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OPERATION OF DOWNHOLE PUMPS UNDER SANDING CONDITIONS

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One of the unfavourable factors of downhole pumping equipment operation at the fields at the final stage of development is high content of mechanical impurities in the pumped fluid.

Similar problems are observed in fields with friable, weakly cemented formations, the fracture products of which flow downhole, resulting in lower extraction rates, equipment damage and higher operating costs.

In oil production practice various technological measures and technical means are used to reduce the negative impact of sand penetration - regulation and optimisation of pumping equipment operation mode to ensure a rational rate of fluid withdrawal, application of technical devices in the form of sand filters and sand anchors and others. However, these measures and recommendations, for the most part, work successfully in the modes of continuous operation of wells. With the growing number of oil fields at the final stage of development, the issue of sanding becomes more and more urgent, as due to low flow rate wells at such fields are often switched to the mode of periodic operation, which favours the formation of sand plugs in tubing above the pump due to sufficient time for sedimentation of mechanical impurities. This can lead to pump jamming or rod breakage during subsequent well pump start-up.

The experience of using sand filters (frame, slotted and others) in the arrangement of downhole pumps has shown that it does not always effectively solve the problem of sand penetration due to clogging of their cells with mechanical impurities and increased hydraulic resistance. This negatively affects the pumping equipment operation due to the shift of characteristics into the zone of suboptimal modes with associated problems for the electric drive. This makes it necessary to carry out underground well workover with removal of deep well pumping equipment for replacement or washing of the filter in surface conditions, as due to their peculiarities in the well pump layout (the filter is located at the intake of the pumping section), washing in well conditions is not always possible.

These problems require not only the creation of effective downhole devices to prevent sand ingress to the pump intake or devices to prevent sand plugs above it, but also acceptable in practice calculation methods for predicting the sedimentation time of mechanical impurities in tubing or determining the minimum required speed of upward oil flow for stable sand removal. These calculation methods would also allow to reasonably regulate the time of technological interruptions while waiting for the wells to start up in periodic operation modes or to predict the time of activation of sand control devices for discharging the sand accumulated above the pump. This is the subject of this article.

As a result of calculation analysis it was established that the main factors affecting the sedimentation process of mechanical impurities in the well are the speed and mode of fluid movement, its viscosity, density and size of the impurities themselves. Moreover, the most sensitive for the calculation accuracy is to take into account the change of fluid viscosity as it moves along the tubing as a result of heat exchange and the change of dissolved gas content due to pressure drop. Although at this stage the proposed methodology does not take into account some factors that can make additional adjustments to the process of sand sedimentation, however, it allows to predict with acceptable accuracy the time of technological interruptions in the well operation to prevent the formation of sand plugs, or the rational mode of operation of pumping equipment, providing the necessary speed of upward flow in the pipe for sand removal.

KEY WORDS: *well, complications, sand ingress, mechanical impurities, downhole pumping equipment.*

ҚҰМДЫҚ ЖАҒДАЙДА ҰҢҒЫМАЛЫҚ СОРҒЫЛАРДЫ ПАЙДАЛАНУ

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Игерудің соңғы сатысында тұрған кен орындарында ұңғылық сорғы жабдықтарының жұмысындағы қолайсыз факторлардың бірі айдалатын сұйықтықтағы механикалық қоспалардың жоғары болуы болып табылады.

Ұқсас мәселелер қабаттары борпылдақ, әлсіз цементтелген тау жыныстарымен бейнеленген, бұзылу өнімдері түбіндегі шұңқырға түсетін кен орындарында байқалады, бұл өндіру жылдамдығының төмендеуіне, жабдықтың бұзылуына және пайдалану шығындарының өсуіне әкеледі.

Мұнай өндіру тәжірибесінде құм шөгінділерінің теріс әсерін азайту үшін әртүрлі технологиялық шаралар мен техникалық құралдар қолданылады - сұйықтықты алудың ұтымды жылдамдығын қамтамасыз ету үшін сорғы жабдығының жұмыс режимін реттеу және оңтайландыру, техникалық құрылғыларды пайдалану. құм сүзгілері мен құм анкерлері және т.б. Дегенмен, бұл шаралар мен ұсыныстар, негізінен, ұңғымаларды үздіксіз пайдалану режимдерінде сәтті жұмыс істейді. Игерудің соңғы сатысында тұрған мұнай кен орындарының санының өсуімен құмның пайда болу мәселесі өзекті бола түсуде, өйткені өндіру қарқынындылығының төмен болуына байланысты мұндай кен орындарындағы ұңғымалар жиі мерзімді пайдалануға ауыстырылады, бұл механикалық қоспаларды тұндыру үшін жеткілікті уақытқа байланысты сорғы үстіндегі құбырларында құм тығындарының пайда болуы. Ұңғыма сорғылары кейіннен іске қосылғанда, бұл сорғының кептелуіне немесе штангалардың сынуына әкелуі мүмкін.

Ұңғымалық сорғыларды орналастыру кезінде құм сүзгілерін (қаңқа, ойық және т.б.) пайдалану тәжірибесі бұл олардың жасушаларының механикалық қоспалармен бітелуіне және гидравликалық кедергінің жоғарылауына байланысты құммен ластану мәселесін әрқашан тиімді шеше алмайтынын көрсетті. Бұл сорғы жабдығының жұмысына теріс әсер етеді, себебі сипаттамалардың оңтайлы емес режимдер аймағына ауысуы электр жетегі үшін ілеспе проблемалар бар. Бұл жер асты ұңғымаларын жөндеуді ұңғымалық сорғы жабдығын алып тастау арқылы сүзгіні жер үсті жағдайында ауыстыруға немесе жууға мәжбүрлейді, өйткені олардың ұңғымалық сорғы орналасуындағы ерекшеліктеріне байланысты (сүзгі сорғы секциясының кірісінде орналасқан), шаю ұңғымадағы жағдайлар әрқашан мүмкін емес.

Аталған мәселелер сорғы қабылдауға құмның түсуіне жол бермейтін тиімді ұңғыма құрылғыларын немесе оның үстінде құм тығындарының пайда болуын болдырмайтын құрылғыларды ғана емес, сонымен қатар құбырлардағы механикалық қоспалардың шөгу уақытын болжау үшін практикалық есептеу әдістерін жасауды талап етеді. тұрақты құмды кетіру үшін қажетті ең аз жоғары жылдамдықтағы мұнай ағыны. Бұл есептеу әдістері сондай-ақ мерзімді жұмыс режимдерінде ұңғымаларды іске қосу қарсаңында технологиялық үзілістер уақытын негізді түрде реттеуге немесе сорғы үстінде жиналған құмды шығару үшін құмды бақылау құрылғыларының іске қосылу уақытын болжауға мүмкіндік береді. Бұл мақалада қарастырылатын мәселе.

Есептік талдау нәтижесінде ұңғымадағы механикалық қоспалардың тұндыру процесіне әсер ететін негізгі факторлар сұйықтың қозғалу жылдамдығы мен режимі, оның тұтқырлығы, тығыздығы және қоспалардың өзіндік мөлшері екені анықталды. Сонымен қатар, есептеудің дәлдігі үшін ең сезімтал фактор жылу алмасу нәтижесінде құбыр бойымен қозғалатын сұйықтықтың тұтқырлығының өзгеруін және қысымның төмендеуіне байланысты еріген газ құрамының өзгеруін есепке алу болып табылады. Бұл кезеңде ұсынылған әдіс құмның тұндыру процесіне қосымша түзетулер енгізуі мүмкін кейбір факторларды есепке алмағанымен, ол ұңғыманың жұмысындағы технологиялық үзілістердің уақытын практикалық дәлдікпен болжауға мүмкіндік береді. құм тығындарын қалыптастыру немесе құмды кетіру үшін құбырдағы жоғары қарай ағынның қажетті жылдамдығын қамтамасыз ететін сорғы жабдығының ұтымды жұмыс режимі.

ТҮЙІН СӨЗДЕР: *ұңғыма, асқынулар, құмның пайда болуы, механикалық қоспалар, тереңдік сорғы жабдықтары.*

ЭКСПЛУАТАЦИЯ СКВАЖИННЫХ НАСОСОВ В УСЛОВИЯХ ПЕСКОПРОЯВЛЕНИЯ

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Одним из неблагоприятных факторов эксплуатации скважинного насосного оборудования (СНО) на месторождениях, находящихся на завершающей стадии разработки, является высокое содержание механических примесей в откачиваемой жидкости.

Аналогичные проблемы наблюдаются на месторождениях, пласты которых представлены рыхлыми, слабосцементированными породами, продукты разрушения которых поступают на забой, что приводит к снижению темпа отбора, повреждению оборудования и росту эксплуатационных затрат.

В практике нефтедобычи используются различные технологические мероприятия и технические средства для снижения негативного воздействия пескопроявления - регулирование и оптимизация режима работы насосного оборудования для обеспечения рационального темпа отбора жидкости, применение технических устройств в виде песочных фильтров и песочных якорей и прочие. Однако эти мероприятия и рекомендации, в большинстве своем, успешно работают на режимах непрерывной эксплуатации скважин. С ростом же числа месторождений нефти, находящихся на завершающей стадии разработки, вопрос пескопроявления становится все более актуальным, так как из-за низкого дебита скважины на таких месторождениях часто переводятся на режим периодической эксплуатации, что способствует образованию песчаных пробок в насосно-компрессорных трубах над насосом за счет достаточного времени на седиментацию механических примесей. При последующем запуске скважинных насосов это может привести к заклиниванию насоса или обрыву штанг.

Опыт применения противопесочных фильтров (каркасных, щелевых и других) в компоновке скважинных насосов показал, что это не всегда эффективно решает проблему пескопроявления из-за забивания их ячеек механическими примесями и повышению гидравлического сопротивления. Это негативно сказывается на работе насосного оборудования из-за смещения характеристик в зону неоптимальных режимов с сопутствующими проблемами *для электропривода. Это вынуждает проводить подземный ремонт скважин с извлечением глубинно-насосного оборудования для замены или промывки фильтра в наземных условиях, так как из-за их особенностей в компоновке скважинного насоса (фильтр располагается на приеме насосной секции), промывка в скважинных условиях не всегда возможна.*

Перечисленные проблемы требуют создания не только эффективных внутрискважинных устройств по предотвращению попадания песка на прием насоса или устройств по предотвращению образования песчаных пробок над ним, но и приемлемых на практике расчетных методик по прогнозированию времени седиментации механических примесей в насосно-компрессорных трубах или определению минимально необходимой скорости восходящего потока нефти для устойчивого выноса песка. Эти расчетные методики позволили бы также обоснованно регулировать время технологических перерывов в ожидании запуска скважин на режимах периодической их эксплуатации или прогнозировать время активации противопесочных устройств для сброса накопившегося над насосом песка. Это и является предметом рассмотрения в данной статье.

В результате расчетного анализа установлено, что главными факторами, влияющим на процесс седиментации механических примесей в скважине являются скорость и режим движения жидкости, ее вязкость, плотность и размеры самих примесей. Причем, наиболее чувствительной для точности расчета является учет изменения вязкости жидкости по мере движения по НКТ в результате теплообмена и изменения содержания растворенного газа из-за падения давления. Хотя на данном этапе предлагаемая методика не учитывает некоторые факторы, которые могут внести дополнительные коррективы на процесс седиментации песка, однако, она позволяет прогнозировать с приемлемой для практики точностью время технологических перерывов в работе скважины для предотвращения образования песчаных пробок, или рациональный режим эксплуатации насосного оборудования, обеспечивающего необходимую скорость восходящего потока в трубе для выноса песка.

КЛЮЧЕВЫЕ СЛОВА: *скважина, осложнения, пескопроявление, механические примеси, глубинно-насосное оборудование.*

Introduction. As a rule, low-yield wells are operated at low velocities of the ascending flow of production fluid in a flow string and at sharp fluctuations in the dynamic fluid level in the well. As a result, more favorable conditions are created in the well for the formation of sand plugs, asphalt-resin and paraffin deposits and salt deposits on surfaces of parts and units of underground equipment. This is also facilitated by frequent failures of downhole pumping equipment due to increased wear of moving elements.

In most oil fields at a later stage of development, the proportion of low-yield wells is increasing. Their operation, as a rule, is complicated by the presence of a high concentration of water, dissolved gases, salts, asphalt-resinous substances and mechanical impurities in the form of sand particles in the produced oil.

At the pumping of wells, there are the following four methods of combating sand ingress [1–4]:

1) prevention and regulation of the ingress of sand particles (mechanical impurities) from the productive formation into the well;

2) ensuring that sand particles coming into the well from the productive formation are brought to the surface;

3) preventing sand particles from entering the well pump by installing sand separators and filters on its receiving part;

4) use of special downhole pumping equipment for oil production in sandy service.

The first method is the main one that is used in practice to combat sand ingress. The ingress of mechanical impurities can be prevented either by installing special filters at the bottom of the well, or by special fastening of the bottom-hole zone of the productive formation.

The flow of sand particles from the productive formation into the production well can be regulated by controlling the amount of oil produced from the well and reducing differential pressure.

Using the second method of combating sand ingress, conditions are created that ensure the removal of sand particles from the well by the flow of produced oil. According to A.N. Adonin [14], for a vertical production well, these conditions are ensured when the ratio of the flow rate of the pumped well fluid to the sedimentation rate of sand particles in the same fluid exceeds 2 … 2,5:

$$V_F / V_S > 2 \ldots 2{,}5,$$

where V_F is an ascending fluid velocity; V_S is the rate of unhindered (gravity) sedimentation of sand particles with a design diameter equal to the average diameter of the largest fraction of sand particles, the volume fraction of which is 20 %.

This ratio can be ensured by selecting combinations of lifting pipes and rods, by changing the supply of the pumping unit by means of adjusting its operating parameters or adding a volume of liquid (oil, water) that does not contain mechanical impurities into the borehole annulus in a ratio of 0.2 ... 0.25 of the supply volume of the borehole pumping unit.

Sand separators and filters used in harmony with the third method are quite effective in preventing sand particles from getting into the well pump only during the initial period of their operation on its receiving part. However, as their operational characteristics deteriorate, in particular due to wear and clogging (reduction of their filtering ability), the concentration of sand in the bottom-hole part of the well will constantly increase until sand plugs are formed.

The use of sand separators is most effective for those production wells in which sand particles enter in small volumes and for a short time. The direct sand separator is also a gas separator. The use of sand separators is not the main, but an auxiliary method of combating sand ingress.

Sand filters installed at the pump inlet prevent sand particles of medium and large sizes. In practice, sand filters of various designs are used: mesh, wire, slotted, metal-ceramic, sand-plastic, gravel, etc.

As a rule, low-yield wells are operated at low velocities of the ascending flow of production fluid in a flow string and at sharp fluctuations in the dynamic fluid level in the well. As a result, more favorable conditions are created in the well for the formation of sand plugs, asphalt-resin and paraffin deposits and salt deposits on the surfaces of parts and units of underground equipment. This is also facilitated by frequent failures of downhole pumping equipment due to increased wear of moving elements.

The development of oil fields at later stages is associated with high water cut and high contents of mechanical impurities in extracted products of wells, since to maintain oil production levels, water is often injected into the reservoir, which is a common method of reservoir pressure maintenance. This method is especially widely combined with heat treatment of the near-well zone and productive formation.

It is known that the products of the majority of fields in Western Kazakhstan (more than 30%) are viscous and highly paraffinic oils. These include the world-famous Uzen, Zhetybay, Karamandybas fields, whose oils are extremely saturated with paraffin dissolved in them (up to 26%), resins and asphaltenes (up to 20%) and contain corrosive gases (H_2S, CO_2), [5,6].

Increased viscosity has a significant impact on the processes of oil production and preparation in the fields [6]. For example, at Northern Buzachi, Karazhanbas and other fields in Western Kazakhstan, the method of pumping hot water into the reservoir is actively used to increase well production rates.

Reservoir pressure maintenance inevitably leads to high filtration rates, which contribute to the stripping and washout of mechanical impurities from weakly cemented reservoirs in the near-well zone due to the destruction of the reservoir frame on the walls of channels and cracks due to the formation of microcracks. In this case, the process of destruction of the reservoir will be continuous due to the constant washout of particles of destroyed rock into the well. Perhaps the intensification of these processes explains the often encountered effect – increased solids content when bottom-hole pressure is below the saturation pressure.

There are many ways how solid particles get into pumping equipment [7]. The main part of them consists of particles removed from the formation during the operation of wells, but a significant part of the solids is extraneous:

- corrosion products of underground equipment and particles that get into the well as a result of repairs and geological and engineering operations;
- insoluble solid inclusions in the kill fluid or proppant fragments after hydraulic fracturing;
- products formed by the interaction of chemically incompatible pumped liquids.

The percentage composition of mechanical impurities contained in well production is determined by the predominance of particles from the formation.

Table 1 contains a proposed classification of the causes of reservoir destruction and sand production. They are divided into three main groups based on the conditions of occurrence:

- geological (particularities of the occurrence of the reservoir layer, lithology);
- technological (conditions of drilling-in and well operation);
- technical (bottom-hole design).

Table 1 - **Classification of causes of reservoir destruction and sand production**

Origin	Percentage	Particle composition	Percentage
Formation	50 - 60	Magnetic and iron particles	25-65
Mixed (formation + surface)	15 - 25	Mineral particles from the formation	20 -25
Surface	10 - 20	Surface particles	10 -50

Geological: formation depth and formation pressure; horizontal component of rock pressure; the degree of cementation of the formation rock, its compaction and natural permeability; the nature of the produced fluid and its phase state; characteristics of formation sand (angularity, clay content); influx of bottom water into the deposit and dissolution of the cementing material; duration of sand removal.

Technological: well flow rate; the value of overbalance and differential pressure; deterioration of natural permeability (skin effect); filtration loads and disruption of capillary adhesion of sand.

Technical: bottom-hole design; the surface of the bottom-hole through which filtration occurs (interval of formation opening, if perforation channels are open or plugged, etc.).

Among the main factors that determine the concentration of impurities, the following are usually pointed out: formation depth and formation pressure; formation permeability; physical and chemical properties of the produced fluid; water cut; characteristics of sand particles; well flow rate; perforation density; drawdown pressure; type of working fluid used in the process of repair and recovery activities.

In relation to underground pumping equipment, mechanical impurities are the main cause of breakdowns and structural defects. According to well-known statistics, the percentage of pumping equipment breakdowns associated with the impact of mechanical impurities far exceeds the influence of other geological and technical factors, the main ones being corrosion and salt formation. For most oil fields, mechanical impurities account for 35-50% of the total number of main causes of failures of deep-well pumps; corrosion, 20-25%; and scaling, 15-20%.

Mechanical impurities that get into the sucker rod pump significantly affect the performance of the plunger and valve pair. Sand causes gross wear of the threaded connections of pump pipes. At the slightest leak in the connections, especially in flooded wells, it quickly corrodes the threads and liquid flows through the resulting channel, reducing the supply, and subsequently leading to its complete cutoff.

The presence of a large amount of poorly permeable sediments at the bottom of the well primarily leads to a decrease in fluid flow rate, because the concentrated mixture in the well increases the back pressure on the bottom and worsens the conditions for the natural flow of fluid. Technical or technological shutdowns of wells contribute to the deposition of sand on the bottom and the formation of plugs, which is often the most serious problem in the operation of sand wells. When sand sediments in the production string, the pump jams, as a rule, when the downhole equipment is stopped.

As a result of the analysis of production materials, it was established that sand ingress, despite the application of the well-known methods to protect downhole pumping equipment, remains a pressing problem for most fields in Kazakhstan. *Table 2* shows statistics on failures of downhole pumping equipment at the Kumkol, Karazhanbas and Northern Buzachi fields, where sucker rod screw pumps are widely used [5,6].

During the analysis of production materials from the Northern Buzachi field, it was found that, despite the high resistance of screw pumps to pumped sand, they often fail due to sand ingress. For instance, more than 50% of screw pump failures were associated with the influence of sand from the formation and 39% with rods parted (*Figure 1*).

Table 2 - **Statistics of failures of sucker rod screw pumps due to sand ingress**

Field	Operator	Number of wells equipped with sucker rod pumps, pc.	Percent of failures of sucker rod pumps because of sand ingress, %
Karazhanbas	JSC "Karazhanbasmunay"	1600	27 %
Northern Buzachi	Branch of "Buzachi Operating Ltd."	900	38%
Kumkol	JSC "PetroKazakhstan"	180	до 40%

It has been noted that some of the produced sand tends to settle above the pump as the fluid rises to the surface. One of the main factors influencing this process is the velocity of the ascending flow during production, the viscosity of the produced fluid and the fractional composition of mechanical impurities (sand) coming from the formation. Due to the inexpediency of changing the fluid viscosity and sand composition, the most practical is to increase the flow rate to bring sand to the surface during well operation. However, in practice there are situations where the flow rate of the produced fluid is not enough to remove all particles, which results in some sand settling above the pump or is suspended in the flow string. This causes an increase in the amount of suspended particles in the liquid, which, during the shutdown of the well, begin to settle in the lower part of the string, where the gas pumping equipment is located, and form a sand plug.

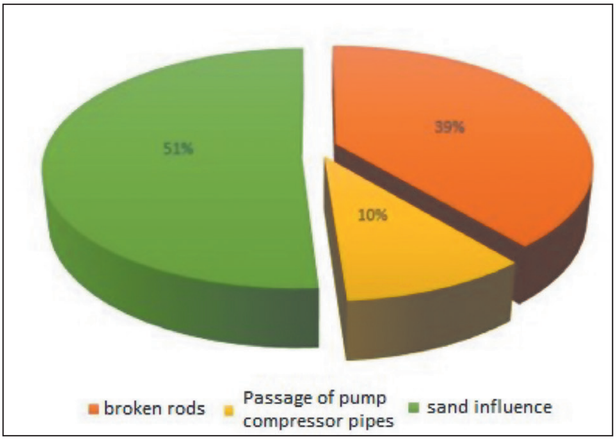

Figure 1 - **Causes of failures of sucker rod screw pumps at the Northern Buzachi field**

In addition to plugging, mechanical impurities in well production also have a significant impact on the service life of submersible equipment. The interaction of mechanical impurities with the moving elements of downhole pumping equipment becomes one of the main causes of wear of its power section. There is no doubt that the intensity of wear is also affected by the granulometric composition of the produced sand. For example, the presence of leaks in the valve pairs of sucker rod pumps when pumping out a low-viscosity liquid with a high sand content leads to intense erosion of the seat and shut-off valve. The operating practice of sucker rod pumps in the fields shows that the largest number of well servicing (about 40%) is caused by valve malfunction.

Intensive recovery of mechanical impurities with well production also causes premature wear of the elements of the production and oil strings. This necessitates unscheduled well servicing at significant financial costs associated with a loss of oil, diversion of own or hired material and human resources, etc.

Field experience in operating wells with sucker rod pumps shows that jamming mostly occurs even during relatively short-term 15-20 minute stops. Tubing pumps, while attempting to move the plunger upward, will immediately jam in the cylinder due to a large amount of sand getting into the gap and a sharp increase in the friction of the plunger in the cylinder. A similar situation can be observed in an insert pump, when due to sand sediment it becomes impossible to remove it from the sitting nipple. It is necessary to perform a cumbersome and dangerous operation of lifting rods and pipes part by part.

Thus, the study of sedimentation of mechanical impurities during oil production under conditions of high sand ingress still remains one of the most urgent.

Solving this problem will make it possible to predict the rational duration of operational shutdowns of wells to prevent sand plugs or to select the operating mode of a downhole pump to ensure sustainable sand removal. The most difficult problem in this regard is to estimate the amount of sedimentation of mechanical impurities in the constrained conditions of a moving fluid in a turbulent flow.

Materials and methods of research. The mechanism of sedimentation and movement of sand particles both in a stationary and flowing fluid is considered in detail by B.M. Latypov [8].

Let's consider the rate of sand sedimentation in a stationary fluid, which corresponds to stopping the pump and cutting off the liquid column in the production string with a check valve.

Sand particles in a liquid medium, the density of which is less than the density of sand particles, settle under gravity, the magnitude of which is determined by the following formula:

$$F_g = \frac{\pi \cdot d_ч^3}{6} \cdot g \cdot (\rho_p - \rho_f), \quad (1)$$

where $d_ч$ is a sand particle diameter; ρ_p, ρ_f are the density of sand particles and liquid, respectively.

In addition, as mentioned above, the process of sedimentation of sand particles is influenced by their shape, density and viscosity of the liquid.

By equating the gravitational force acting on a sand particle to the vertical resultant force of resistance to friction between the surface of a sand particle and a liquid, it is possible to obtain the following:

$$F_g = \frac{\pi \cdot d_ч^3}{6} \cdot g \cdot (\rho_p - \rho_f) = \pi \cdot d_ч^2 \cdot \tau_0, \quad (2)$$

where τ_0 is a vertical resultant friction stress on the surface of a sand particle.

From formula (2), the diameter of the largest spherical sand particle suspended in a liquid is determined:

$$d_0 = \frac{6 \cdot \tau_0}{g \cdot (\rho_p - \rho_f)}. \quad (3)$$

However, due to the absence of an ideal Bingham fluid in real well conditions, the use of formula (3) is not entirely correct.

The performed studies [8,9,10] determined the critical values of the limiting shear stress of a fluid at which particles of various diameters will be in suspension. For example, for 0.2 mm particles, the critical shear stress ranges from 0.2 to 0.4 Pa.

Using Yalin's method [9], for particles with a diameter of less than 1 mm, the calculated critical shear stress of a fluid equaled 0.83 Pa.

In field practice, sand particles with a size of less than 1 mm are most often found in a production fluid. Therefore, when pumping a well fluid having a maximum shear stress of more than 0.83 Pa, a change in the fluid flow rate will have a minor effect on the sand particles from the well. In this case, the removal of sand particles from the well can occur even at minimal ascending velocities of the well fluid.

If under gravity a sand particle increments the velocity, then it will be affected by the resistance force directed opposite to the velocity vector of its deposition.

The value of this resistance force in the general case can be determined using the following formula:

$$F_F = C_d \cdot S \cdot \frac{\rho \cdot u^2}{2}, \quad (4)$$

where C_d is a fluid resistance coefficient; S is a particle cross-sectional area; u is a particle velocity.

Particle can deposit in a liquid medium in different modes depending on the rate of particle sedimentation and the physical characteristics of the medium. In this case, each deposition mode is characterized by its own value of the resistance coefficient of the medium depending on the Reynolds number (Re).

When a spherical particle settles according to Stokes' law, it is acted upon by a resistance force equal to [9]:

$$F_F = 3 \cdot \pi \cdot \mu \cdot d \cdot \nu. \quad (5)$$

In this case, the settling rate of a spherical particle can be determined as follows:

$$u = \frac{g \cdot (\rho_ч - \rho_ж) \cdot d^2}{18 \cdot \mu}. \quad (6)$$

From formula (6) it follows that the settling rate of a spherical particle is affected by the difference in the densities of the particle and the medium, by the size of the particle and the viscosity of the medium. For particles that do not move according to Stokes' law, the value of the sedimentation velocity can be determined using Cheng's formula [10]:

$$\vartheta_s = \frac{\nu}{d} \cdot (\sqrt{25 + 1{,}2 \cdot d_k^2} - 5))^{1{,}5}, \quad (7)$$

where ν is a kinematic viscosity; d is a particle diameter; d_k^2 is a dimensionless diameter depending on the relative densities of sand and liquid.

Formula (7) obtained from an analysis of experimental data from various sources allows to calculate the settling velocity of sand particles moving both according to Stokes' law and at high Reynolds numbers.

Results and discussion. As a result, the estimated values of the sedimentation rate of sand particles with a density of 2,650 kg/m³ in a liquid with a density of 1,000 kg at various values of its kinematic viscosity are exemplified in *Figures 2* and *3*.

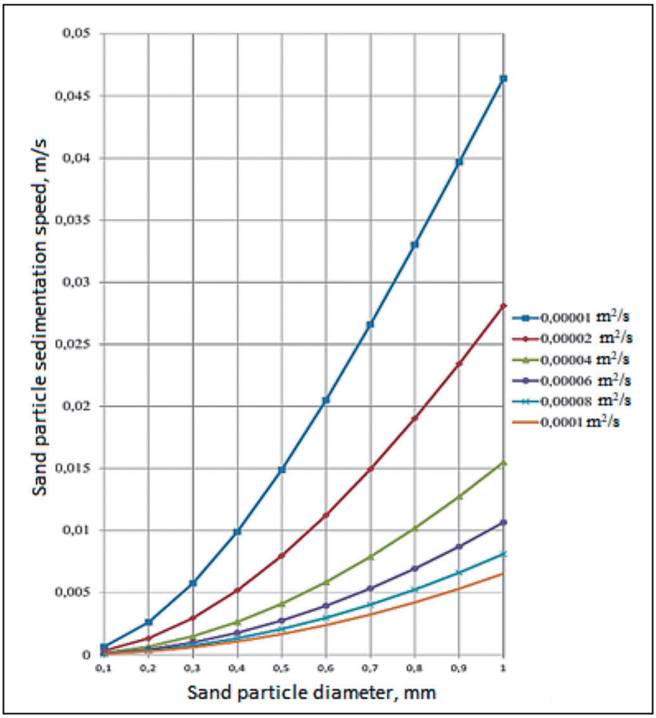

Figure 2 - **Dependence of the sedimentation rate of sand particles of various sizes in a liquid at values of kinematic viscosity of the liquid from $1 \cdot 10^{-6}$ to $10 \cdot 10^{-6}$ m²/s**

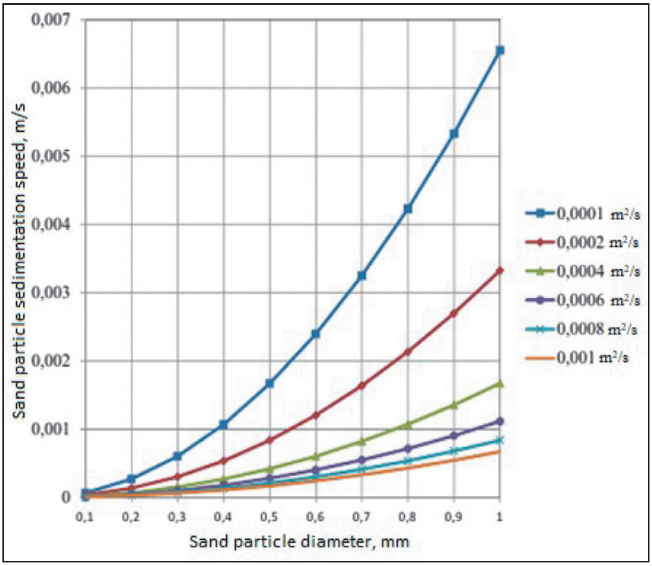

Figure 3 - **Dependence of the sedimentation rate of sand particles of various sizes in a liquid at values of kinematic viscosity of the liquid from $10 \cdot 10^{-6}$ to $100 \cdot 10^{-6}$ m²/s**

It should also be taken into account that temperature and the amount of dissolved gas in the oil can have a significant effect on viscosity (*Figure 4*). Viscosity of oil as it moves from bottomhole to wellhead can change significantly not only due to intensive heat dissipation from the tubing walls, but also due to gradual decrease in the amount of dissolved gas in it as the hydrostatic pressure decreases.

The fluid flow regime along the tubing height also changes and establishing the boundaries of fluid flow regime transition can also improve the calculation accuracy.

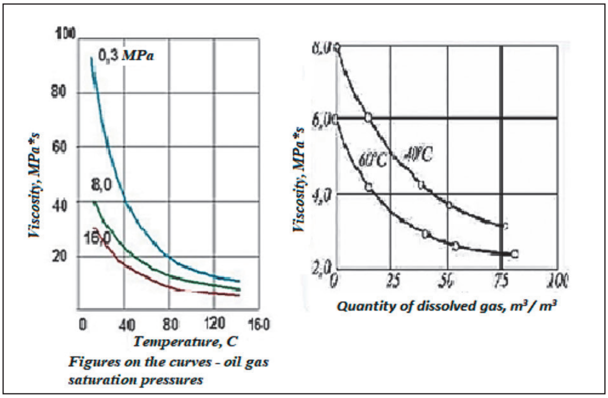

Figure 4 - **Effect of oil temperature and amount of dissolved gas on oil viscosity**

As can be seen from the above data, with an increase in viscosity, the rate of sand sedimentation decreases significantly, which must be taken into account when choosing a technology for protecting downhole pumping equipment from sand ingress. Moreover, liquid viscosity has a more significant effect on sand sedimentation than the density and size of its particles.

Conclusions. The analysis of existing methods of mechanical impurities control in the practice of downhole oil production shows that up to the present time this problem remains actual and requires further research to develop new technologies and technical devices to reduce their negative impact both on reliability of downhole pumping equipment and on the efficiency of their operation.

No less urgent is the development of acceptable for practice methods of calculated determination of sedimentation time of mechanical impurities in downhole conditions for selection of pump operation mode. It will allow to prevent formation of sand plugs during technological breaks in operation, or to provide stable sand removal. at the fields with periodic mode of well operation.

As a result of the calculation analysis according to the above method it was established that the main factors influencing the process of sedimentation of mechanical impurities in the well are the speed and mode of fluid movement, its viscosity, density and the size of the impurities themselves. Moreover, the most sensitive for the accuracy of calculation is the consideration of the change of fluid viscosity as it moves along the tubing as a result of heat exchange and the change of dissolved gas content due to pressure drop. Their change affects both the fluid flow regime and sedimentation regime of mechanical impurities contained in it.

The proposed methodology does not take into account some factors that can make additional adjustments to the process of sand sedimentation, but it allows us to estimate the necessary data both for regulating the time of technological breaks in the well operation and activation of the parameters of the anti-sanding device in the mode of their periodic operation, and for selecting the operating mode of the HFO, providing the necessary speed of the upward flow in the tubing for sand removal.

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