phase through a granular layer. This phenomenon is caused by the balance (or imbalance) of two key forces: the aerodynamic resistance created by the flow and the gravitational effect on the particles. An alternative option for forming a fluidized layer is possible with a combination of aerodynamic resistance and centrifugal forces.

When a gas flow is fed through the base of the apparatus containing granular material, it is filtered through interparticle pores. At the initial stage, at low gas velocities, the aerodynamic resistance forces are insufficient to overcome the gravitational attraction, and the layer retains its structural integrity. However, as the flow velocity increases, the hydrodynamic effect on the particles increases, which leads to their mutual repulsion and an increase in the volume of the layer.

When a critical velocity is reached, an equilibrium is reached between the lifting force of the aerodynamic resistance and the force of gravity, as a result of which the particles pass into a suspended state, demonstrating properties characteristic of a liquid. Further intensification of the flow causes a decrease in the average density of the layer, increasing pseudo-fluidization to the point where the particles completely lose cohesion and are evacuated by the flow.

When the material layer passes into a fluidized state, it is transformed from a stationary layer into a dynamic system. In this case, the particles acquire properties similar to those of a liquid. The contact area of the particles with the gas flow increases, which leads to a sharp increase in the ability to transfer heat from the flow to the particles.

For the phenomenon of fluidization to occur in a layer of bulk material, the air flow must have sufficient pressure and speed. The air flow moves upward, passing through the layer of particles (with a linear increase) through a multitude of holes in the distributor located in the lower part of the layer. At low air flow speed, the pressure on the particles is insignificant, and the layer maintains the state of a stationary layer. With a further increase in the flow speed, an aerodynamic effect occurs that is opposite to the gravity of the particles, which leads to the expansion of the layer by volume, and the particles begin to move away from each other.

When the flow speed reaches a critical value, the friction force between the particles and the air becomes equal to the weight of the particles. At this point, the vertical component of the compression pressure disappears, the lifting force balances the gravity, and the particles are suspended in the air flow. When the gas velocity reaches a critical value, the material layer passes into a completely fluidized state, called a fluidized bed, and acquires properties similar to a liquid.

A further increase in the gas velocity leads to a decrease in the bulk density of the particle layer, and the fluidization becomes more intense until the particles cease to form a stable layer and begin to move chaotically in the flow. In this state, each particle is surrounded by a gas flow, and the heat and mass transfer processes are most intense. In full fluidization, the bed of material takes the shape of the chamber, and its surface remains perpendicular to the gravity vector. Objects with a density lower than the bed's density float to the surface, performing oscillatory movements, while denser objects sink to the bottom. When an air flow with sufficient pressure and speed passes through a bed of stationary spherical particles, the latter begin to expand (the particles become "mobile"). In this state, the system reaches minimum fluidization, which is described by the modified Ergun equation:

$$\frac{\Delta P}{H_{mf}} = \frac{150\mu_f(1-\varepsilon_{mf})^2 V_{mf}}{\varepsilon_{mf}^3 d_p^2} + \frac{1{,}75(1-\varepsilon_{mf})\rho_f V_{mf}^2}{\varepsilon_{mf}^3 d_p}. \quad (2)$$

For particles of arbitrary shape, the pressure drop in the state of minimal fluidization is expressed by the following equation. In this case, the sphericity of the particles (φ) is taken into account through the equivalent diameter (d_m):

$$\frac{\Delta p}{H_{mf}} = 150\frac{(1-\varepsilon_{mf})^2 \mu_f V_{mf}}{\varepsilon_{mf}^3 (\phi d_m)^2} + 1{,}75\frac{(1-\varepsilon_{mf})\rho_f V_{mf}^2}{\varepsilon_{mf}^3 \phi d_m}. \quad (3)$$

For the bed to transition from a stationary state to a fluidized state, the air flow pressure must be sufficient to overcome the weight of the particles, which is determined by the following equation:

$$\Delta p = \frac{m}{\rho_p A}(\rho_p - \rho_f). \quad (4)$$

In this equation, it is assumed that there are no interaction forces between the particles in the layer and between the particles and the walls of the tank, which eliminates additional pressure growth. Thus, the pressure drop remains constant as the gas velocity increases from the minimum fluidization velocity to the moment when the particles begin to be carried away.

Ergun's equations also show that the pressure drop in a fluidized bed depends on: particle size (d_p), bed porosity (ε), gas temperature (t). According to the last equation, the pressure drop of a gas flow through a bed of particles depends on: the mass of the material (m), surface area (A), particle density (ρ_p), gas density (ρ_f).

Thus, the value of minimum fluidization velocity ($V_m f$) for non-spherical particles can be calculated by solving the following equation based on the equations presented above:

$$\frac{mH_{mf}}{\rho_p A}(\rho_p - \rho_f)g = 150\frac{(1-\varepsilon_{mf})\mu_f V_{mf}}{\varepsilon_{mf}^3 (\phi d_p)^2} + 1.75\frac{\rho_f V_{mf}^2}{\varepsilon_{mf}^3 \phi d_p}. \quad (5)$$

The minimum fluidization velocity (V_{mf}) is determined by the following parameters: bed height at minimum fluidization (H_{mf}), particle mass on the air distributor (m), gas distribution area (bed cross-section, A), particle (ρ_p) and gas (ρ_f) density, average particle diameter d_p, particle sphericity (φ), bed porosity at minimum fluidization (ε_{mf}).

Thus, based on theoretical calculations (Fig. 2) and experimental studies, it has been established that the solids bed at the well bottom is not stable and, in most cases, corresponding to real well operating conditions, is in a fluidized state. Based on this, it can be argued that the conditions of oil wells are favorable for the formation of a solids bed at the well bottom, and its size is not limited and depends only on the production capacity of the formation. This confirms the assumption that the solids bed can completely block the perforation holes. Also, experimental studies have shown that an ascending two-phase flow (water/gas), equivalent to oil well flow rates from 4 to 12 m^3/day and a relative gas content of up to

50 %, is not able to transport either proppant or sand, which confirms theoretical calculations according to the Stoke's equation. At the same time, this does not explain the reason for the transport of solids, namely proppant, in oil wells with low-flow rates.

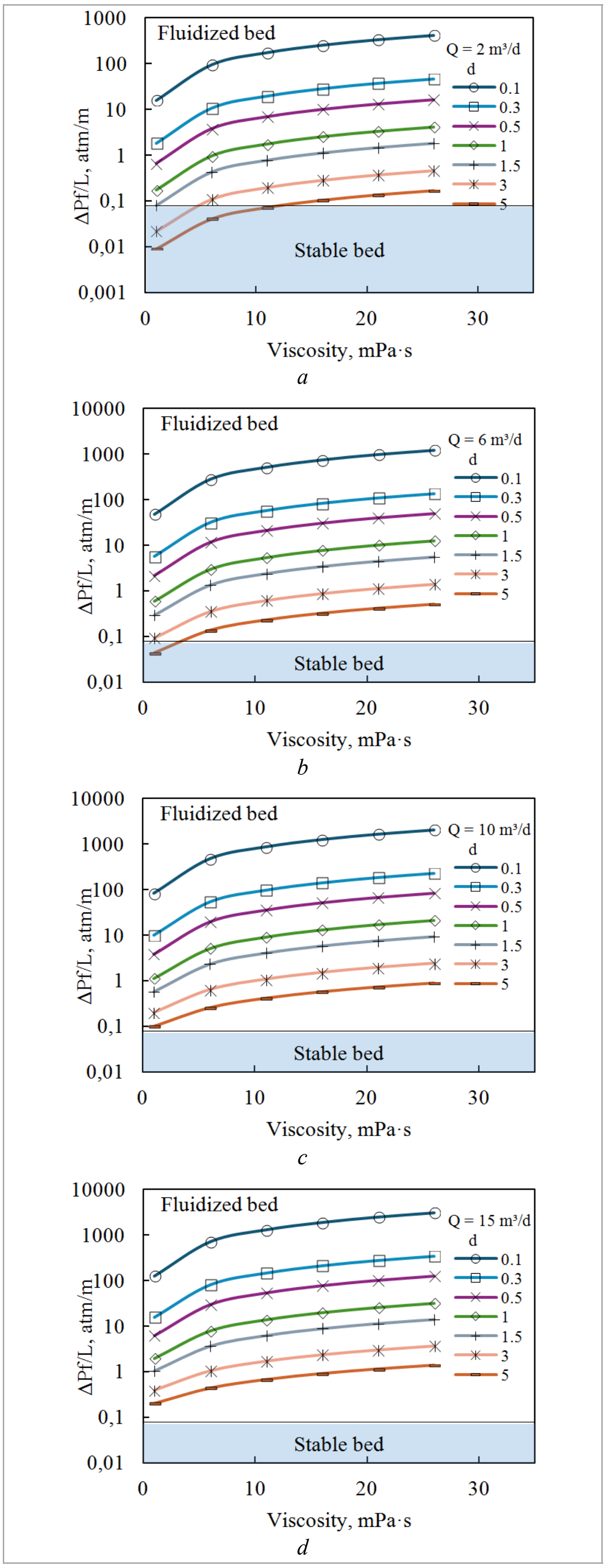


Fig. 2. Calculated values of filtration pressure drop in solids bed depending on the viscosity of the fluid for a flow of 2 m^3/day (*a*), 6 m^3/day (*b*), 10 m^3/day (*c*) and 15 m^3/day (*d*)

2.2. Droplet proppant transport

The transport capacity of a three-phase immiscible flow was studied using a proppant bed as an example, which, as shown by the studies above, is less prone to transport by a water-gas flow. When water, oil/kerosene, and air were fed through a proppant bed together, it was found that oil/kerosene droplets were capable of capturing proppant and transporting it. It was also found that the flow rate of water, kerosene, or oil did not affect the relative proppant content in the ascending flow. It was found that the proppant transport intensity was affected by the volumetric gas content in the ascending flow and the pipe inclination angle. The graphs (Fig. 3) show that when oil and kerosene floated in a vertical pipe, the largest amount of proppant was carried out with a maximum concentration of 3.7 g/l. The proppant concentration in the flow decreased as the zenith angle of the pipe increased, and when the inclination was more than 60°, the proppant was not carried out by either kerosene or oil. The proppant concentration is highly dependent on the presence of gas in the upstream flow. Without gas, the proppant concentration in oil is minimal, and in kerosene it is absent. The quantitative gas content has little effect on the proppant concentration in the oil flow, but in kerosene, the proppant concentration tends to increase with increasing gas content (Fig. 3, *b*).

The influence of the angle of inclination and the presence of gas on the transport capacity of the flow and the concentration of proppant is determined by the way in which kerosene and oil exit the proppant bed, since at the moment of exit from the bed, droplets are formed and proppant grains are captured. During the experimental studies, it was visually established that in a two-phase flow without gas, oil and kerosene float on the surface of the proppant bed in several ways – in the form of drops coming out of the surface of the proppant bed or in the form of a rill flowing along the pipe wall. The formation of a drop of oil or kerosene occurs on the surface of the proppant bed or on the tip of the rill. The surface of the bed has low filtration resistance, since the proppant grains lie unevenly and the distance between them is large. Due to this, the particles on the surface of the bed are less fluidized and are poorly captured by the ascending flow. With low viscosity kerosene, the proppant is not captured by drops without gas at all. High viscosity oil is able to capture proppant in rills and carry it away with the ascending flow (Fig. 4).

It was visually established that oil with higher viscosity is more prone to floating up in the form of rills both in the flow without gas and with gas (Fig. 4). Formation of oil or kerosene rills along the pipe wall is more prone in an inclined pipe, since lighter oil and kerosene move along the upper wall of the inclined pipe (Fig. 4). In both cases, the probability of proppant particle capture is higher in the fluid in which the flow velocity in the rill or in the droplet is higher than the proppant settling velocity. In high-viscosity oil, the proppant settling velocity is lower than the oil floating velocity, therefore, proppant is carried away in the flow without gas, and with kerosene, proppant is not carried away without gas (Fig. 3).

The concentration of proppant in a 2-phase flow of water and oil without gas is significantly lower than with gas. Without gas, the oil rises in a thin and relatively smooth rill along the pipe wall (Fig. 4). Due to the high viscosity, the oil rill can reach a significant height above the proppant bed. Figure. shows that the oil rill reaches a height of 50 cm above the proppant bed, then at the tip of the rill it is transformed into oil drops. The photo also shows how the proppant grains gradually rise along the rill and when a drop is formed, they float to the top with them. The proppant moves uniformly along the entire length of the oil rill. In places of rill curvatures, the proppant collects in a heap due to the reduced flow rate.

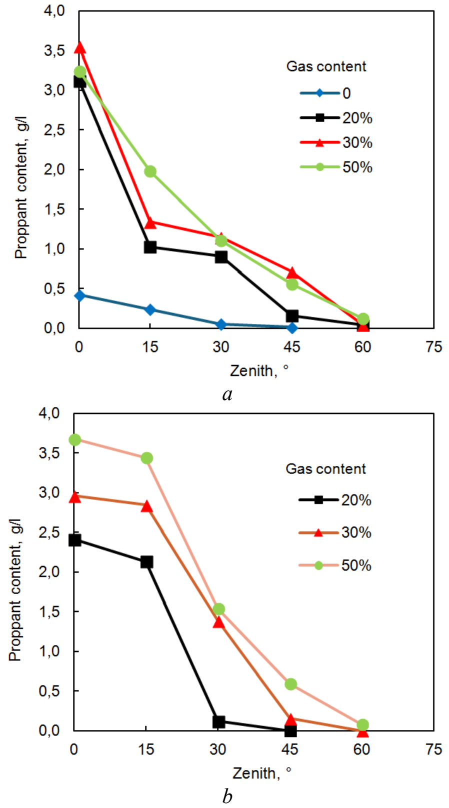


Fig. 3. Concentration of proppant in the ascending flow depending on the wellbore inclination angle and gas content: *a* – Oil; *b* – kerosene

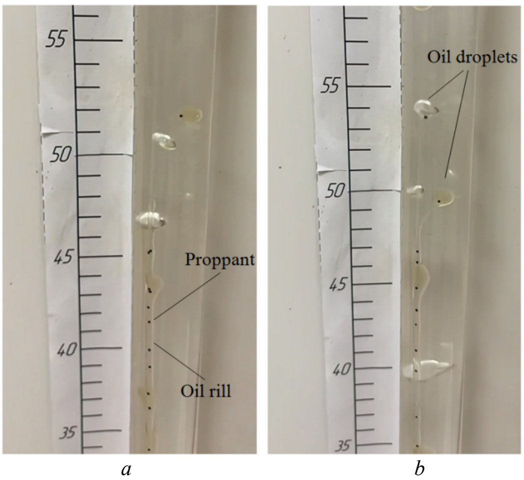


Fig. 4. Formation of oil droplets and proppant capture in a vertical pipe with gas

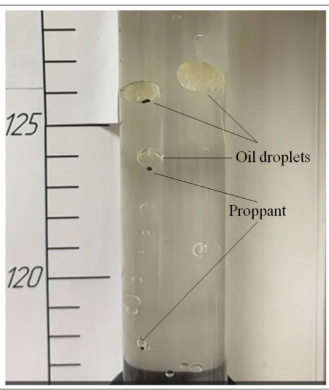


Fig. 5. Oil droplet formation and proppant entrapment in a vertical pipe without gas

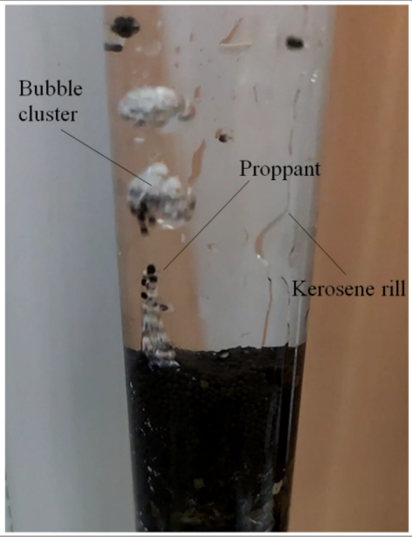


Fig. 6. Formation of kerosene droplets and proppant capture in a vertical pipe when exiting the proppant bed

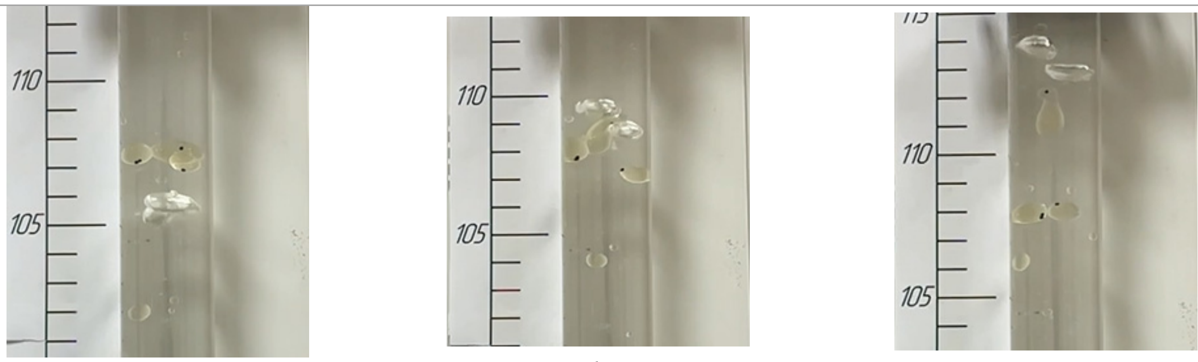
Proppant in high-viscosity oil is transported in droplets in several ways: within a droplet in the oil phase, at the bottom of a single oil droplet in the water phase, and at the bottom of several oil droplets in the water phase. High-viscosity droplets also have an emulsified water-oil nature, caused by the combined floating of oil and water through the porous proppant bed.

It has been experimentally established that without gas, kerosene does not transport proppant because kerosene, leaving the proppant bed, is not able to pick up proppant grains from the surface, since it has insufficient viscosity. With kerosene, proppant transport occurs only when fed together with gas (Fig. 3, *b*). In this case, a direct dependence of the proppant concentration in the flow on the gas content is observed, which is also confirmed visually (Fig. 6).

The effect of gas on the transport capacity of kerosene is due to the fact that, leaving the proppant bed, gas bubbles throw up proppant particles and thereby facilitate its capture by kerosene droplets. It was also found that kerosene and gas jointly exit from the same points on the surface of the proppant bed (Fig. 6). This phenomenon is due to the fact that rising gas bubbles fluidize the proppant bed, locally increasing the distance between the proppant grains and forming a fluidized channel with high conductivity. And in the rest of the proppant bed filled with water, the relative phase permeability for kerosene is low.

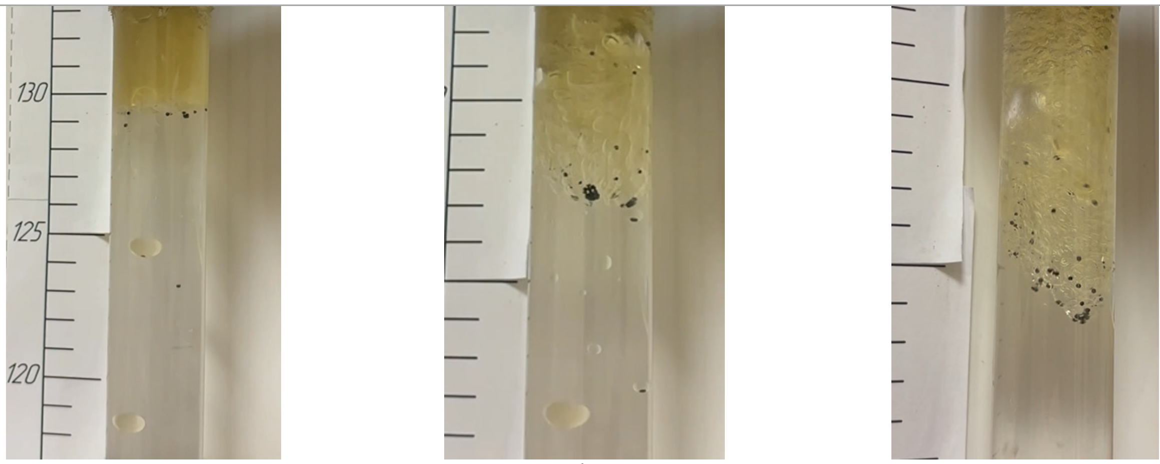
Visual observation also showed that when gas is supplied, kerosene can also flow out of the proppant bed in the form of a kerosene rill along the pipe wall (Fig. 6). Unlike oil, a kerosene rill is not able to pick up and carry out proppant grains due to its low viscosity (Fig. 6). However, the flow inside the proppant bed is not stationary due to the fact that the emerging gas causes pressure pulsations, as a result of which the gas outlet location is constantly changing. When gas passes through a kerosene rill, proppant is thrown up and its droplet capture is induced (Fig. 6).

Thus, it has been established that the main condition for proppant transport is capture by droplets when exiting the bed. The mechanism of proppant capture by droplets of low-viscosity kerosene has also been disclosed, which consists in throwing up particles by exiting gas bubbles and holding them in droplets due to surface tension forces. In highly viscous oil, proppant capture occurs due to excess of the oil ascent velocity compared to the proppant settling velocity. It has also been established that the proppant concentration does not depend on the viscosity of the immiscible fluid.



a *b* *c*

Fig. 7. Interaction of oil droplets with trapped proppant and gas bubbles: *a* – joint movement; *b* – disturbance of droplets by bubble; *c* – droplet and gas slug



a *b* *c*

Fig. 8. The interface between water and oil phases in the pump intake zone: *a* – emulsified zone when gas passes; *b* – flat zone without gas

2.3. Joint ascent of bubbles and droplets with captured proppant

When floating up the pipe, oil droplets and gas bubbles in water move with different velocities, which causes vortices and strong mixing in the ascending flow. Flow perturbations lead to internal vortices inside the droplets, and they can also change their shape. Proppant grains captured inside the droplets are held by interfacial tension forces, but with significant droplet deformation or change in its direction, sudden stops or accelerations, proppant can theoretically jump out of the droplet due to inertia, overcoming the interfacial tension force. In connection with the theoretical probability of proppant escape and the effect on the ability of proppant transport, experimental studies of the effect of gas bubbles in the flow on the stability of proppant removal by the droplet flow were performed in this work.

The influence of gas bubble ascent velocity on the stability of proppant capture by oil and kerosene droplets was studied. Visual observations showed that when overtaken by bubbles, oil droplets slightly change their shape, but proppant never separates from the droplets. Several types of interaction between bubbles and droplets were also established. Bubbles smaller than ½ the pipe diameter do not have a disturbing effect on droplets with proppant. The photographs (Fig. 7) show that bubbles and droplets can move together. When droplets are in a hydrodynamic zone of low pressure (Fig. 7, *c*), they rise extremely quickly. A video of the experimental studies can be viewed by following the link provided in the Attachments section.

In the kerosene experiments, the gas bubbles tend to form dense clusters [55] and float together (Fig. 6). The kerosene film on the bubble surfaces prevents them from merging into one large bubble as in the oil experiments. Because the bubbles in the kerosene experiments float in clusters, they not only have a gentler effect on the kerosene droplets, but also promote their faster transport to the top.

In addition to transport along the wellbore, a mandatory condition for proppant to enter the pump is its retention and accumulation in the annular space near the pump intake. It has been visually established that the emulsion structure in the pump intake area helps to retain a larger amount of proppant than with a smooth phase boundary (Fig. 8). It has also been established that the presence of gas in the flow helps to form an emulsion structure (Fig. 8, *b*, *c*). The rising gas bubbles pick up water and mix it with oil and kerosene at the phase boundary, which leads to the formation of a large intermediate emulsification zone. The presence of proppant in the emulsion above the interface is due to the fact that droplets of oil and kerosene with captured proppant can move after the gas bubbles.

Operation of wells after hydraulic fracturing without cleaning the bottomhole from residual proppant, as well as wells with a tendency to produce proppant, carries high risks of early failure of pumps. In the work, based on the results of experimental studies, the mechanism of proppant transport in low-flow oil wells is revealed. An illustration of the mechanism of proppant capturing and transport is shown in Figure. . The proppant, weakly fixed in the crack, is carried to the bottomhole of the well by the flow of formation fluid, where it accumulates and forms a bed. The fluid flowing out of the formation, passing through the bed, fluidizes it. The rising oil droplets and gas bubbles pick up the proppant and transport it to the pump intake, where the proppant is held fairly well by the emulsified oil before being sucked in (Fig. 8).

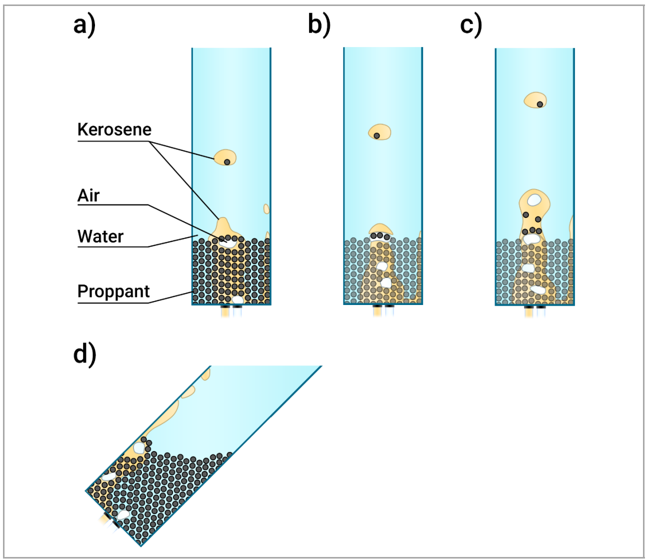


Fig. 9. Illustration of the mechanism of proppant production and its transport to the pump intake in an oil well (*a*) – general view; (*b*) – oil seepage through the proppant bed; (*c*) – free proppant in the crack; (*d*) – oil droplet exiting on the surface of the proppant bed

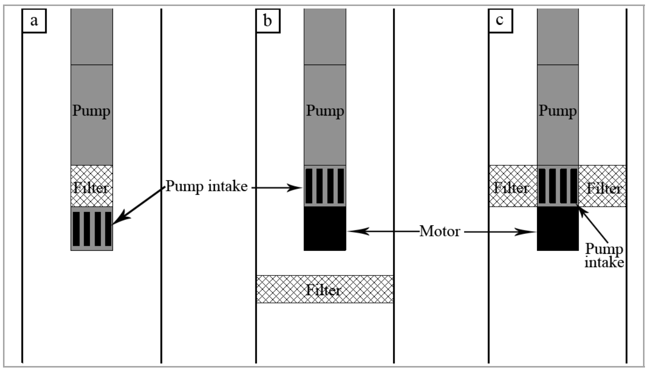


Fig. 10. Filter installation options: *a* – rod pump; *b*, *c* – ESP

As the results of field trials show, the methods used to protect pumps from ingress of proppant, namely the use of gravity separators, show poor efficiency. Knowing the mechanism of proppant transfer, it can also be confirmed that devices operating on the principle of gravitational separation will not work.

Effective means to protect the pump are filtration devices that allow to keep particles from 850 microns in size (since this is the smallest particle size of the proppant fraction 16/20). For such valves, coarse filters can be used, for example, mesh filters or filters with gravel packing.

The location of the filter depends on the layout of the submersible pump. If a pump is installed without a submersible electric motor (Fig. 10, *a*), such as sucker rod pumps, then the filter can be installed directly at the pump intake, since nothing prevents its installation If there is a submersible electric motor in the pump layout, such as an ESP, it prevents the filter from being installed at the pump intake. In this case, one option is to install the filter on the casing below the pump intake, but above the perforation interval (Fig. 10, *b*), another option is to install the filter in the annular space opposite the pump intake (Fig. 10, *c*).

Conclusions

The study provides critical insights into the mechanisms governing proppant transport in low-flow oil wells following hydraulic fracturing, addressing a persistent challenge in the industry. Key findings reveal that proppant, despite its tendency to settle rapidly under theoretical assumptions, is effectively transported to the pump intake due to the interaction with immiscible hydrocarbon droplets and free gas bubbles. This mechanism, driven by interfacial tension forces and the dynamic behavior of multiphase flow, operates independently of fluid viscosity, which was previously considered a primary determinant of transport capacity. The experiments demonstrate that the proppant concentration in the flow does not correlate with well flow rates, underscoring the dominance of multiphase flow dynamics over hydrodynamic factors in low-flow scenarios.

The presence of free gas bubbles is identified as a pivotal factor in enhancing proppant transport, as they facilitate the capture and elevation of proppant particles by oil and kerosene droplets. This finding aligns with field trial data, which shows a strong inverse relationship between gas content under bottomhole conditions and pump operating time, with high gas saturation leading to accelerated pump failure. The contradiction between theoretical predictions based on the Stoke's equation and observed low-flow transport phenomena highlights the inadequacy of single-phase models for assessing proppant behavior in real-world, multiphase environments. This discrepancy necessitates a reevaluation of existing methodologies for predicting critical flow rates and designing proppant management strategies.

Statistical analysis of field trial data further revealed limitations in correlating pump failure solely with fluid properties or operating modes, emphasizing the complexity of interactions in low-flow wells. The study's experimental approach, utilizing a plexiglass pipe model with controlled variables, elucidates that fluidization of the proppant bed, induced by gas and oil phases, is the primary driver of transport. This fluidization process, observed across a range of well angles and flow rates, occurs even at low fluid viscosities, challenging conventional assumptions about gravitational separation. The results also demonstrate that particle size distribution, particularly the presence of larger proppant grains, influences localized fluidization and transport pathways, with gas bubbles acting as key agents in mobilizing these particles.

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