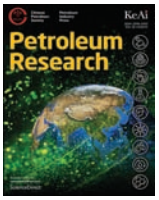
Petroleum Research 11 (2026) 163–175

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/



Full Length Article

An experimental study of proppant transport mechanisms to the pump intake in low-flow oil wells



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ARTICLE INFO

Article history:
Received 9 June 2025
Accepted 27 July 2025
Available online 5 August 2025

Keywords:
Proppant
Proppant management
Sand management
Sand production
Proppant production
Oil well

ABSTRACT

The exploitation of low-flow oil wells following hydraulic fracturing is often hindered by residual proppant and proppant production during early production phases, which can infiltrate pumps and drastically shorten their service life. Managing proppant reliably and cost-effectively in these wells remains challenging due to the limited understanding of proppant transport mechanisms from the well bottom to the pump intake. This manuscript addresses this critical knowledge gap by presenting novel experimental insights into proppant transport in low-flow oil wells, marking the first elucidation of the underlying mechanism. Through innovative laboratory experiments simulating post-fracturing well conditions, we demonstrate that proppant invariably ascends to the pump intake, driven by a previously unrecognized process: droplets of immiscible hydrocarbon fluids capture and transport proppant particles upward. Comparative analyses using fluids of varying viscosities reveal, for the first time, that the viscosity of the immiscible phase has negligible impact on droplet transport capacity. Additionally, our studies establish that proppant concentration during transport is independent of well flow rate, challenging conventional assumptions. A key novel finding is the pivotal role of free gas bubbles in enhancing proppant transport probability, as they facilitate capture by oil and kerosene droplets; higher gas content correlates directly with elevated proppant concentrations in the flow. These experimental discoveries are validated by field trial data from wells with high free gas content under bottomhole conditions, where reduced pump operational times were observed, confirming the mechanism's real-world relevance. By unveiling this transport mechanism, the manuscript provides a foundational basis for developing targeted proppant management strategies, offering new pathways to enhance pump longevity and operational efficiency in low-flow oil wells.

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1. 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 (Novikov and Martyushev, 2024; Turbakov and Shcherbakov, 2015). At such fields, hydraulic fracturing is vital to maintaining the economic efficiency of oil production (Dieng et al., 2023; Guo et al., 2025; Khizhniak and Dieng, 2023). 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 (Guo et al., 2024; Pandey, 2023; Parker et al., 1999). One possible way to reduce costs at low-flow wells is to avoid additional interventions

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Peer review under the responsibility of Editorial Office of Petroleum Research.

https://doi.org/10.1016/j.ptlrs.2025.07.007
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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 (Dengaev et al., 2022). 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 (Peretomode et al., 2022; Webster and Tovar, 1999), 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. 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 (Ahad et al., 2020; Salahi et al., 2021) 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. 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 (Khan et al., 2024). 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. 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 (Zhiliang et al., 2025). 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. 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 (Yang et al., 2019) 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, in work (Deal et al., 2023) 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 (Bakyt et al., 2022; Feng et al., 2023; Najmi et al., 2015; Nejati et al., 2025). The presence of immiscible phases in the flow leads to flow disturbance and local eddies, intensifying the transport of solids. In works (Najmi et al., 2015; Zhang et al., 2022) 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 (Nejati et al., 2025) 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.

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. Also, based on the analysis, it can be preliminarily concluded that the conditions for proppant transport in vertical and slightly curved low-flow oil wells, typical for the Perm region fields, are very unfavorable, since the proppant size is large enough and its settling rate is greater than the fluid flow rate in the wells. 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. All this necessitates additional research to uncover the proppant transport mechanism and improve proppant management techniques.

2. Field trials

Field trials of well operation without proppant cleaning after hydraulic fracturing were conducted at Perm region fields. Wells for trials were selected based on comparative theoretical calculations of proppant settling velocity and expected fluid flow velocity in the well. Proppant has a fairly regular spherical shape, so its settling velocity can be calculated using the Stoke's equation:

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

where d– particle diameter, ρ_p– particle density, ρ_f– density, μ_f– fluid viscosity.

Comparison of theoretical proppant settling velocities according to the Stoke's equation (1) and fluid velocities in the wells showed that at planned and actual flow rates, the fluid velocity in all wells is lower than the estimated proppant settling velocities. The graphs (Fig. 1) show the ratios of actual and equivalent oil and water flow rates to viscosity. An equivalent flow rate is understood as a flow rate at which the fluid velocity is equivalent to the proppant settling velocities. From the graphs (Fig. 1) it is clear that the actual flow rates are much lower than the equivalent ones. Thus, it was concluded that the probability of proppant transport is low and the well pumps should operate for a long time without

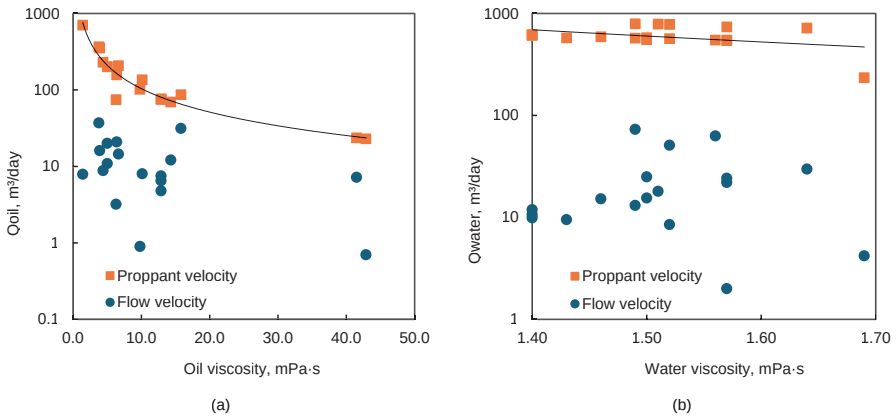


Fig. 1. Comparison of the actual flow rate and the estimated equivalent flow rate corresponding to the proppant settling velocity in oil (a) and water (b). Blue dots correspond to the actual well flow rates, orange dots correspond to the equivalent flow rates corresponding to the proppant settling velocity.

accidents without well interventions. Based on this conclusion, it was decided to conduct field trials on well operation after hydraulic fracturing without well cleaning from the remaining proppant.

Field trials were conducted on 18 wells, 10 of which were equipped with sucker rod pumps and 8 with electric submersible pumps (ESP). Six wells with sucker rod pumps were equipped with gravity solid separators. 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.

It is obvious that the pump service life is affected not only by its design, but also by the concentration of solids and proppant in the fluid. All other things being equal, pumps of the same design will fail faster with a higher proppant content. To establish additional causes and conditions under which pumps fail faster, a statistical analysis of the data on the influence of well operating modes and fluid properties on the service life of pumps was performed. The results of the analysis by pump types and the values of the correlation coefficients are presented in Table 1.

The statistical analysis showed that the correlation coefficients between the operating time, operating modes and liquid properties differ by pump types. The most significant relationship was found between the ESP operating time and oil viscosity with a correlation coefficient of 0.77. This means that the higher the oil viscosity, the longer the ESP operates. On the one hand, a liquid with a higher viscosity has a higher proppant transport capacity according to the Stoke's equation (1), and on the other hand, more viscous oil can have better lubricating properties and reduces the degradation of ESP parts. There is no statistical relationship between the Rod pump operating time and oil viscosity. The difference between the two types of pumps is due to different friction modes of the parts in the pumps. The lubrication effect is also confirmed by the fact that for both pump types, the correlation coefficients between the operating time and Oil ratio in gas-fluid mixture (GFM) have increased positive values, the more oil in the mixture, the better the lubrication and the longer the pump operating time.

Some factors have the same negative values of correlation coefficients for both types of pumps, such as: water density, free gas content under bottomhole (BH) conditions and oil velocity. The same effect of these factors on the operating time of both types of pumps has a physical explanation associated with the probability of proppant transport. Water density determines proppant buoyancy and its transport ability. The higher the water density, the better the proppant is transported, the higher its concentration in the fluid and the shorter the pump operating time. Oil velocity determines the oil flow rate and, accordingly, the amount of proppant that gets into the pump. The more proppant, the faster the pump wears out. At the same time, the negative effect of Free gas at BH on the pump operating time is not clear. However, it has been established that wells with the highest Free gas at BH have the shortest operating time of 2 days. 2 wells, in which the Free gas at BH content is zero, i.e. the bottomhole pressure is higher than the saturation pressure, the operating time is the longest and is 206 and 406 days. It is also unclear why the influence of such factors as oil and water viscosity, liquid flow rate on the pump operating time is not statistically confirmed, although all these parameters are part of the Stoke's equation and should have significant negative correlation coefficients. The remaining factors have low or different values of correlation coefficients for different types of pumps.

Thus, based on the field trials data, it was found that statistical analysis does not reveal the true causes of pump failure, and some parameters, on the contrary, are confusing, such as, for example, the effect of oil viscosity, with an increase in which the ESP operating time increases, although intuitively high viscosity should contribute to better proppant transport and rapid wear of the pumps. Also, the quality of statistical data is affected by the limited number of wells, which is associated with high costs for conducting field trials of this kind. Thus, the results of field trials showed that proppant is transported in wells to the pumps and causes their failure. Preliminary, it can be concluded that proppant transport is caused by the fact that the proppant settling rate under well conditions is lower than in theoretical calculations and the Stoke's equation is not suitable for estimating the equivalent flow rate of wells at which proppant transport does not occur. Also, statistical assessment does not reveal the main reasons, in this regard, experimental studies of proppant transport in oil wells were carried out in the work, the methodology and results of which are presented below.

3. Methodology

During well operation, regardless of water cut, the fluid flow along the wellbore from the perforation interval to the pump has a

Table 1
Well operating parameters and values of correlation coefficients for pump operating days.

Parameter	Value			Correlation coefficient to Work days		
	Min	Max	Average	All pumps	Rod	ESP
Pump	–	–	–	0.54	–	–
Work days	2	406	169	1.00	1.00	1.00
Fluid rate, m^3/day	2.0	73.0	22.6	0.34	−0.15	0.05
Oil rate, m^3/day	0.7	37.1	12.1	0.43	0.07	0.26
Water cut	0.15	0.95	0.42	−0.29	−0.49	−0.24
Oil viscosity, mPa·s	1.4	42.9	12.0	−0.16	−0.08	**0.77**
Oil density, kg/m^3	780	898	851	0.00	0.06	0.37
Water viscosity, mPa·s	1.40	1.69	1.51	−0.02	−0.21	−0.02
Water density, kg/m^3	1125	1183	1162	−0.14	**−0.47**	**−0.46**
Casing ID, m	0.089	0.153	0.134	0.39	0.03	0.14
Gas-oil ratio (GOR) m^3/m^3	9	106	42	−0.02	−0.19	−0.24
Gas content, m^3/m^3	8	103	41	0.16	0.05	−0.17
Saturation pressure, MPa	5.13	14.50	8.53	0.07	−0.10	−0.32
Formation temperature, °C	21	35	26	−0.10	−0.38	−0.06
Bottomhole pressure, MPa	2.89	10.60	5.46	0.35	−0.03	−0.07
Free gas at BH, m^3/m^3	−0.013	1.126	0.331	**−0.45**	**−0.31**	**−0.33**
GFM rate at BH, m^3/day	2.5	73.5	25.7	0.24	−0.25	0.02
Oil ratio in GFM	0.05	0.82	0.48	0.59	**0.69**	**0.47**
Water ratio in GFM	0.11	0.95	0.37	−0.20	−0.42	−0.16
Gas ratio in GFM	0.00	0.47	0.15	−0.37	−0.18	−0.26
Water velocity, m/s	0.01	0.06	0.02	0.15	−0.25	−0.02
Oil velocity, m/s	0.17	0.24	0.20	0.08	**−0.29**	**−0.25**
Gas velocity, m/s	0.21	0.28	0.24	−0.02	−0.55	−0.11
Perforations to Pump distance, m	6	549	95	0.27	−0.45	0.02

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. 2). 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°. 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 (1).

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

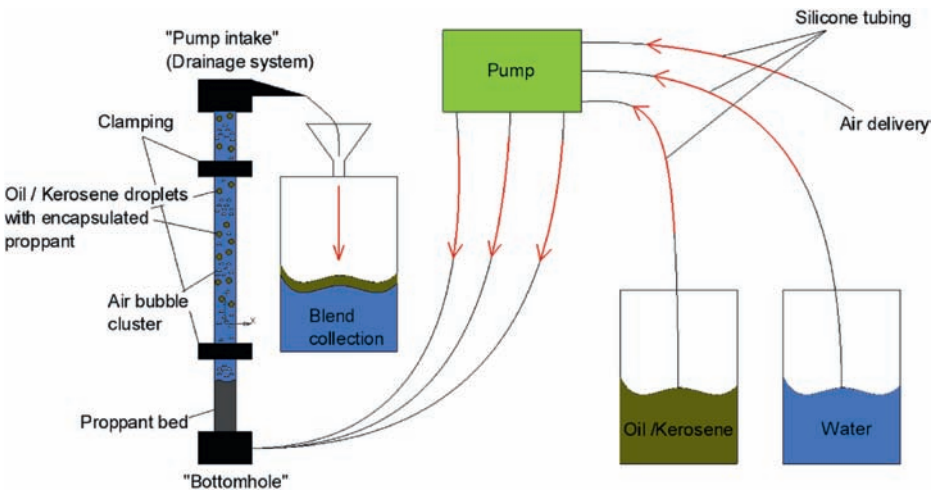


Fig. 2. Scheme of the experimental setup.

bubbles in water (Fig. 2). 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.

4. Results and discussion

4.1. Solids bed dynamics

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.

The stability of the solids bed is determined by the ratio of its hydraulic resistance to its own weight. Since the solids bed is not consolidated and is maintained in a stable state only by gravity, upon reaching a certain pressure gradient, the solids bed can transition to a fluidized state. The dependence of the pressure drop on the flow rate and the dynamics of the solids bed are conventionally shown in Fig. 3. According to the fluidization theory, the solids bed is in a stable state at low flow rates, in which the grains are motionless relative to each other - a zone of linear increase in filtration resistance from the flow rate (Fig. 3). Upon reaching the flow rate at which the filtration resistances of the bed (ΔP_f) become equal to the weight of the solids column taking into account buoyancy (P_b), discontinuities begin to appear inside the bed, voids are formed in the form of drops or bubbles. This is how an unstable fluidized state begins, in which the grains in the bed begin to move. The intensity of particle movement depends on the flow rate. The hydraulic resistance of a fluidized solids bed remains constant until complete dispersion and entrainment. The pressure gradient for fluid flow through a solids bed can be determined using the Ergun formula:

$$\frac{\Delta P_f}{L} = \frac{150\mu(1-m)^2\vartheta}{m^3 \cdot d^2} + \frac{1.75(1-m)\rho\vartheta^2}{m^3 \cdot d} \quad (2)$$

Theoretical calculations of the stability of various solid beds in a well depending on the particle size and fluid properties were performed. The graphs (Fig. 4) show the calculated values of the pressure gradient of a solid bed with particle sizes from 0.1 to 5 mm depending on the viscosity of the fluid for wells with equivalent flow rates of 4 and 12 m^3/day. The graphs highlight the stability zones of the solid bed in blue. The graphs show that the solid bed takes a fluidized state even at very low fluid viscosity and a relatively small well flow rate (Fig. 4b). At a higher flow rate of 12 m^3/day (Fig. 4c), the solid bed is fluidized at any viscosity of the fluid.

An example of a fluidized bed in an experimental setup with water and gas passing through a sand layer is shown in Fig. 4. During fluidization, the size of the solids bed increases, since its porosity increases due to the distance of particles from each other. It is also seen in Fig. 4 that the size of the fluidized solids is limited and is determined by the flow rate and fluid properties. Above the fluidized bed, there is a tail bed zone in which the sand concentration is reduced, but remains quite high. In the setup pipe, fewer particles rise above 30 cm, and above 140 cm, which corresponds to the height of the drainage, sand is not carried out at all, which is visible in the photograph of the filter placed in the drainage (Fig. 4a).

It should be noted that the dependencies shown in (Fig. 4b and c) do not take into account the relative phase permeability of the solids bed. The presence of immiscible oil and gas phases in water contributes to a significant increase in filtration resistance and a tendency to fluidization at low flow rates. The results of laboratory studies confirm that the presence of gas contributes to stronger fluidization of a pure sand bed (Fig. 4). The photograph (Fig. 4a) shows that the sand bed liquefied by a water-gas flow has a height of about 13 cm (see the scale on the left), the initial static height of the bed is 5 cm. For comparison, the height of the fluidized sand bed with a pure water flow with an equivalent flow rate is 6 cm. The reason for more intense fluidization is the higher gas ascent velocity and swirls in the flow.

The intensity of fluidization is also affected by the particle size distribution of the solid bed. Solid beds with large particles have lower filtration resistance and a lower tendency to fluidization. As clearly shown in the photograph, in a mixed sand-proppant bed (Fig. 4d), fluidization occurs locally in places with lower filtration resistance. In a mixed bed, the fluid flow washes highly conductive proppant conduits consisting only of large proppant grains. Proppant conduits are not stationary, they can move, since the proppant inside them is also fluidized. At the exit from the conduits, the proppant is thrown up by gas bubbles to a small height and settles back, forming proppant craters. Purely proppant craters are formed due to their lower buoyancy compared to sand. And since the flow of liquid occurs only through washed proppant conduits, there is no tail with suspended sand above the mixed sand-proppant bed and therefore the transport of solids to the

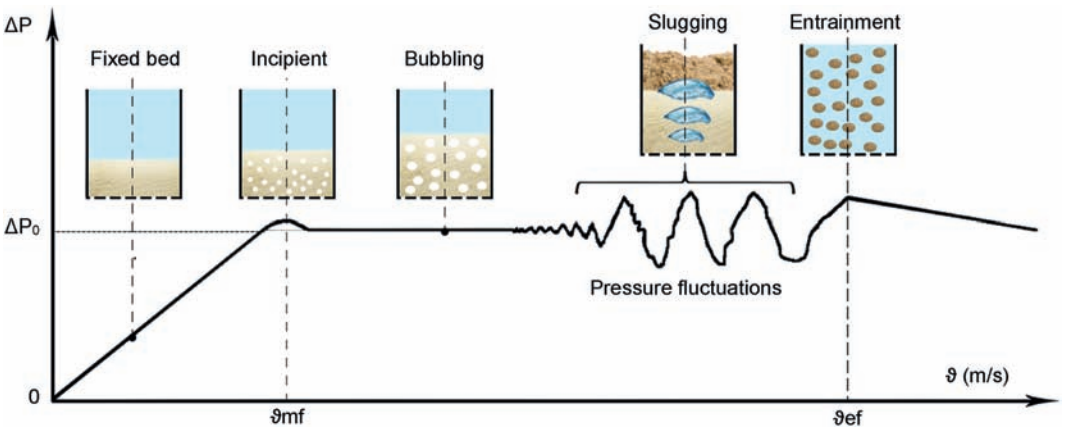


Fig. 3. Schematic representation of the dependence of pressure drop on flow velocity and the state of the solids bed.

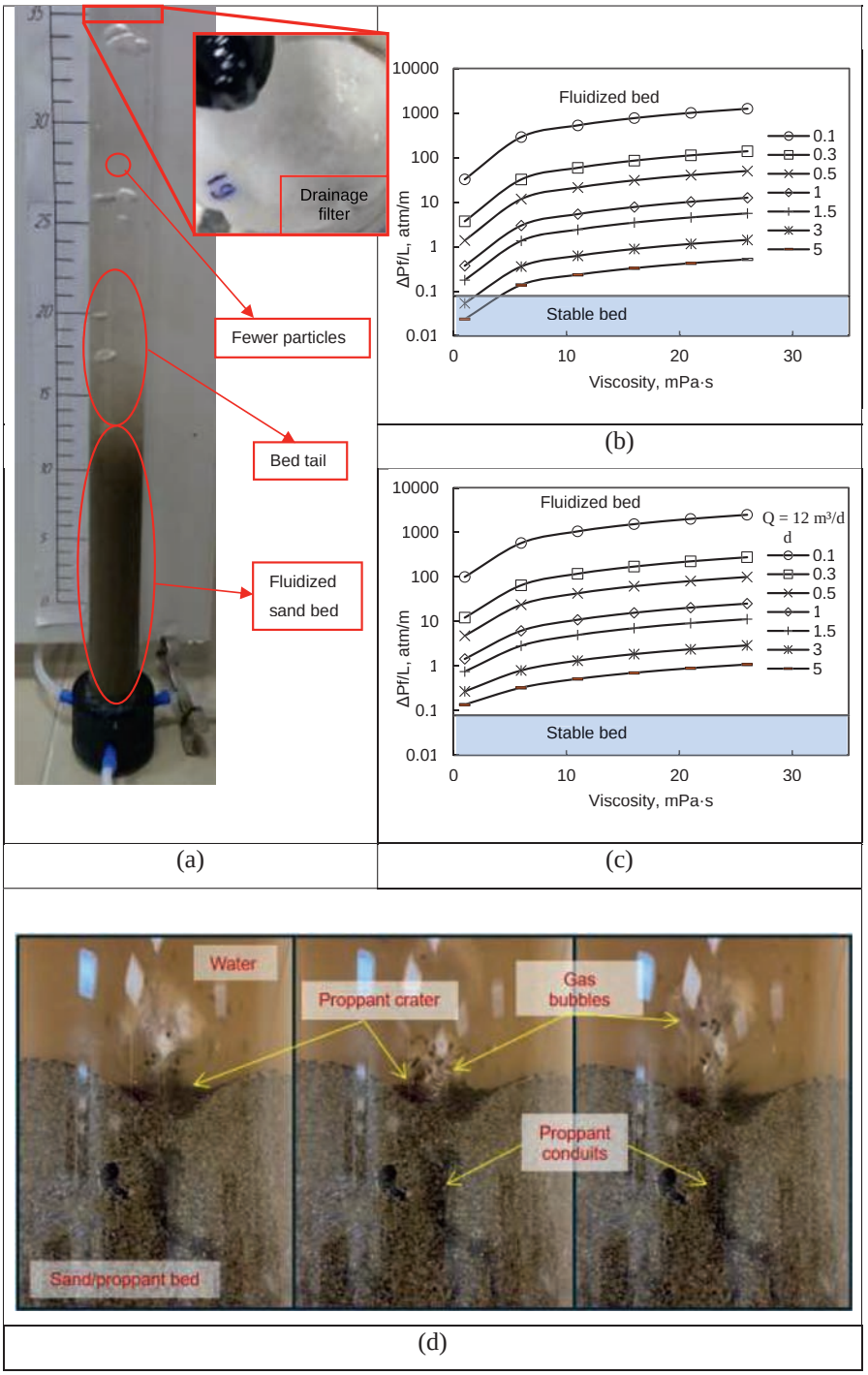


Fig. 4. Fluidized sand bed in the experimental setup, scale is given in cm (a). Dependences of the bed filtration pressure gradient on the viscosity of the fluid for wells with different flow rates: (b) – 4 m^3/day; (c) – 12 m^3/day; (d) – gas passage through a mixed sand-proppant bed.

pump intake in wells with mixed and purely proppant beds is unlikely in low-flow wells.

Thus, based on theoretical calculations 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.

4.2. *Proppant transport in a 3-phase immiscible flow*

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. 5) 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. 5b).

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. 6).

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 (Figs. 7 and 8). 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. 6). 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. 5).

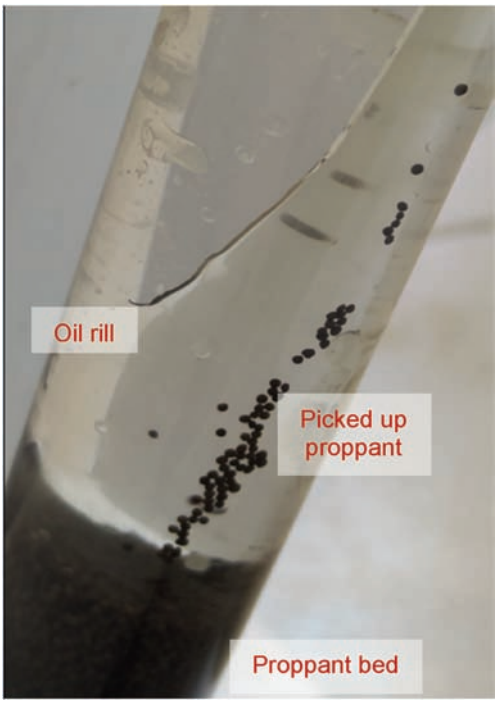


Fig. 6. Oil rill at the top wall of an inclined plexiglass pipe.

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. 7). Due to the high viscosity, the oil rill can reach a significant height above the proppant bed (Fig. 7). Fig. 7 shows that the oil rill reaches a height of 33 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.

Gas supply causes disturbances in the proppant bed and in the flow, which causes the shape of the oil rill to become more tortuous, with small bubbles and water droplets appearing in the

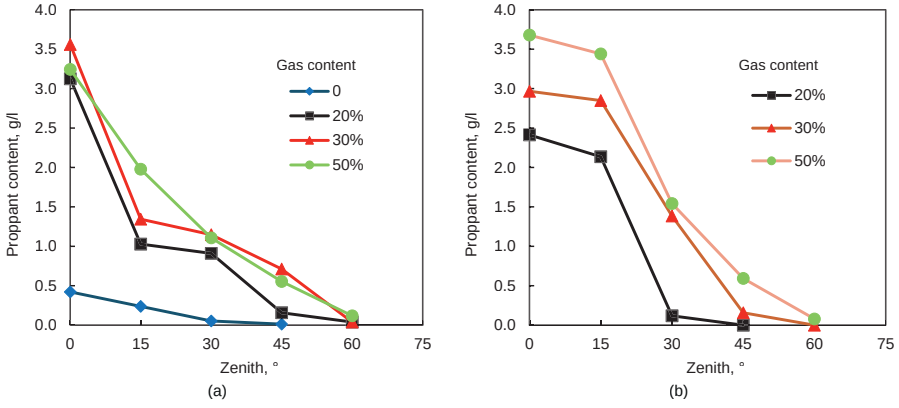


Fig. 5. Concentration of proppant in the ascending flow depending on the wellbore inclination angle and gas content: (a) – Oil; (b) – kerosene.

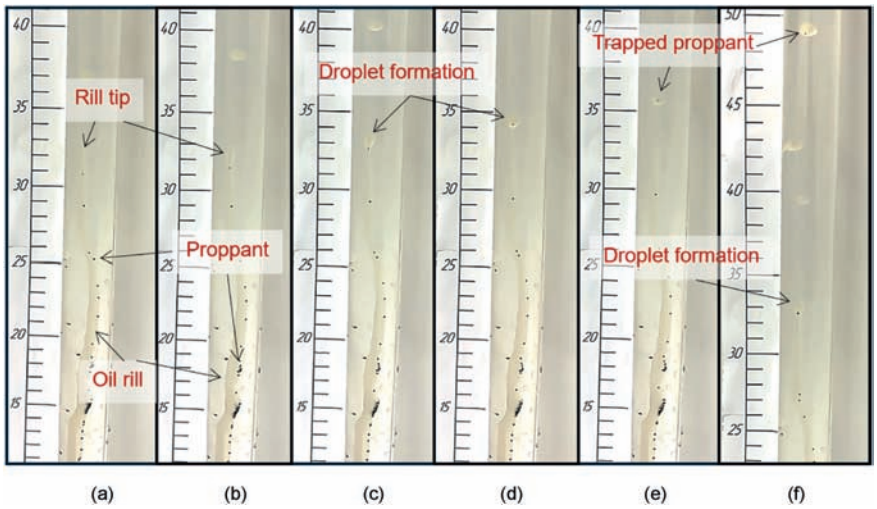


Fig. 7. Oil droplet formation and proppant entrapment in a vertical pipe without gas.

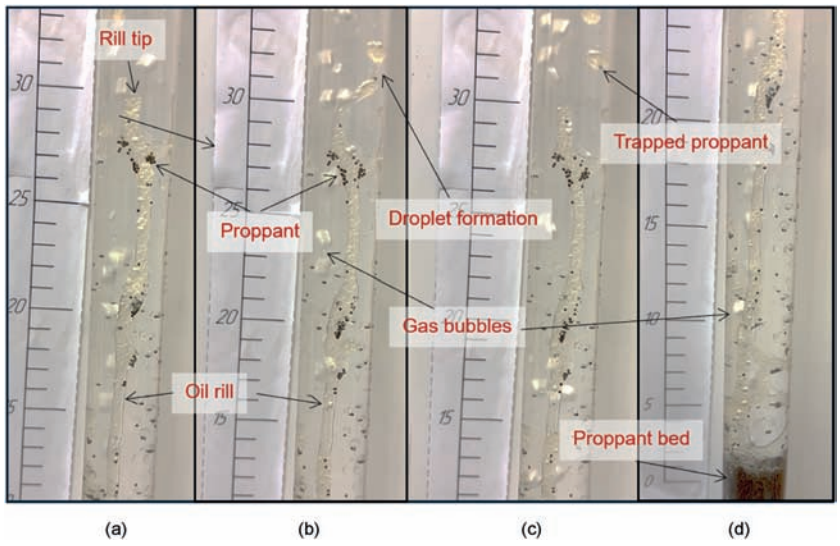


Fig. 8. Formation of oil droplets and proppant capture in a vertical pipe with gas.

rill itself (Fig. 8). Due to the disturbance of the proppant bed surface by the floating bubbles, the amount of proppant in the rill increases, which is noticeable visually (Fig. 8), as well as by measurements (Fig. 5a). With gas, the height of the oil rill rise is almost the same as without gas (Fig. 7). At the tip of the oil rill, the proppant is also captured by the forming droplets and floats to the top.

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. 5b). 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. 9a, b, c).

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. 9d and e). 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. 9d). Unlike oil, a kerosene rill is not able to pick up and carry out proppant grains due to its low viscosity (Fig. 9d). 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. 9e).

Thus, it has been established that the main condition for proppant transport is capture by droplets when exiting the bed.

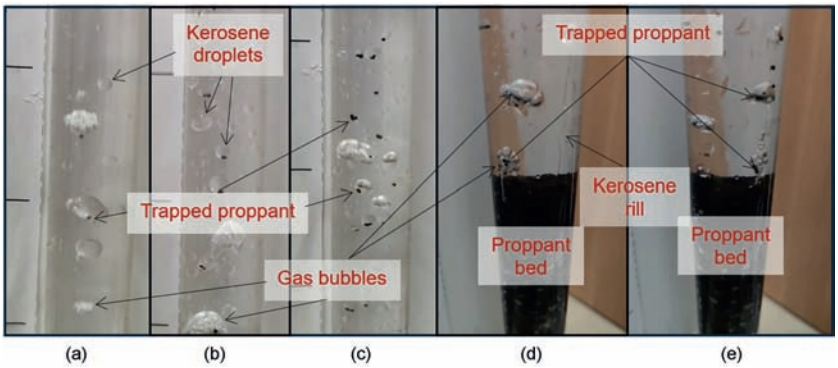


Fig. 9. Transport of proppant by kerosene droplets with a gas content of 20% (a), 30% (b) and 50% (c). Formation of kerosene droplets and proppant capture in a vertical pipe when exiting the proppant bed: (d) – with a kerosene rill on the wall of a plexiglass pipe, (e) – destruction of a kerosene rill by gas bubbles.

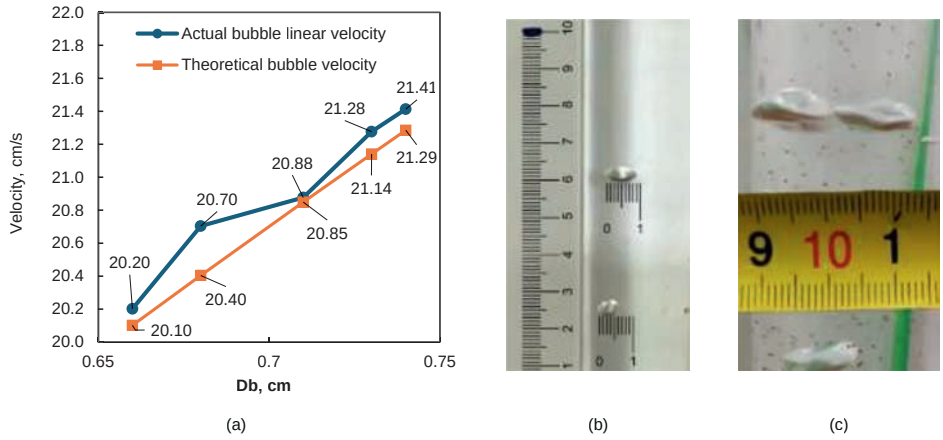


Fig. 10. Dependence of bubble velocity on diameter in a vertical pipe (a). Bubble size in open volume (b) and after passing through a sand bed (c).

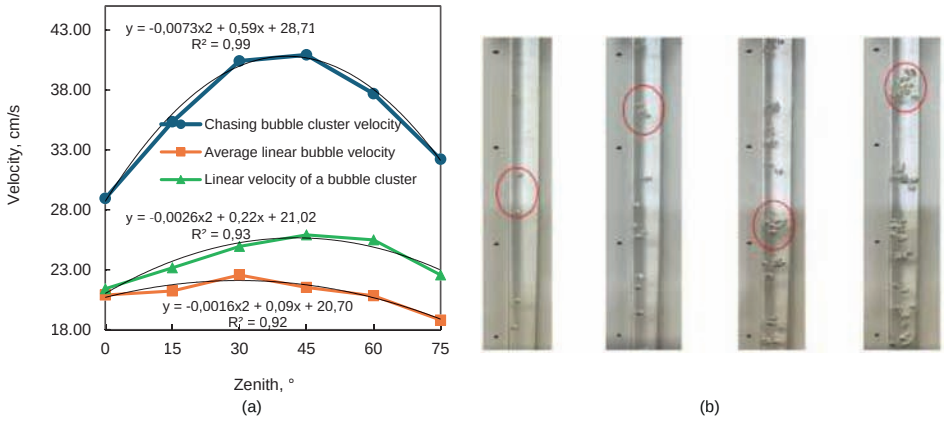


Fig. 11. Dependence of the average velocity of a single bubble, clusters and catching clusters on the zenith angle of the pipe (a), clusters of gas bubbles in an ascending flow (b).

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.

4.3. 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

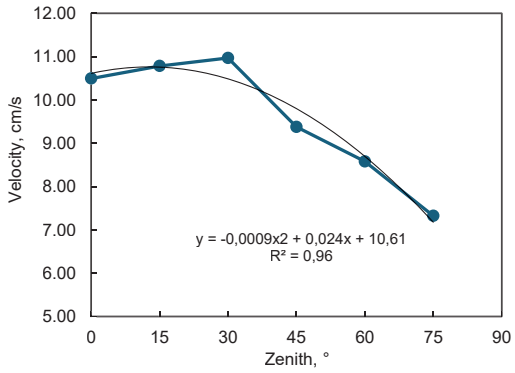


Fig. 12. Dependence of oil droplet velocity on the zenith angle of the pipe.

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.

It has been experimentally established that in a vertical pipe with water with a small influence of surface tension and viscosity, the actual ascent velocity of individual gas bubbles coincides with the calculated one (Fig. 10) according to the formula (R.M. Davies and G.I. Taylor, 1950):

$$u = 0,707\sqrt{gd} \quad (3)$$

The velocity of bubbles is affected by their size, which is determined by many factors in real conditions - interfacial tension, temperature, pressure, etc. It has been experimentally established that when gas passes through a solid bed at the bottom of a pipe, regardless of the gas flow rate and the initial shape, the bubbles merge and increase in size. The enlarged bubbles flatten when floating under the influence of liquid resistance and acquire a disc-shaped form. Their diameter ranges from 0.5 to 1.5 cm (Fig. 10 c).

As the gas bubbles move along the pipe, they form clusters of two to twenty bubbles, depending on the gas content (Fig. 11b). Bubble clusters are formed by the following mechanism (Ozerov et al., 2010): at first, single bubbles move at a small height from the bottom of the pipe. As it rises, the leading bubble causes vortices in the flow and carries some of the fluid with it. The following bubble enters the ascending flow of the first bubble and its resulting ascent velocity becomes higher. As a result, the bubble catches up with the bubble in front. Surface tension forces and vortices in the flow prevent the bubbles from merging. The bubbles in the cluster are divided into the main bubbles, moving ahead and forming the core of the cluster, and the catching bubbles, rising from below at a higher speed due to vortices and counter-currents. The size of a bubble cluster strictly depends on the gas content and the size of the pipe in which they emerge, but the ascent velocity of the clusters does not depend on its size. In this paper, the average ascent velocity of bubble clusters was measured experimentally and its dependence on the zenith angle of the pipe was established. The high ascent velocity of bubbles in an inclined pipe is due to the presence of circulation flows along the upper and

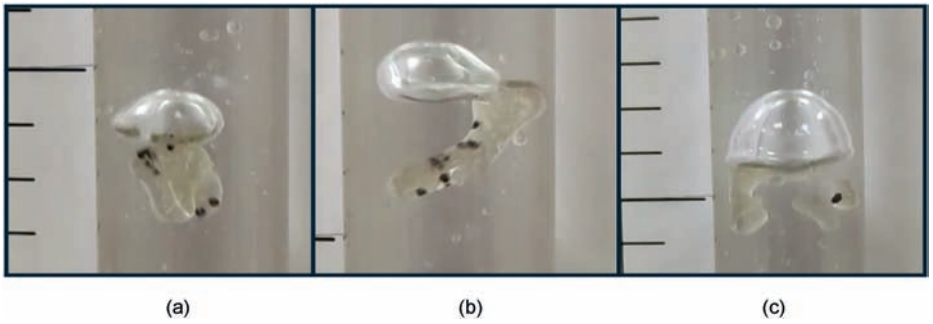


Fig. 13. Interaction of oil droplets with trapped proppant and gas bubbles: (a) – joint movement; (b) – disturbance of droplets by bubble; (c) – droplet and gas slug.

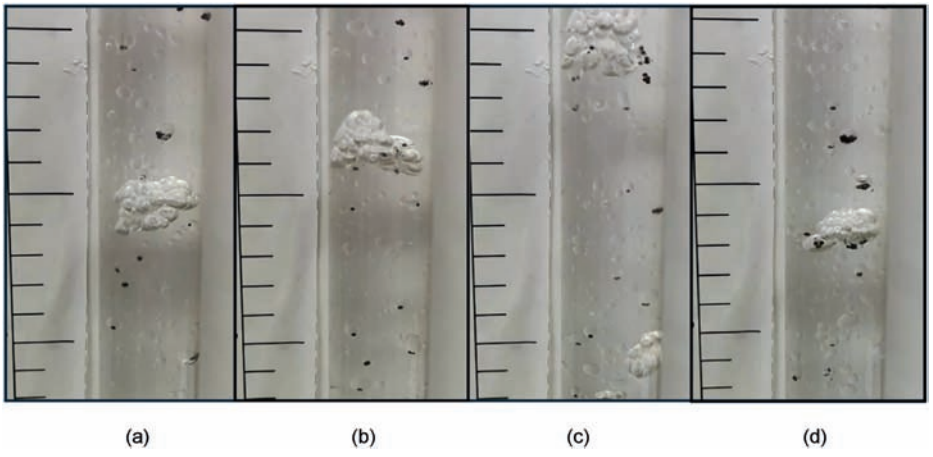


Fig. 14. Interaction of kerosene droplets with captured proppant and a cluster of gas bubbles.

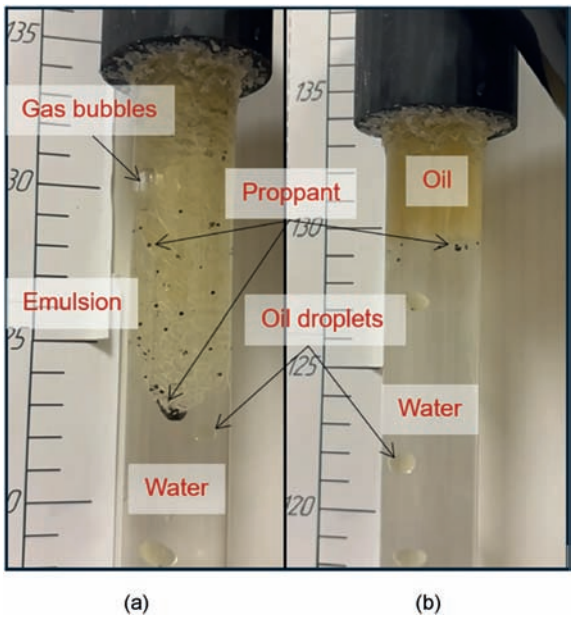


Fig. 15. The interface between water and oil phases in the pump intake zone: (a) – emulsified zone when gas passes; (b) – flat zone without gas.

lower walls of the pipe. A decrease in the ascent velocity after a zenith angle of 45° is caused by an increase in the friction force of the bubbles against the upper wall of the pipe. The dependence of the average linear velocity of a bubble on the pipe inclination angle is shown in the graph (Fig. 11a). The shape of the curves of the ascent velocity of bubble clusters on the zenith angle is parabolic. The maximum velocity of a single bubble corresponds to a zenith angle of 30° and for bubble clusters - 45°. It was found that the average velocity of the catching cluster is, on average, 1.5 times higher. The maximum speed of the catch-up cluster is also at a zenith angle of 30° – 45°. The influence of the zenith angle of the plexiglass pipe on the kerosene droplets velocity is established (Fig. 12). The velocity curve is described by a polynomial equation, and the maximum velocity corresponds to an angle of 30°.

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. 13) show that bubbles and droplets can move together. When droplets are in a hydrodynamic zone of low pressure (Fig. 13a), they rise extremely quickly. Bubbles with a diameter from ½ to 1 pipe diameter (Fig. 13b) pass near oil droplets, deform them, and can lead to their separation, but the proppant does not fall off. With slug flow of gas (Fig. 13c), oil droplets flow around the bubble, pressing against the pipe wall. In this flow mode, the breakup of droplets into small droplets is more likely, as a result of which droplets with captured proppant of critical size and negative buoyancy can be formed. 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 and float together (Fig. 14). The kerosene film on the bubble surfaces prevents them from merging into one large bubble as in the oil experiments (Fig. 13). 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 (Fig. 14b, c, d).

4.4. Proppant at the phase boundary (near the pump intake)

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. It has also been established that the presence of gas in the flow helps to form an emulsion structure. 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

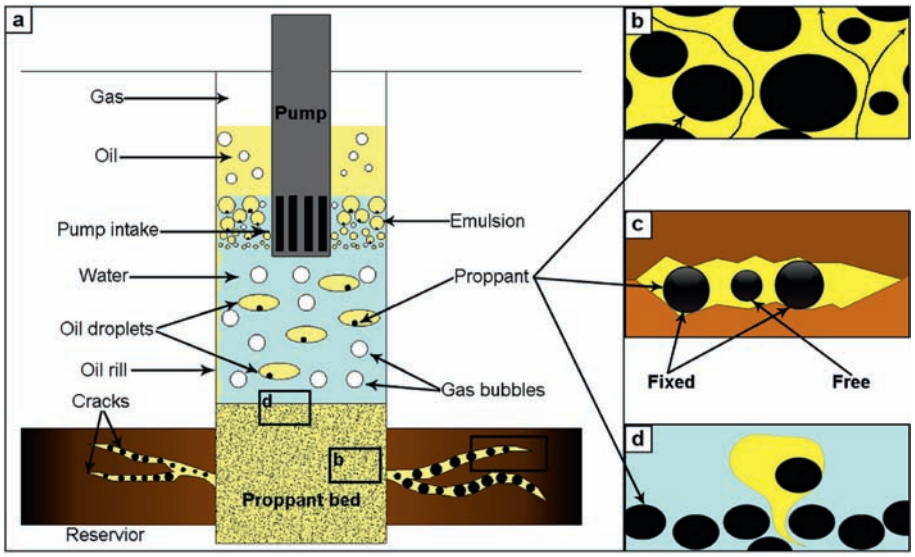


Fig. 16. Illustration of the mechanism of proppant production and its transport to the pump intake in an oil well (a) – general view; (b) – oil seepage through the proppant bed; (c) – free proppant in the crack; (d) – oil droplet exiting on the surface of the proppant bed.

of oil and kerosene with captured proppant can move after the gas bubbles.

4.5. Proppant transport mechanism to the pump intake

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 transport to the pump intake in an oil well is shown in Fig. 16. 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. As calculations have shown (Fig. 4b and c), the proppant bed is very easily fluidized, and thus does not create obstacles to the production of new proppant from the formation. 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. 15a).

5. 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.

These findings have significant implications for improving proppant management strategies in low-flow oil wells. By understanding the role of immiscible phases and gas in proppant transport, operators can optimize well operating modes, design more effective filtration systems, and minimize unnecessary interventions. The study underscores the importance of integrating multiphase flow dynamics into proppant management protocols, particularly in regions like the Perm oil fields where low-flow conditions prevail. Future work should focus on refining predictive models to account for these interactions, validating the mechanisms in diverse geological settings, and developing cost-effective solutions that leverage the observed transport phenomena to prolong pump life and enhance operational efficiency. Ultimately, this research lays the foundation for a more nuanced approach to proppant management, reducing costs and environmental impacts while ensuring sustainable production in low-flow wells.

Attachments: https://doi.org/10.5281/zenodo.15233760.

CRediT authorship contribution statement

Evgenii Kozhevnikov: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Fedor Belkov:** Investigation. **Mikhail Turbakov:** Data curation. **Zakhar Ivanov:** Visualization, Investigation. **Evgenii Riabokon:** Resources, Data curation. **Dmitrii Fedurov:** Investigation. **Mikhail Guzev:** Validation, Supervision. **Evgenii Gladkikh:** Resources, Investigation. **Jiangyu Wu:** Validation.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgement

This research was funded by Ministry of science and higher education of the Russian Federation (Project № FSNM-2024-0008).

References

Ahad, N.A., Jami, M., Tyson, S., 2020. A review of experimental studies on sand screen selection for unconsolidated sandstone reservoirs. J. Pet. Explor. Prod. Technol. 10, 1675–1688. https://doi.org/10.1007/s13202-019-00826-y.

Bakyt, N., Zhang, H.-Q., Zhu, H., 2022. Modeling sand transportation in Wells under different multiphase flow conditions. In: SPE Annual Caspian Technical Conference. SPE. https://doi.org/10.2118/212093-MS.

Davies, R.M., Taylor, G.I., 1950. The mechanics of large bubbles rising through extended liquids and through liquids in tubes. Proc. R. Soc. Lond. A. Math. Phys. Sci. 200, 375–390. https://doi.org/10.1098/rspa.1950.0023.

Deal, E., Venditti, J.G., Benavides, S.J., Bradley, R., Zhang, Q., Kamrin, K., Perron, J.T., 2023. Grain shape effects in bed load sediment transport. Nature 613, 298–302. https://doi.org/10.1038/s41586-022-05564-6.

Dengaev, A., Shishulin, V., Safiullina, E., Palyanitsina, A., 2022. Modeling results for the real horizontal heavy-oil-production well of mechanical solids. Energies (Basel) 15, 5182. https://doi.org/10.3390/en15145182.

Dieng, A., Khiznyk, G.P., Poplygin, V.V., 2023. Prediction of the efficiency of hydraulic fracturing based on reservoir parameters. Int. J. Eng. 36, 2169–2174. https://doi.org/10.5829/IJE.2023.36.12C.05.

Feng, Y., Lei, Y., Zheng, M., Li, Z., Zhao, N., Ren, J., Fang, L., 2023. Flow regime and critical deposition velocity of liquid–solid two-phase flow in pipeline: progress and perspectives. Phys. Fluids 35. https://doi.org/10.1063/5.0172006.

Guo, J., Xie, J., Lv, B., Fan, H., Cui, J., Zhou, F., Guo, Z., Zhu, J., 2024. Preparation and characterization of nanotitania@fatty acid modified quartz sand proppant with super-hydrophobic and oleophilic properties. Colloids Surf. A Physicochem. Eng. Asp. 699, 134623. https://doi.org/10.1016/j.colsurfa.2024.134623.

Guo, J., Xie, J., Lv, B., Hu, L., Sun, Y., Duan, Y., Wu, W., Zhou, F., Zhu, J., 2025. Preparation and properties of epoxy semi-coated quartz sand proppant decorated with stearic acid functionalized TiO2 nanoparticles. Adv. Compos. Hybrid Mater. 8, 192. https://doi.org/10.1007/s42114-025-01251-y.

Khan, J.A., Zainal, A.Z., Idris, K.N., Herman, A.P., Cai, B., Maoinser, M.A., 2024. Sand screen selection by sand retention test: a review of factors affecting sand control design. J. Pet. Explor. Prod. Technol. 14, 2157–2182. https://doi.org/

10.1007/s13202-024-01803-w.
Khizhniak, G.P., Dieng, A., 2023. Influence technological parameters on hydraulic fracturing efficiency. Bulletin of the Tomsk Polytechnic University Geo Assets Engineering 334, 120–125. https://doi.org/10.18799/24131830/2023/6/4092.
Najmi, K., Hill, A.L., McLaury, B.S., Shirazi, S.A., Cremaschi, S., 2015. Experimental study of low concentration sand transport in multiphase air–water horizontal pipelines. J. Energy Resour. Technol. 137. https://doi.org/10.1115/1.4029602.
Nejati, H., Shad, S., Yousefirad, S., Sheikhi, A., 2025. Liquid–liquid–solid three-phase flow in horizontal Wells: flow pattern modeling and dimensionless analysis. J. Pet. Explor. Prod. Technol. 15, 59. https://doi.org/10.1007/s13202-025-01954-4.
Novikov, V.A., Martyushev, D.A., 2024. Study of the influence of well operation parameters of a carbonate reservoir oil formation on the coefficient of productivity using statistical methods of analysis. Georesources 26, 187–199. https://doi.org/10.18599/grs.2024.4.10.
Ozerov, A.Yu, Guo, L., Joseph, D.D., Matsumoto, Y., Sommerfeld, Y., Wang, Y., 2010. Cluster regime—the new regime of flowing of gas-liquid mixture in vertical columns (based on experimental data). In: The 6TH International Symposium on Multiphase Flow, Heat Mass Transfer and Energy Conversion, pp. 348–354. https://doi.org/10.1063/1.3366389.
Pandey, V.J., 2023. Proppant flowback prevention and control by analysis of early time well production data. In: SPE Annual Technical Conference and Exhibition. SPE. https://doi.org/10.2118/214959-MS.
Parker, M., Weaver, J., Van Batenburg, D., 1999. Understanding proppant flowback. In: SPE Annual Technical Conference and Exhibition. SPE. https://doi.org/10.2118/56726-MS.
Peretomode, E., Oluyemi, G., Faisal, N.H., 2022. Sand production due to chemical-rock interaction. A review. Eng. Fail. Anal. 142, 106745. https://doi.org/10.1016/j.engfailanal.2022.106745.
Salahi, A., Dehghan, A.N., Sheikhzakariaee, S.J., Davarpanah, A., 2021. Sand production control mechanisms during oil well production and construction. Petroleum Research 6, 361–367. https://doi.org/10.1016/j.ptlrs.2021.02.005.
Turbakov, M., Shcherbakov, A., 2015. Determination of enhanced oil recovery candidate fields in the volga-ural oil and gas region territory. Energies (Basel) 8, 11153–11166. https://doi.org/10.3390/en81011153.
Webster, C.McK., Tovar D, J.J., 1999. Solving sanding problems using a sand production management system. Case histories. In: SPE Offshore Europe Oil and Gas Conference and Exhibition. SPE. https://doi.org/10.2118/56948-MS.
Yang, Y., Peng, H., Wen, C., 2019. Sand transport and deposition behaviour in subsea pipelines for flow assurance. Energies (Basel) 12, 4070. https://doi.org/10.3390/en12214070.
Zhang, R.-Y., Li, J., Yang, H.-W., Zhang, G., Hao, X.-N., Liu, P.-L., 2022. Experimental study of the critical sand starting velocity of gas-water-sand flow in an inclined pipe. Pet. Sci. 19, 2981–2994. https://doi.org/10.1016/j.petsci.2022.09.004.
Zhiliang, W., Zhenhua, W., Zhensong, W., Manlai, Z., Ruiquan, L., 2025. Study of sand particle transport characteristics and different critical velocities in sand-producing Wells via indoor experiments. Sci. Rep. 15, 9707. https://doi.org/10.1038/s41598-025-87386-w.