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Scientific and Methodological Support of Sand Management During Operation of Horizontal Wells

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P A P E R I N F O

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A B S T R A C T

The paper presents a new scientifically based approach for the selection of sand control technology, which is dedicated to enhance the efficiency of the development of unconsolidated reservoirs. Established laboratory and methodological complexes for physical simulating of the sand producing process were analyzed in order to obtain new knowledge and confirm the available theories. All of them have their advantages and disadvantages, but their simultaneous application revealed characteristic dependencies between the sand production and the studied parameter (grain size distribution, pressure drop, clay content, water cut, gas/oil ratio, etc.). Author proposed concepts of mathematical apparatus improvement to increase the quality of assessing the ability of formation fluids to transport particles of different grain size distribution within the formation, as well as in the inner part of tubing. The effect of each of the characterizing factors on suspended solids concertation (SSC) was studied as a result of more than 300 laboratory experiments. According to the observation, there is a sharp decrease in SSC after the first stage (sampling). Thus, the author determined that the main inflow of mechanical impurities occurs during flow stimulation and after shutdowns. In conclusion, author substantiated the method for limiting sand production using polymers with shape memory based on the results of the performed set of tests. Proposed method allows limited passage of particles with diameter less than 50 μm, which creates conditions for noncolmaticity of screen while maintaining geomechanical stability of bottom-hole formation zone.

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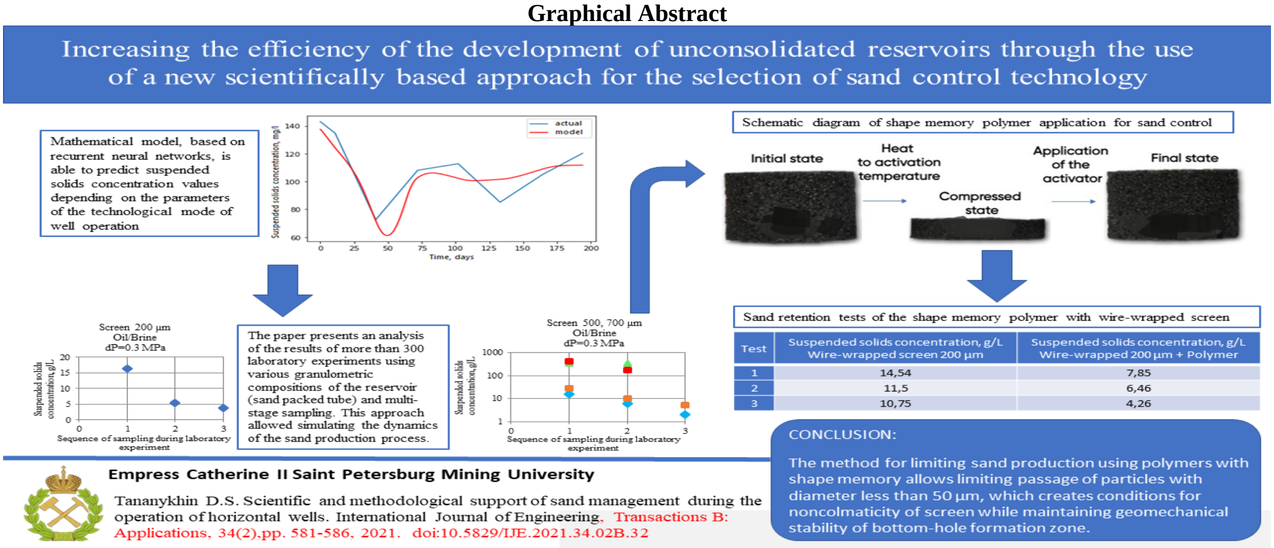
Graphical Abstract



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NOMENCLATURE

u_c^*	critical velocity of the single-phase flow (ft/s)	V_{sl}	reduced particle velocity
u_0^*	friction velocity, (ft/s)	D	pipe diameter
u_t	rate of sedimentation, (m/s)	x	the energy required to maintain suspended particles per unit length of the pipe
C_V	solids concentration, (m^3/m^3)	N_{Re}	Reynolds number
v	kinematic viscosity, (ft/s)	ρ_G	gas specific gravity
d	grain diameter	V_M	mixture velocity
$V_{L,C}$	critical velocity of the fluid, м/c	V_p	particle velocity
g	gravity	Fr	Froude coefficient
ρ_P	particle density	WC	water cut
ρ_L	fluid density	GOR	gas-oil ratio

1. INTRODUCTION

Sand production occurs in a wide range of hydrocarbon reservoirs, both composed of relatively young rocks of the Quaternary period and consolidated reservoirs at the final stages of development (1). Sand-related challenges significantly disrupt the oil production process, since it adversely affects the complex of subsurface and surface equipment and creates difficulties in the operation of wells (2, 3). The topic of horizontal wells operation with sand production is particularly relevant. Their application is justified by much higher well productivity (compared to vertical ones) and a large sweep efficiency.

Sand production is also a relevant scientific challenge. This is primarily due to the need for inherent scientific research and the development of a systematic approach, which consists in the reasonable choice of the most effective technologies (4, 5), as well as in the integrated simulating (numerical, physical and field) of processes occurring in the system «well-bottom hole zone».

Based on the results of laboratory tests and mathematical modelling (6-8), it was revealed that the greatest sand production occurs at the stage of flow stimulation due to violation of the initial geomechanical state of the bottomhole formation zone.

Sand production depends on the water/oil/gas distribution in the total flow of the fluid (9, 10). Some researchers argue that this is solely a problem of arch stability (11), whilst others argue that this is an issue of wetting and chemical reactions (12) or strain softening due to water incorporating into the rock matrix (13).

There are many technologies and technical solutions to prevent sand production, such as screens, different form of gravel packings, chemical consolidation, technological restrictions and some other forms or combinations of them. Every technology has both advantages and disadvantages. Screens (wire-wrapped, weaved, slotted liners et al.) are prone to erosion (13-15) and corrosion (16, 17). Slotted liners are usually restricted on the open to flow area (OFA), because high OFA results in decreasing strength of the whole screen (which is basically a tubing with slots (cuts) of specific pattern and opening size) (18). Another problem is screen replacement – since borehole walls can collapse onto the screen surface, this causes an issue of lifting the whole tailpiece onto the surface.

Chemical consolidation technologies usually result in low retained permeability of the reservoir after treatment (17) and their efficiency largely depends on the clay content and water saturation of the reservoir (18). Chemical consolidation also requires treatments on the periodic manner between 0.5 and 1.5 years (19). But none of the above solves a root cause of sand production – geomechanical instability.

Gravel packs are able to solve a significant amount of complications caused by the geomechanical factor. However, in the case of horizontal completions, the use of gravel packs is limited due to the large volumes of borehole space that need to be filled with gravel. The use of unsorted (cheaper) gravel can lead to increased production of rock particles in certain packing areas under conditions of high heterogeneity. Unsorted gravel also favours conditions of “hot-spots” (zones with lack of gravel or extremely high permeability), which will result in screen losing it’s efficiency in terms of sand retaining and will further favour faster terms of erosion (20, 21).The use of sorted gravel is often not possible due to its high cost.

This paper presents a method of limiting sand production by utilizing shape memory polymers which have a mesh structure and can allow the passage of particles with a diameter of less than 50 μm, which leads to less "blockage" of the screen.

2. MATERIALS AND METHODS

Traditionally, the criteria for selecting sand control technologies is based either on empirical correlations or on field experience in the operation of similar objects (22-24). Nowadays, there has been a growing interest in using a laboratory infrastructure to investigate the technologies of operating wells with different types of completion. The most common methods of testing sand-related challenges are: slurry sand retention test (25-28) and prepack sand retention test (26, 29-35). A comparative analysis of current laboratory procedures is presented in Table 1.

2. 1. Mathematical Models of Critical Flow Velocity in Horizontal Wells There are two main approaches of models for determining critical flow velocity in a horizontal well. The first approach is based on the description of the forces and processes that affect the solid particle: its picking up, transfer and deposition. This approach is reflected in the theory of Salama (36).

The second approach is based on the theory of turbulence: the balance between the energy required to weigh particles and the energy released when the turbulent vortices are stratified. Models Oroskari and Turian (37), Danielson (38) and others (39-41) are the most widespread.

However, the hydrodynamics of a multiphase system is much more complex than a single-phase one. The flow tends to separate due to the different density and viscosity of the liquid and gas fluid (42). Various structural forms (43) can characterize the gas-liquid flow. Gas-liquid flow's structure refers to mutual arrangement or distribution of gas and liquid phases in process of their simultaneous movement through the well (44).

Different phases move at different velocity. It leads to a very important phenomenon - the "slippage" of one phase relative to others. Comparative analysis of mathematical models for calculation of critical velocity is given in Table 2 (45, 46).

2. 2. Advanced Software for Calculating Sand Production During Operation of Oil And Gas Wells Author identifies the following software programs that allow calculating critical velocity of produced solid particles in horizontal multiphase flow:

TABLE 1. Comparative analysis of laboratory methods for testing sand-related challenges during the development of oil and gas fields

Method	Measurement parameters	Simulated conditions	Testing sample
Prepack sand retention test	1. Drop pressure during filtration	Long-term well operation, wellbore collapse	Core sample - sand packed tube /mechanical screen, gravel pack or chemical treatment
Slurry sand retention test	2. Suspended solids concentration	Flow stimulation, first inflow of the well	Not applicable/ mechanical screen, gravel pack
Linear sand control evaluation	3. Particle size distribution of produced particles	Long-term well operation, wellbore collapse	Sand packed tube / mechanical screen, gravel pack, chemical treatment
Radial sand control evaluation	4. Permeability	Long-term well operation, wellbore collapse	Sand packed tube /Full size mechanical screen, gravel pack, chemical treatment

TABLE 2. Comparative analysis of mathematical models for calculation of critical velocity in horizontal well

No.	Author	Particle diameter, µm	SSC, mg/l	Mathematical correlation
		Single phase flow		
1	Thomas (44)	0.4-950	More than 20000	$u_c^* = u_0^* \left[1 + 2.8 \left(\frac{u_t}{u_0^*}\right)^{0.33} \sqrt{C_V}\right]$ $u_0^* = \left(100 u_t \left(\frac{v}{d}\right)^{2.71}\right)^{0.269}$
2	Oroskar and Turian (38)	-	-	$\frac{V_{L,C}}{\sqrt{gd\left(\frac{\rho_P}{\rho_L}-1\right)}} == 1{,}85 {C_V}^{0{,}1536} (1-C_V)^{0{,}3564} \left(\frac{d}{D}\right)^{-0.378} {N_{Re}}^{0.09} x^{0.30}$
		Multiphase flow		
3	Salama (37)	-	-	$V = 1.3 \left(\frac{V_{sl}}{V_M}\right)^{0.53} d^{0.17} v_L^{-0.09} \left(\frac{\rho_P - \rho_L}{\rho_L}\right)^{0.55} D^{0.47}$
4	Stevenson(45)	512-1010	2 000	$\frac{V_p}{V_{sl}} = 0.95 \left(1 + \frac{V_{SG}}{V_{SL}}\right) - \left(1.38 \frac{V_{SG}}{V_{SL}} + 0.88\sqrt{Fr}\right) \cdot$ $\cdot \left(Re\sqrt{Fr} \left(\frac{d}{D}\right)^{1.5}\right)^{-0.18}$
5	Danielson(39)	280-550	1 000	$V_{L,C} = 0.23 v^{-1/9} d^{1/9} (gD((\rho_P - \rho_L) - 1))^{5/9}$
6	Ibarra (46)	211-297	2 500 – 10 000	$\frac{V_{L,C}}{\sqrt{gd\left(\frac{\rho_P}{\rho_L}-1\right)}} == 1.3277 \left(\frac{V_{SL}}{V_{L,C}}\right)^{-0.285} (1-C_V)^{-35.490} \left(\frac{d}{D}\right)^{-0.378} {N_{Re}}^{0.09}$
7	Hill (47)	211-297	2 500 – 10 000	$\frac{V_{L,C}}{\sqrt{gd\left(\frac{\rho_P}{\rho_L}-1\right)}} = 1.85 C_V^{0.1536} (1 - -C_V)^{0.3564} \left(\frac{d}{D}\right)^{0.378} {N_{Re}}^{0.09}$

- OLGA Schlumberger (software was used for investigations (47, 48).
- ANSYS Fluent (software was used for calculations (49).

The OLGA dynamic multiphase flow allows you to perform calculations for a complex modeling of the behavior of solid phases, calculate the change in the flow rate in general and each phase separately, and calculate the precipitation of solid particles.

Main advantages are a quick calculation time and a focus on the oil and gas industry. The main drawback is the complexity of setting up and using the program.

As for ANSYS Fluent software, the combination of DEM (discrete element method) and CFD (computational fluid dynamics) packages allows you to simulate a gas/liquid-solids system. The program allows you to take into account both the interaction between particles and a high concentration of particles. Modeling of solid particles is possible in the DEM-CFD Coupling Module, where it is possible to specify the number of suspended particles, their size and density. The advantage of CFD 3D programs is the high accuracy of calculations, taking into account different factors that affect the transport of formation particles. However, an increase in accuracy leads to an increase in calculation time. Comparative analysis of the sand simulating software is provided in Table 3.

One of the software allows us to simulate the transport of solid particle and erosion process of oil and gas equipment (50). PETRONAS software is more designed to determine the risk of equipment erosion, but it can calculate the critical flow velocity to prevent the formation of a sand plug in the well.

SYNTEF's Multiphase Transport and Flow Assurance software, which has a module for simulating the transport of solid particles in horizontal wells and pipelines, is on the global market too.

As a result of the analysis, the author registered a software program that allows calculating the size of particles that can be produced from a horizontal well by upflow.

TABLE 3. Software products related to sand production simulation

Module	Software product	Advantages	Disadvantages
Sand transport in the well	OLGA	- Quick calculation time; - Adapted for oil and gas industry;	- Complexity of setting up
	ANSYS Fluent	- High accuracy	- Not adapted for oil production; - Complexity of setting up

2. 3. Creating a Predictive Mathematical Model Using Recurrent Neural Networks The algorithm of the mathematical model consists of using the long-term short-term memory (LSTM) model, which is a type of recurrent neural network. Each row of input data about the target parameter and characteristics has its own time - the measurement date. Therefore, the dependence of suspended solids concentration on the parameters of the process mode of the well was considered in the form of a time series (51-53).

The proposed model consists of 6 layers (Figure 1): input layer, two layers of long-term short-term memory, two layers of regularizers and output layer. The mean-square error is used as a function of calculating deviation, and the Adam algorithm (adaptive moment estimate) is used as an optimizer. The data entered into the model were pre-standardized and divided by proportion: 70% - training, 10% - validation, 20% - test.

The training process was conducted on several models to obtain reliable results. Models differ in the parameter of the lines from each other. Then best model has been selected according to the information obtained after testing.

The results of using the developed mathematical model are presented below.

3. RESULTS

This paper presents an analysis of the results of more than 300 laboratory experiments using various granulometric compositions of the reservoir (sand packed tube) and multi-stage sampling. This approach allowed simulating the dynamics of the sand production process.

The author found that the distribution of phases in the fluid flow affects the amount of suspended particles in the filtrate when using the same screens. An increase in the share of brine leads to an increase in suspended solids concentration. The SSC of any brine-oil mixture is lower than the SSC values in pure oil filtration. An increase in the gas fraction, on the contrary, leads to a decrease in SSC (Figure 2).

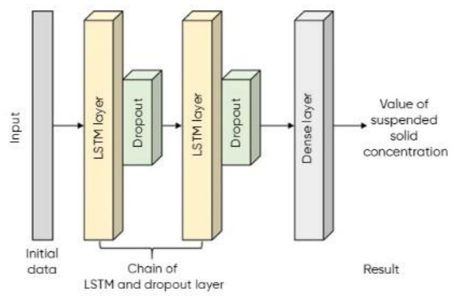

Figure 1. Schematic diagram of the proposed model

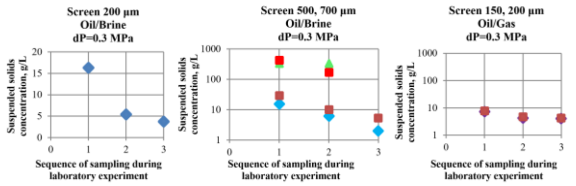

Figure 2. Amount of suspended solids concentration depending on the filterable phases

At the same time, the SSC naturally decreases, primarily due to the formation of arched systems near the holes of the screen (14, 32, 54-58). The scheme of the arch system is shown in Figure 3.

An increase in the pressure drop during filtration of various mixtures, on average, leads to an increase in SSC by 2.6 times with a range of 1.2-8 times depending on the sampling stage (Figure 4).

The results of physical experiments showed the greatest impact of the flow stimulation stage on the stability of the bottomhole formation zone and on the amount of sand produced.

3. 1. Assessment of the Ability of Fluids to Transport Formation Particles of Different Grain Size Distribution

One of the goal of the paper is to determine the critical flow velocity. Existing mathematical models and correlations on the calculation of critical flow velocity have been discussed in detail above. All correlations are based on laboratory tests performed for the flow of mechanical impurities in brine.

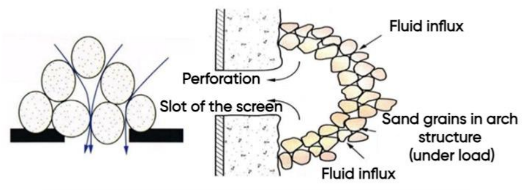

Figure 3. Arch system located near perforations/screen slots (2)

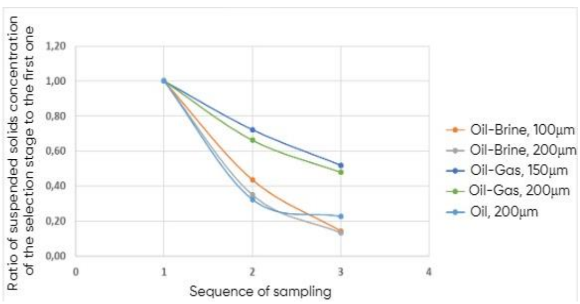

Figure 4. Stabilization of sand production during laboratory experiment

The physical characteristics of brine differ significantly from those of oil, especially high viscosity oil.

Moreover, many of the models considered are adapted only for suspensions with high concentrations of suspended particles, for example, pulp.

The author conducted a parametric study for particles of different diameters with different water cut and different gas factor. The critical velocity was determined graphoanalytically using graphs constructed as a result of mathematical modeling (Figure 5). "Black line" indicates a line showing the volume fraction of particles deposited on the bottom of the pipe; "red line" indicates the flow rate. As can be seen from the graph, when the flow rate decreases to 0.149m/s, particles with a diameter of 300 µm with a water cut of 20 % will begin to form a fixed layer.

The critical flow rate varies differently for mixtures with different proportions of water (Figure 6). The obtained results of numerical modeling are in line with the generally accepted opinion that the growth of the linear particle size leads to an increase in the critical flow rate:

1. When pure oil flows (water cut 0 %), an increase in the linear grain size leads to an increase in the critical flow rate, which is consistent with the generally accepted ideas about the transport of mechanical particles.

2. For a mixture with a low water content (water cut 5 %, 10 %, 20 %), the critical velocity does not depend on the particle diameter.

3. For a highly aqueous liquid (water cut 50 %, 70 %), the critical velocity does not change for particles in the diameter range of 100-1000 µm. At the same time, the value of the critical velocity for small particles (50 µm) is higher than for larger ones.

Thus, with a water cut of 50-70 %, a layer of water is formed in the lower part of the pipe, the low viscosity of which does not allow to "pick up" and ensure the transfer of particles with a size of less than 50 µm.

As can be seen in Figures 6 and 7, an increase in the proportion of water in the flow leads to an increase in critical velocity, since water has less ability to carry particles in a horizontal part.

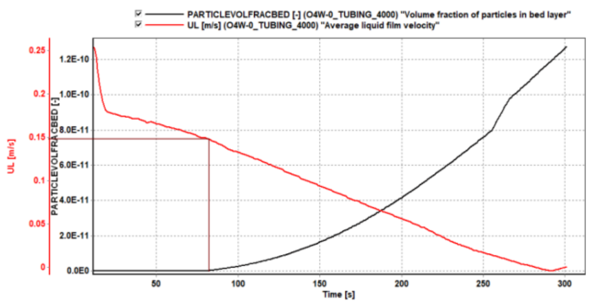

Figure 5. Critical velocity for sand grains of 600 µm with water cut 0%

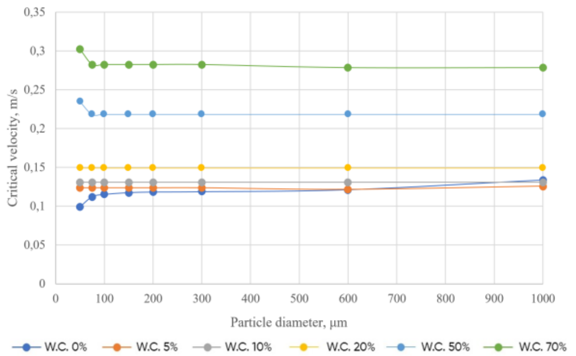

Figure 6. Critical velocity for different particle diameters and water cut (W.C.)

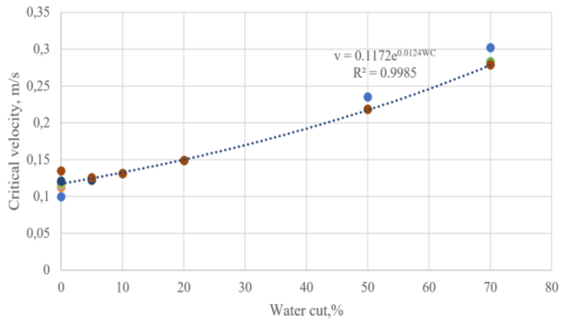

Figure 7. Dependence of critical velocity on water cut

Since critical velocity depends little on particle size, for future calculations it is proposed to use correlation 1 to calculate critical flow velocity depending on water cut (Figure 7). The coefficient of determination for the proposed expression is 0.9985.

$$v = 0{,}1172e^{0{,}0124 \cdot WC} \quad (1)$$

where v – critical velocity, m/s; WC – water cut, %

Similarly, critical velocities for the gas-liquid mixture were determined (Figure 8). The increase in gas-oil ratio results in an increase in critical flow rate. At the same time, the velocity increases with an increase in the size of the solid particle.

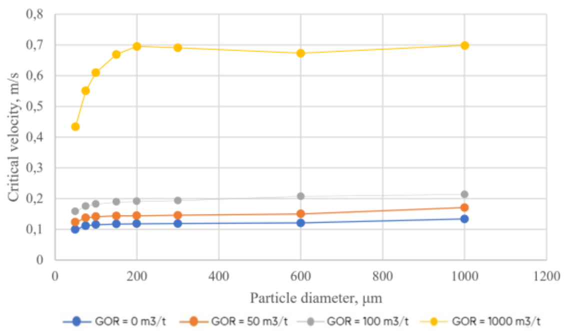

Figure 8. Critical velocity for different particle diameters and gas-oil ratio

Increasing the amount of gas reduces the viscosity and density of the oil, which reduces the drag force on the solid particle from the fluid surface. The ability of the fluid to allow the movement of sand is reduced.

3. 2. Results of Using Developed Mathematical Model Using Recurrent Neural Networks

The Mining University team initiated a program for creating a mathematical model for sand prediction, which takes into account quantitative and qualitative using recurrent neural networks based on field data on the technological modes of well operation. The model allows us to predict the trend and direction of change of the suspended solids concentration, as well as its absolute values depending on the main technological parameters. As a basis for modeling, a type of recurrent neural network (RNN) network of long short-term memory (LSTM) is used.

The proposed model consists of 6 layers: input layer, two LSTM layers, two layers of Dropout regularizers and output layer. The standard error (MSE) is used as a function for calculating deviation, and the Adam algorithm is used as an optimizer. The data submitted to the model are pre-standardized and divided by proportion: 70 % - training, 10 % - validation, 20 % - prediction. The average absolute error (MAE) acts as a measure of assessing the quality of model training. As a result, 3 out of 4 wells with a reach of more than 100 mg/l give a satisfactory result.

The applicability of the model is limited to the prediction of SSC values of 20 mg/l as a minimum and 1000 mg/l as a maximum. Values beyond these limits cannot be predicted by the model due to the peculiarities of the recurrent neural network architecture used.

Limitations in the initial data are conditioned by physical meanings of each of the indicators – there are no direct limitations of the model operation depending on the values of the initial data.

The input data fed into the model are:

1. P_{res} - minimum limitation is 1 bar, no maximum restriction.
2. $P_{at\ the\ intake}$ - minimum limit of 1 bar, no maximum restriction.
3. P_{wf} - minimum limit of 1 bar, no maximum limit, but does not exceed reservoir pressure.
4. H_D - minimum restriction of 0 m, but will not exceed well depth.
5. P_{buf} - minimum restriction of 1 bar, no maximum restriction.
6. Q_{oil} - minimum restriction of 0 m^3/d, no maximum restriction.
7. Q_{liq} - minimum limit of 0 m^3/d, but not less than Q_{oil}, no maximum restriction.
8. Water cut - minimum limitation of 0%, maximum limitation of 100%.

The created mathematical model, based on recurrent neural networks, is able to predict suspended solids concentration values depending on the parameters of the technological mode of well operation. It can be used in the field to control the sand production, calculate the time of bottomhole filling, predict downhole pumping equipment failures, etc.

The results of using the developed mathematical model based on neural networks to determine the predicted indicators of the number of suspended particles in the well are presented in Figure 9. As the initial value (blue line), field data with technological modes of well operation were used.

Next step is to develop a software module to determine the scenario of filling the horizontal wellbore. Section of the horizontal well with a particle accumulation is determined by setting the initial flow rates, the well profile and grain size distribution (Figure 10).

According to the information received, it can be concluded that the greatest accumulation of mechanical particles occurs in the "toe" (the flow rate is not enough for the sand production) and in the "heel" (due to the inclination of the section) of the horizontal well.

3. 3. Justification of Sand Control Technology Using Shape Memory Polymers

According to the results of analysis of more than 300 laboratory experiments, it was established that the greatest sand production occurs at the stage of flow stimulation (i.e., the first tens to hundreds of tons of produced hydrocarbons). Therefore, it is necessary to implement sand control technologies already at the stage of flow stimulation. The use of mechanical control methods in the event of frequent well shutdowns is futile. In case of gas flow the sand production is almost not stabilized (it does not decrease during long-term filtration), which indicates the possibility of using the technology with shape memory polymer when producing gas-oil mixtures.

It is important to note that each shape memory polymer has its own activation temperature (the start point of the transition to the initial state). First, the shape memory polymer is heated to the activation temperature, then compressed to the minimum possible dimensions, after which it is cooled and the polymer in this state can be freely transported. The form recovery will begin after the polymer is reheated to its activation temperature. A screen with a polymer is installed at the bottom-hole zone (the temperature of which should be lower than the activation temperature) and activation fluids are used a catalyst that reduces the activation temperature of the polymer to a target level (Figure 11).

The major element of the shape memory polymer is the activator and its concentration in the liquid the lower the bottomhole temperature, the higher concentration of the activator is necessary to reduce the activation temperature. Almost all Russian sand-producing oil fields are confined to PK1-3 layers, which located at a depth of 1000-1200 meters, and therefore have a low bottomhole temperature (in the range of 10-30 ˚C). Accordingly, the use of this technology can be limited by the need to use a high concentration of activator (up to 10 % by volume) in the liquid, which reduces the economic attractiveness (high costs for polymer engineering and activator chemicals) of this method of sand control.

The sand-limiting method developed in this paper allows limited transport of particles with a diameter of less than 50 μm, which creates conditions for non-colmatibility of the screen while maintaining its efficiency in terms of reducing the number of produced particles. Photo of the expandable screen element are shown in Figure 12.

The use of this polymer consists of two steps:

1) Delivery of slotted screen with pre-installed polymer pellets to bottom hole formation zone (screen

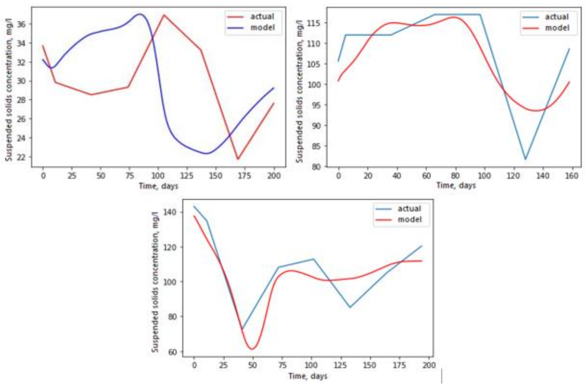

Figure 9. Results of using the developed mathematical model to predict sand production

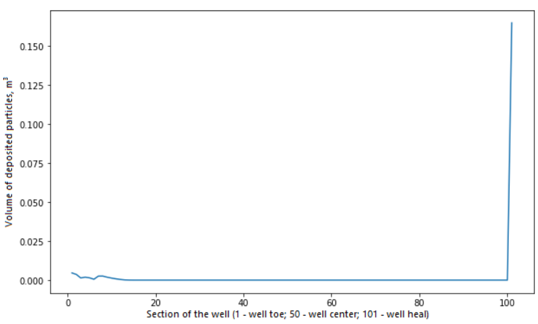

Figure 10. A number of suspended particles deposited depending on section of the horizontal well

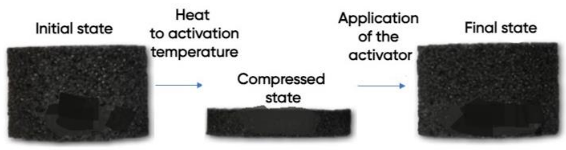

Figure 11. Schematic diagram of shape memory polymer application

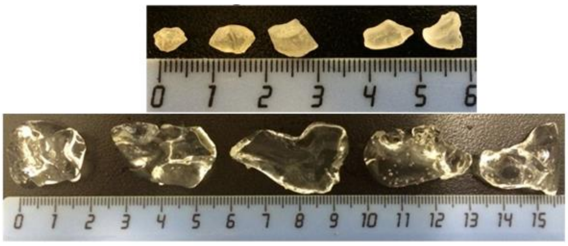

Figure 12. Photo of the expandable polymer screen in laboratory conditions

aperture does not allow polymer pellets to "fall out" during transportation).

2) Activation of the polymer in order to swell it and fill the entire volume between the lowered equipment and the wellbore by using the activator fluid.

Based on the results of laboratory studies of the developed technology using a polymer with shape memory, a decrease in the number of suspended particles by more than 46% was obtained (Table 4).

There are a slight decrease in the permeability of the polymer structure after the completion of laboratory experiments. The average permeability reduction is 6% (Table 5).

4. DISCUSSION

The selection of the technology for limiting sand production is based on the results of analysis of the following factors (59):

- Well profile: vertical, inclined or horizontal;
- Well completion: open or cased.
- Particle size analysis;
- Cost-effectiveness.

There are some tips how to make right selection of sand control technologies, for example, decision trees, based on the data presented in the scientific paper (60).

It is also necessary to understand the advantages and disadvantages of current methods. Most of them are described in Table 6.

TABLE 4. Laboratory tests of the shape memory polymer with wire-wrapped screen

Test	Suspended solids concentration, g/L	Suspended solids concentration, g/L
	Wire-wrapped screen 200 µm	Wire-wrapped 200 µm + Polymer
1	14,54	7,85
2	11,5	6,46
3	10,75	4,26

TABLE 5. Analysis of the permeability reduction of the shape memory polymer with wire-wrapped screen

Test	Initial data	Final data, % of original value
	Wire-wrapped screen 200 µm	Wire-wrapped screen 200 µm + Polymer
1	100	95%
2	100	96%
3	100	93%

TABLE 6. Advantages and disadvantages of sand control technologies

Technology	Advantages	Disadvantages
Pressure control	- Prevents formation destruction - no capital expenses	- underestimation of the well productivity
Selective perforation	- Prevents formation destruction	- underestimation of the well productivity - narrow applicability range - creation of a geomechanical reservoir model is required
Oriented perforation	- Prevents formation destruction	- underestimation of the well productivity - narrow applicability range - creation of a geomechanical reservoir model is required
Chemical consolidation	- Prevents formation destruction - cost-effective for small intervals (compared to the gravel packing) - compatible with mechanical methods of sand control	- reduction of permeability - cost-effective only for shallow thickness (up to 5 meters) - low efficiency of the repair and insulation works - service life is limited (1-2 years for epoxy resins)
Slotted screens	- Low cost - passage of medium and large size particles - easiness of installation - compatible with inflow control devices	- screen erosion - inefficient for passage small particles - not applicable in heterogeneous formations - low reliability

Wire-wrapped screens	- Compatible with inflow control devices - filtration area is larger than in slotted screens	- high cost - screen clogging - screen erosion - risk of screen damage during installation - high skin factor
Wire-mesh screens	- Compatible with inflow control devices - filtration area is larger than in slotted screens	- high cost - screen clogging - screen erosion - risk of screen damage during installation - high skin factor
Expandable screen	- Supports the wellbore; - low skin factor	- high cost - risk of screen damage during installation
Ceramic screens	- Less prone to erosion than metal screens	- high cost - screen clogging - risk of screen damage during installation
Wire-wrapped screens with gravel packed	- Thinnest passage zone - transport of different sizes particles can be achieved by controlling the packaging	- high cost - screen clogging - screen erosion - not applicable formations with a clay content
Gravel Pack in the open hole	- Applicable in long sections (up to 150 m) - filtration of small and medium-sized particles - durability - high reliability	- sharp decrease in productivity - complexity of screen creation process - high cost

Currently, single sand screens (slot or wire-wrapped) are the most widespread within the oil and gas fields in Russia.

Regardless of sand control technology that limits sand production, some of the destructed formation will be produced from the reservoir into the well. Produced sand will be accumulated in the well if the flow of liquid or gas does not transport solids to the wellhead. The accumulation of mechanical particles in the well will lead to a gradual filling of perforations and a decrease in production rate. In extreme cases, it is possible to form a sand plug and completely stop the well.

It is necessary to determine the nature of the movement of the sand-liquid mixture to predict accident-free operation of producing wells.

The main measurement parameters of the developed procedure for conducting laboratory experiments on sand packed tubes to establish the effectiveness of the sand control technology are: the number of suspended particles in the produced mixture, the particle size distribution of mechanical particles in the produced mixture during multi-stage sampling, and the relative permeability. These parameters make it possible to comprehensively assess the dynamics of the sand production process when using any sand control technology.

As a result of a series of laboratory experiments, it was established:

1. The number of suspended particles in the produced mixture depends on the volume distribution of phases in the fluid flow - filtration of pure oil leads to the highest suspended solids concentration (SSC). An increase in the proportion of brine leads to an increase in SSC. Filtration of gas-oil mixtures leads to the lowest SSC.

2. The number of suspended particles naturally decreases over time, due to the formation of arched systems and blocking of pore channels. The process of reducing SSC over time has been called "stabilization." The rate of "stabilization" depends on the volume distribution of phases in the fluid flow:

Water-oil mixtures have a high initial SSC, but over time the SSC value decreases to 15 – 25 % of the initial one;

• Gas-oil mixtures have a low initial SSC (compared to water-oil mixtures), but over time the SSC decreases only to 45 – 55 % of the initial one.

This phenomenon is associated with turbulization of the gas phase in the fluid flow high velocities of the gas phase lead to turbulent flow near the walls of the pore channel, due to which the separation of particles is more likely.

3. The increase in pressure drop leads to an increase

in the number of suspended particles in the produced mixture. It was experimentally established that with a quadruple increase in pressure drop (depression), on average, SSC increases 2.6 times. In this case, depending on the volume distribution of phases in the fluid flow and the "stage" of sand production, the SSC can increase by 1.2 to 8 times.

4. A decrease in grain size distribution does not result in an increase in the number of produced particles when using wire screens of the same aperture and design. This is due to an increase in the strength of the sand packed tubes due to cohesive interaction between particles. In addition, the decrease in grain size distribution indicates a high content of clay in its composition, which also plays the role of a consolidating material in the formation.

5. Oil flow leads to the transport of the ever-increasing diameter of rock particles due to the high flow force – over time, the flow of the oil phase entrains and carries out increasingly large particles. In the fine to medium part of the grain-size distribution (D25 and D50 of the original composition), the volume distribution of phases in the fluid flow does not significantly affect the transport capacity of particles. Water-oil fluids tend to increase the diameter of the produced mechanical impurities over time in the area of large grain-size distribution.

6. Application of mechanical screens leads to a decrease in the permeability of the system «screen – sand packed tube». However, the screen aperture and filtration pressure drop do not significantly affect the permeability. In most cases, decrease in the permeability does not depend on the suspended solids concentrations in the produced mixture and the particle size distribution of the produced particles, which suggests that the permeability of the system «screen – sand packed tube» changes mainly in the remote zone of the formation.

4. 1. Assessment of the Ability of Formation Fluids to Transport Particles of Different Grain Size Distribution The complete production of sand particles can only be achieved by increasing the flow rate of fluid. To prevent the formation of a sand plug in the production casing, with a water cut of 4 %, the critical liquid flow rate should exceed 0.123 m/s, which corresponds to a production rate of 214 m^3/day.

The increase in water cut will have a beneficial effect on the transport of sand in the horizontal well due to the increase in liquid production rate.

The growth of the gas factor, on the contrary, will negatively affect the mode of sand movement.

The amount of suspended particles in the studied range (20 – 2000 mg/l) does not significantly affect the transport of sand in the well. Areas with fixed sand are observed in the same areas. However, an increase in suspended solids concentration will lead to faster sand accumulation and early formation of a sand plug.

Critical velocities for streams with 50 μm and 200 μm particle diameters are substantially the same. For this reason, it is not necessary to install well screens with a small gap size. It is recommended to install wire-wrapped screens with an aperture of 200 μm instead of 150 μm, which will reduce the pressure drop on the screen and increase the well productivity.

4. 2. Development of a Combined Method for Limiting Sand Production Using Swellable Screen Elements The concept of the method is to use already existing mechanical screens with the addition of a gravel-like chemicals. Expandable polymer is required to prevent coarse sand particles and the mechanical screen in turn will trap fine particles. The screen can also be holes inside the base pipe (production string), so that this element is not an obligatory part of the structure. The approximate structure of the technology is shown in Figure 13.

There are three main mechanisms for initiating the process of sand production. Two of them consist in violation of petroleum geomechanics due to exceeding the compressive and tensile strength by shear and tensile stresses, respectively. The dynamics of sand production due to tensile stresses, as a rule, is a short-term and local nature and does not lead to significant consequences during well operation. The third mechanism is associated with the volumetric destruction of pore space and is currently poorly studied due to the complexity of physical processes and the impossibility of clearly formalizing the challenge due to too many influencing factors. In addition, the presence of such a factor as the migration of microparticles of rocks during the fluid production in a porous medium should be noted.

According to laboratory experiments, a high pressure drop leads to selective production of sand particles with diameters of 1 – 20 μm and 40 – 200 μm. Literature analysis (61, 62) has shown that particles with a diameter of less than 50 μm do not create sand plugs, since they are carried out of the wellbore even at low rates, but have a significant effect on skin factor of the screen.

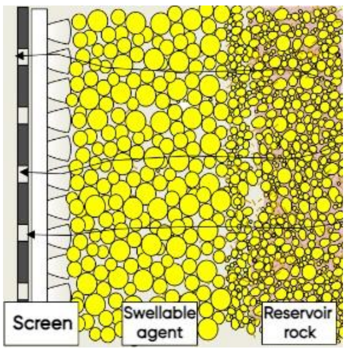

Figure 13. Scheme of reservoir with wire-wrapped screen with polymer

5. CONCLUSION

The paper presents a new concept of using shape memory polymers with wire-wrapped screens. Results of integrated modeling, including physical (laboratory), hydrodynamic and geomechanical, as well as analysis of the experience of using mechanical and chemical technologies for sand control in field conditions were revealed. Shape memory polymer technology will significantly reduce the suspended solids concertation during the well operation and will allow to avoid changes in the structure of the pore space near the bottom hole formation zone.

Results of the investigation might be presented in the following aspects:

1. A physical modeling method was developed to study the sand production process depending on the simulated operating conditions of the well (water cut, free gas content, pressure drop, etc.).

2. Author improved a set of mathematical models describing the process of sand production from the stage of initiation of violation of the stable geomechanical state and until the separation of rock particles from the walls of the wellbore and their further transportation along the horizontal well.

3. A mathematical model was created using recurrent neural networks to predict sand production in horizontal wells. The developed model makes it possible to determine the relationship between the number of suspended particles concentration and the main process parameters (oil flow rate, liquid flow rate, water cut, drop pressure) and use them to predict sand production.

4. A software module has been developed to determine the sections of the most probable accumulation of sand sediment with the calculation of the percentage of overlap of the inner diameter along the length of wellbore.

5. Proposed and substantiated is technology of sand control using shape memory polymer with wire-wrapped screen, which will allow limited passage of particles with diameter less than 50 μm, which creates conditions for non-colmatability of screen while maintaining permeability.

Directions for future research:

1. The creation of a database of well-founded and confirmed experiments will make it possible to evaluate the proposed sand control technologies at the expert level.

2. The application of the developed technology will improve the efficiency of wells operation that complicated by sand occurrence and significantly reduce the workover operations.

3. The use of the proposed methodological approach will allow for a better choice of technology for sand control and will also allow to maintain a geomechanically stable of the bottomhole formation zone.

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Persian Abstract

چکیده

این مقاله یک رویکرد مبتنی بر علمی جدید را برای انتخاب فناوری کنترل شن و ماسه ارائه می‌کند که به افزایش کارایی توسعه مخازن تجمیع نشده اختصاص دارد. مجتمع‌های آزمایشگاهی و روش‌شناسی ایجاد شده برای شبیه‌سازی فیزیکی فرآیند تولید شن و ماسه به منظور کسب دانش جدید و تایید نظریه‌های موجود مورد تجزیه و تحلیل قرار گرفت. همه آنها مزایا و معایب خود را دارند، اما کاربرد همزمان آنها وابستگی های مشخصه ای بین تولید ماسه و پارامتر مورد مطالعه (توزیع اندازه دانه، افت فشار، محتوای رس، قطع آب، نسبت گاز به نفت و غیره) را نشان داد. نویسنده مفاهیم بهبود دستگاه ریاضی را برای افزایش کیفیت ارزیابی توانایی سیالات سازند برای انتقال ذرات با توزیع اندازه دانه های مختلف در سازند و همچنین در قسمت داخلی لوله پیشنهاد کرد. اثر هر یک از عوامل مشخص کننده بر هماهنگی جامدات معلق (SSC)در نتیجه بیش از ۳۰۰ آزمایش آزمایشگاهی مورد مطالعه قرار گرفت. با توجه به مشاهده، کاهش شدید SSC پس از مرحله اول (نمونه برداری) وجود دارد. بنابراین، نویسنده تعیین کرد که جریان اصلی ناخالصی های مکانیکی در طول تحریک جریان و پس از خاموش شدن رخ می دهد. در نتیجه، نویسنده روش محدود کردن تولید شن و ماسه با استفاده از پلیمرهای دارای حافظه شکل را بر اساس نتایج مجموعه آزمایش‌های انجام شده اثبات کرد. روش پیشنهادی اجازه عبور محدود ذرات با قطر کمتر از ۵۰ میکرومتر را می دهد که شرایطی را برای غیرکلماتیک بودن صفحه و در عین حال حفظ ثبات ژئومکانیکی ناحیه تشکیل سوراخ پایین ایجاد می کند.