PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

O ESTUDO DA DEPENDÊNCIA DAS PROPRIEDADES REOLÓGICAS DAS COMPOSIÇÕES DE FORMAÇÃO EM GEL NA ABERTURA DE FENDAS AO MODELAR SEU FLUXO EM UM VISCÔMETRO ROTACIONAL

THE STUDY OF THE DEPENDENCE OF THE RHEOLOGICAL PROPERTIES OF GEL-FORMING COMPOSITIONS ON THE CRACK OPENING WHEN MODELING THEIR FLOW ON A ROTATIONAL VISCOMETER

ИЗУЧЕНИЕ ЗАВИСИМОСТИ РЕОЛОГИЧЕСКИХ СВОЙСТВ ГЕЛЕОБРАЗУЮЩИХ СОСТАВОВ ОТ РАСКРЫТОСТИ ТРЕЩИНЫ ПРИ МОДЕЛИРОВАНИИ ИХ ТЕЧЕНИЯ НА РОТАЦИОННОМ ВИСКОЗИМЕТРЕ

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RESUMO

O período atual de produção de petróleo é caracterizado pela deterioração da estrutura das reservas de petróleo devido ao alto corte de água do produto e baixas taxas de produção de petróleo. Para reduzir o aumento do corte de água, são geralmente realizados trabalhos de reparo e isolamento. Isso implica na injeção de sistemas de polímeros reticulados ou o tratamento da zona de formação de fundo de poço com sistemas de polímero-gel. Esse problema é especialmente relevante para reservatórios fraturados, que geralmente são representados por rochas carbonáticas. Este artigo é dedicado ao estudo da dependência das propriedades reológicas das composições formadoras de gel na abertura de fissuras em reservatórios de carbonato. A relevância do trabalho se baseia no rápido envolvimento no desenvolvimento de campos de petróleo com reservatórios de carbonato, o que é complicado por um grande número de trincas de vários tamanhos. Foram descritos os tipos de reservatórios fraturados, as características de desenvolvimento de cada tipo e as complicações na produção de hidrocarbonetos a partir da estrutura de poros fraturados do reservatório. A pesquisa também apontou métodos e tecnologias para limitar o fluxo de água em fendas ou poros de alta permeabilidade. As propriedades reológicas dos fluidos ao se mover dentro de poros e rachaduras foram relatadas. Foi apresentada a dependência de alterações nas propriedades reológicas da composição para limitar o influxo de água à base de carboximetilcelulose no tamanho de poros, cavernas e trincas. A física do movimento e formação de gel dentro dos reservatórios fraturados, que permitirá prever mudanças no tempo de formação do gel e na resistência plástica de cada objeto individualmente, foi reportada. De acordo com este estudo, é possível usar os recursos das propriedades reológicas das composições formadoras de gel para aumentar a eficiência do uso de tecnologias de impermeabilização na produção de poços ou alinhar o perfil de injetividade dos poços de injeção.

Palavras-chave: *obras de acabamento e isolamento, composição gelificante, propriedades reológicas, limitação da entrada de água, revisão geral de poços.*

ABSTRACT

The current period of oil production is characterized by the deterioration of the structure of oil reserves because of high water cut of the product and low oil production rates. To reduce the increased water cut, repair and insulation works are often performed. This implies in the injection of cross-linked polymer systems or the treatment of the bottom hole formation zone with polymer-gel systems. This problem is especially relevant for fractured reservoirs, which are often represented by carbonate rocks. This article is devoted to the study of the dependence of the rheological properties of gel-forming compositions on the crack opening in carbonate reservoirs. The relevance of the work relies on the rapid involvement in the development of oil fields with carbonate reservoirs which is complicated by a large number of cracks of various sizes. The types of fractured reservoirs, the development features of each type, as well as complications in the hydrocarbon production from the fractured-pore structure of the reservoir were described. The research also pointed methods and technologies for limiting

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water flow in cracks or pores of high permeability. The rheological properties of fluids when moving inside pores and cracks were reported. The dependence of changes in the rheological properties of the composition for limiting water inflow based on carboxymethylcellulose on the size of pores, caverns and cracks were presented. The physics of movement and formation of gel inside the fractured reservoirs, which will allow predicting changes in the gel formation time and plastic strength for each object individually was described. According to this study, it is possible to use the features of the rheological properties of gel-forming compositions to increase the efficiency of the use of water-proofing technologies for producing wells, or to align the injectivity profile of injection wells.

Keywords: *workover and insulation works, gelling composition, rheological properties, limitation of water inflow, overhaul of wells.*

АННОТАЦИЯ

Текущий период добычи нефти характеризуется ухудшением структуры запасов нефти из-за высокой обводненности продукта и низких темпов добычи нефти. Для уменьшения повышенной обводненности часто проводятся водоизоляционные работы. Это подразумевает закачку сшитых полимерных систем или обработку призабойной зоны полимерно-гелевыми системами. Эта проблема особенно актуальна для трещиноватых коллекторов, которые часто представлены карбонатными породами. Данная статья посвящена изучению зависимости реологических свойств гелеобразующих композиций от раскрытия трещины в карбонатных коллекторах. Актуальность работы заключается в быстром росте разработки нефтяных месторождений с карбонатными коллекторами, что осложняется большим количеством трещин различного размера. В данной работе описаны типы трещиноватых коллекторов, особенности разработки каждого типа, а также сложности при добыче углеводородов из трещинно-поровой структуры пласта. Исследование также указало методы и технологии для ограничения потока воды в трещинах или порах с высокой проницаемостью.Авторами описаны реологические свойства жидкостей при движении внутри пор и трещин. Представлена зависимость изменения реологических свойств составов для ограничения водопритока на основе карбоксиметилцеллюлозы от размера пор, каверн и трещин. Описана физика движения и образования геля внутри трещиноватых резервуаров, что позволит прогнозировать изменения времени образования геля и пластической прочности для каждого объекта в отдельности. Согласно этому исследованию, можно использовать особенности реологических свойств гелеобразующих композиций для повышения эффективности использования водоизоляционных технологий при добыче нефти из добывающих скважин или для выравнивания профиля приемистости нагнетательных скважин.

Ключевые слова: *ремонтно-изоляционные работы, гелеобразующий состав, реологические свойства, ограничение водопритока, капитальный ремонт скважин.*

1. INTRODUCTION:

The current period of oil production is characterized by the deterioration of the structure of oil reserves, the addition of heterogeneous reservoirs to the development, and the sharp transition of the leading production sites to the final development stage, which is characterized by high water cut of the product and low oil production rates. To reduce the increased water cut, repair and insulation works are often performed. Such an approach implies the injection of cross-linked polymer systems, or the treatment of the bottomhole formation zone with polymer-gel systems (Nikitin and Petuhov 2011;Strizhnev, 2010; Petkovićet *al*., 2019).

This problem is especially relevant for fractured reservoirs, which are often represented by carbonate rocks. Owing to their high conductivity, fractures in such oil and gas reservoirs are, as a rule, the main ways of filtering formation fluids, while the majority of hydrocarbon reserves can be concentrated in a matrix with relatively low permeability (Nazri*et al*., 2018).

Fracturing of rocks depending on the measurement methods is characterized by: intensity (total width of crack opening per unit length of the well, mm / m); specific water absorption (water absorption by the massif per unit length of the well and unit of hydrostatic head per unit time, l / s • m2); rheometric permeability (drop in air pressure when it spreads in the well per unit length per unit time, Pa / m • s) and other parameters. Depending on the presence of cracks and caverns, the collectors are divided intoporous, cavernous porous, cavernous, fissured-porous, fissured-cavernous, fissured-cavernous-porous (Rajss, 2012).

However, most experts (Rajss, 2012, Hanin, 2013; Yemelyanov*et al.,* 2018 a,b;) dwell on the division of reservoirs into fractured-pore and fractured-non-porous. In fractured-porous reservoirs, oil is located inside the blocks of the porous medium, and cracks play the role of connecting channels through which filtration is carried out. The fractured-non-porous blocks are impermeable and do not contain hydrocarbons; oil is concentrated in a system of connected caverns, through which filtration is carried out.

To generalize and typify the geological and physical characteristics of the reservoir, it is necessary to classify carbonate reservoirs. There are several types of division of carbonate reservoirs:

1. According to the Viktorin V.D. – by collector productivity and its composition (Hanin, 2013);
2. according to Amelin I.D. – by the size of cracks (Gol'f-Raht, 1986);
3. according to Chernitsky A.V. – by the ratio of reserves in the media (Ibatullin, 2011);
4. according to R. Nelson - according to the ratio of reserves in media and the share of their participation in filtration (foreign classification) (Blazhevich*et al*., 1999).

The main ones are the first and fourth type of classification. The first type is based on the dividing of rocks according to the predominant type of fluid-containing and conductive systems. Viktorin V.D. divided the collectors into high, medium, low and potentially productive, assigned a certain type to each group and assigned them boundary values of porosity and permeability (Hanin, 2013). For example, the low-permeability group is composed of fractured-pore and fractured-cavernous rocks with permeability from 1 to 10 mD, open porosity of 4-8% and oil saturation from 57 to 74%.

According to the Nelson classification, collectors are divided into 4 types depending on the increase or decrease in the effect of cracks. In the first type, the effect of cracks is maximum, therefore, the main reserves are confined to cracks, the matrix of the reservoir has low porosity and permeability. In this type, productivity is associated only with cracks. In the second type, the main reserves are contained in the matrix, cracks provide the main productivity. The matrix of the reservoir has low permeability, but can have both low, medium and, in rare cases, high porosity. In the third type, the matrix of the reservoir contains the main oil reserves, has high permeability and porosity, and cracks complement the matrix permeability. In the latter type, cracks do not contribute to the permeability and porosity of the matrix of the formation but introduce anisotropy into the formation. In this type, productivity is directly dependent on the reservoir matrix.

Further, depending on what type of reservoir the developed reservoir belongs to, mechanisms of oil displacement from reservoirs are selected. According to Golf-Rakht(Gol'f-Raht, 1986), the following mechanisms of oil displacement from the matrix are distinguished elastic mode, capillary impregnation, gravity drainage of oil by water, horizontal (displacement due to differential pressure) (Susanti*et al.,* 2018).

When oil is displaced from fractured-porous reservoirs, gravitational drainage of oil by water predominates, and piston displacement occurs in fracture systems. In a pore structure, the process of oil displacement by water or gas is based on the combined action of gravitational and capillary forces. However, the predominance of certain forces largely depends on the nature of the wettability of the rock (Suryono*et al.,* 2019; Polyakova*et al.,* 2019):

In hydrophilic reservoirs, water, as a rule, quietly passes into blocks, as a result of which gravitational forces prevail over capillary forces, and as a result, water displaces oil from the pores (Vogrinec andPremrov, 2018).

In hydrophobic reservoirs, due to the action of capillary forces, water cannot penetrate into the blocks, and displacement is possible only if the gravitational force overcomes the resistance of capillary pressure (inlet pressure). The smaller the pore size, the higher the pressure at which water enters the unit. Therefore, it is extremely difficult to displace oil from a hydrophobic, highly fractured reservoir. Experience in the development of deposits with carbonate reservoirs shows that the matrix of the rock due to the hydrophobicity of carbonate rocks is blocked by the displacement agent, and at the same time, production rates in the area with a reservoir pressure maintenance system are sharply worsened (Neizvestnaya*et al*., 2018).

The main problem with this displacement is the high pressure gradients that lead to an increase in the filtration rate to values higher than critical in the near-wellbore zone, which contributes to the premature breakthrough of the underlying water into the wells and, thereby, the capillary impregnation process is disrupted, which is the most effective method of displacing oil from porous blocks (Hermawan*et al.,* 2019;Zakki*et al.,* 2019).

For fractured reservoirs when developing oil deposits by water flooding, breakthroughs of injected or formation water through a system of fractures to producing wells are characteristic. Herewith, oil is displaced from them very efficiently, and the coefficient can reach significant values:

0.8–0.85. Experience shows that oil is also displaced from the matrix of fractured-pore reservoirs, however, the displacement coefficient is relatively low – it does not exceed 0.3 even for hydrophilic reservoirs. Oil displacement from fractured reservoirs occurs under the influence of two most important factors.Thefirst one is transient pressure gradients in the matrix-fracture system.Thesecond one isthe process of capillary impregnation. In this case, capillary impregnation itself occurs extremely slowly (Balakin*et al.*, 1988; Strizhnev*et al.*, 2006; Surguchev*et al.,* 1997).

So, this research is aimed at studying the movement and formation of a stable gel depending on the size of the pore space of the carbonate reservoir.

2. MATERIALS AND METHODS:

One of the most important problems in recent decades has been the restriction of water inflow into wells draining a fractured formation, as well as the isolation of a highly conductive single fracture, which connects a production well with an injection well or aquifer. Instant watering of the recovered fluid occurs as a result of the breakthrough of formation and injection waters through highly permeable reservoirs and fractures. Under these conditions, an important task is to restrain water drainage in the highly permeable part and fractures of the reservoir. One of the main methods in the middle of the last century was polymer flooding. This method, due to the property of polymers to increase the viscosity of water, helps to reduce the ratio of the mobility of water and oil, thereby removing the possibility of a breakthrough of water due to heterogeneity of the reservoir. For this operation, it is necessary to pump a significant amount of the composition into the reservoir, therefore this method did not become widespread in water inflow limitation. In view of this factor, technologies with the use of low-volume injections (rims), which lead to the creation of a water-proof screen in the bottom-hole zone of production wells, have gained popularity in reducing the movement of water through cracks and highly permeable layers. For measures to limit water inflow through injection wells, cheaper and more affordable reagents are used (Vlasov*et al.*, 1988; Nikitin2012**;** Petrov*et al.*, 1995).

However, the behavior of polymer-gel system under reservoir conditions has been poorly studied, since until recently it was impossible to conduct experiments under conditions close to reservoir conditions. The advent of modern rotational viscometers allows to simulate the movement of the gel in cracks by adjusting the gap in the measuring system (for example, “plate-plate”).

In order to study the behavior of polymer systems in cracks of various openings, a laboratory was conducted to determine the dependence of the rheological properties of polymers on the probable opening of an insulated crack in a laboratory for increasing oil recovery at the Mining University.

Two samples of polymer-gel systems with an assumed different viscosity were taken. To prepare the gelling composition № 1, the following reagents were mixed: a carboxymethyl cellulose polymer, a chromium acetate crosslinker and a copper sulfate catalyst (thickener). All the components are environmentally friendly and harmless. This composition is recommended when limiting water inflow in cracks. To reduce the movement of water in highly permeable interlayers, a gel-forming composition is proposed, consisting of carboxymethyl cellulose polymer, chromium acetate and sodium acetate, which significantly reduces the viscosity of the composition after preparation but during gelation it does not reduce the strength characteristics of the composition.

An Anton Paar MCR 102 rheometer was used, which is highly accurate in studying the properties of various liquids. The device is described in detail in papers (Roshchin, 2014). At this device, it is possible to change the gap in the plate-plate system to simulate the flow of fluid in a crack with an openness of up to 1 mm. In this case, this option was used to study the behavior of the gel-forming composition in the fractures of the formation of different openness.

The experiment was carried out as follows: a sample of a gel-forming composition was placed on the plate with a dispenser, then a certain gap and a formation temperature of 25 °C were established. After that, within 2 minutes, the shear rate linearly increased from 0 to 100 s^{-1}, simulating the movement of the gel along the crack. During the experiment with gel samples № 1 and № 2, the following gaps were established: 1; 0.8; 0.6 and 0.5 mm.

3. RESULTS AND DISCUSSION:

Figure 1 shows graphs of the dependence

of the shear stress of gel №1 on time with an increase in shear rate from 0 to 100 s^{-1}. The graph shows the influence of the established gap on the rheological properties of the gelling composition. This can be explained as follows: firstly, the effect on the gel-forming composition occurs with different masses, changing with a change in the gap. For example, the mass of the gel enclosed in the space between the fixed plate and the rotor plate in the gap of 0.5 mm will be less than the mass of the gel in the gap of 1 mm. Therefore, the transfer of mechanical energy from a viscometer to a gel sample will occur in the same way, however, the ratio of the transferred energy to the mass of the sample will vary significantly.

Reducing the gap from 1 mm to 0.5 mm doubles the energy transferred to the unit mass of the gel used for the experiment. Secondly, at the indicated shear rates, the conversion of mechanical energy into heat is likely, which allows the creation of additional chemical bonds in the gel-forming composition. It is due to such effects that it is possible to substantiate an additional parameter of the selectivity of the composition, which manifests itself in gel strengthening in small cracks and pores, and its further movement along large highly permeable channels, which allows the gel-forming composition to penetrate as deep as possible into the treated area of the reservoir and isolate large highly permeable channels. Due to this, some reagent savings are possible, since it is mainly large cracks that are filtration channels for water that will be insulated.

Also, by the method described above, a less viscous gelling composition № 2 was investigated. Figure 2 shows the dependence of shear stress on the time of gel-forming composition № 2 with a gradual linear increase in shear rate. This graph shows that the addition of sodium acetate to the gel No. 1, consisting of a polymer CMC-500 and a crosslayer of chromium acetate, reduces the viscosity of the composition, without violating the strength characteristics and the dependence of the gel formation time on the opening of cracks.

The smaller difference between the values of the effective viscosity (shear stress) for different crack openings is explained by the fact that the conversion of mechanical energy to thermal energy will first be directed to increase the viscosity in the pore space and then to create additional chemical bonds in the gel-forming composition.

4. CONCLUSIONS:

1. The dependence of the rheological properties of the gel-forming compositions on the crack opening during modeling of their flow on a rotational viscometer was established. Wherein, phenomena have been identified that can play a positive role in the operation of waterproofing work in wells that have uncovered oil or gas formations.
2. It was found that the addition of sodium acetate to the gel-forming composition based on a polymer of carboxymethylcellulose and a crosslinking of chromium acetate reduces the initial viscosity of the initial composition, without violating the dependence of gel formation in pores of various sizes, which allows for selective injection of the gel-forming composition into cracks.
3. The dependence of rheological properties, gel-forming formulations of opening the crack allows us to offer the highest quality gel-forming composition to improve the effective use of waterproofing technology or alignment profile injectivity of injection wells.

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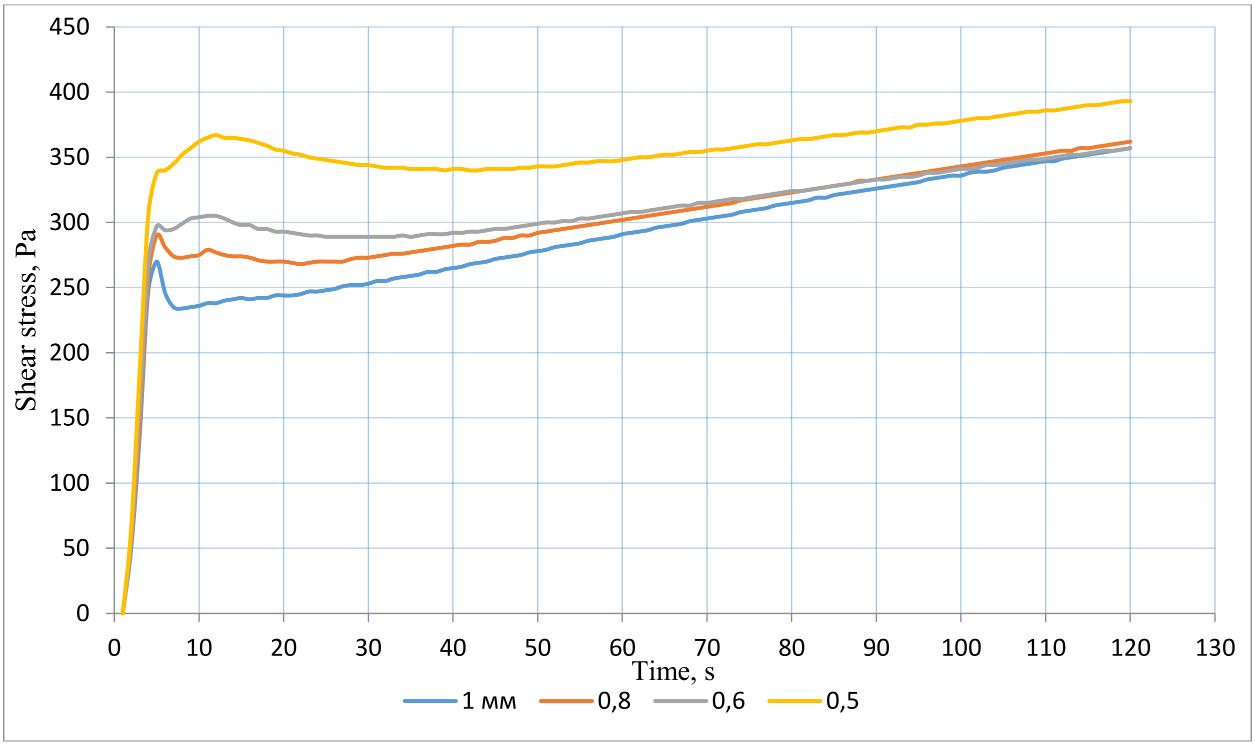

Figure 1. *Dependence of the shear stress on time of gelling composition № 1 with a linear increase in shear rate from 0 to 100 s^{-1}*

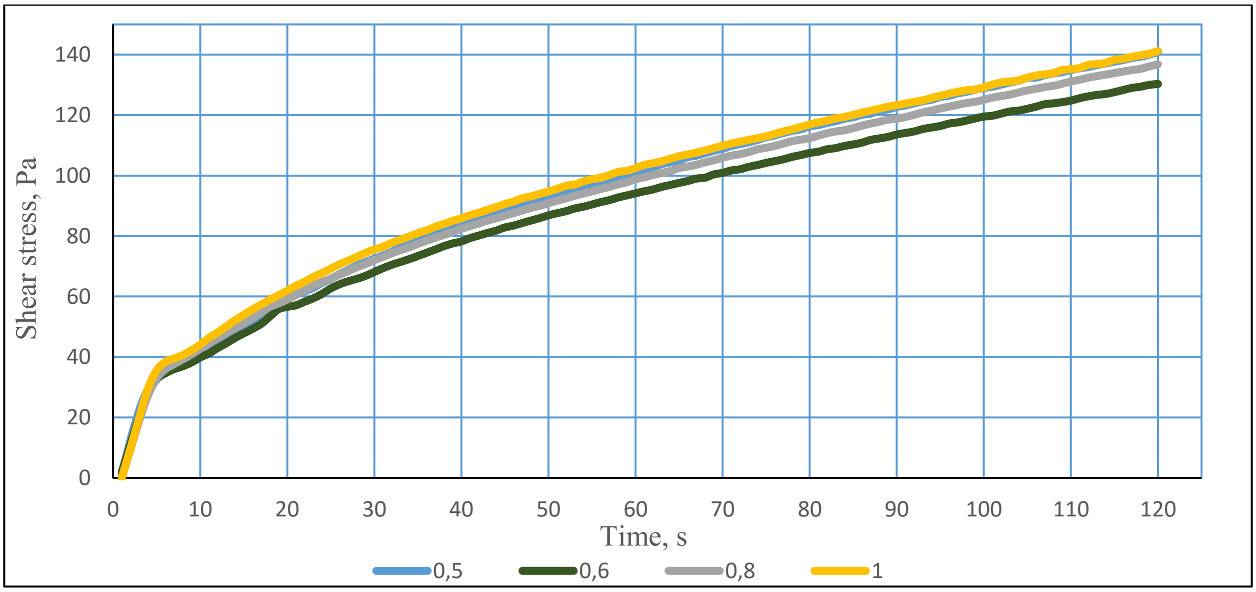

Figure 2. *Dependence of the shear stress on time of gelling composition № 2 with a linear increase in shear rate from 0 to 100 s^{-1}*