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DETERMINING THE EFFECT OF VIBRATING WAVE SWABBING ON THE FUNCTIONAL PROCESSES IN CARBONATE LOW-PERMEABILITY RESERVOIRS

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This paper investigates the method of vibrating wave swabbing, which is used to stimulate the flow of liquid to the well.

This method is known to generate mechanical waves in the soil that open microcracks and pores, increasing the flow of hydrocarbons. A carbonate reservoir with low permeability, which is quite common in the oil and gas industry, was considered as the study object. Therefore, the object of research was carbonate low-permeability reservoirs. After all, their low permeability makes the extraction of oil and gas from them a difficult task.

As a result of processing, it was established that increasing the amplitude of pressure fluctuations contributes to increasing the efficiency of the vibration wave action, as the permeability of the reservoir increases more intensively, which was confirmed by the coefficient of determination, which was $R^2=0.92$. And an increase in the frequency of oscillations, on the contrary, reduces it, because the depth of the effective zone of vibrational action decreases; in this case, the coefficient of determination was $R^2=0.81$.

To study the effect, a laboratory setup was designed that included a plunger device that generated fluid perturbations in a conditional borehole. The resulting elastic waves were measured by a manual contact vibrometer.

Vibrating wave swabbing is a promising method for intensifying hydrocarbon production.

The influence under investigation could be implemented in oil and gas fields with carbonate low-permeability reservoirs. This would lead to an increase in fluid production and improved efficiency of the oil and gas industry

Keywords: vibrating wave swabbing, low-permeability reservoir, increased permeability, amplitude of pressure fluctuations, intensification

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1. Introduction

Carbonate low-permeability reservoirs (CLRs) are of significant interest for oil and gas production. However, their low permeability makes mining a difficult task. Vibrating wave swabbing (VWS) can be a promising method for intensifying the flow of fluids to wells. After all, it is a method of intensification of fluid inflow to wells, which uses vibration waves to destroy mechanical crusts and increase the permeability of the reservoir, clean the pore channels of the reservoirs, and initiate the filtration of fluids in low-permeability reservoirs [1].

Vibrating wave swabbing can be used to increase reservoir oil yield, increase the flow rate of wells, and clean contaminated soils. To establish the interaction of these parameters, it is advisable to use statistical analysis. It is an important tool for the study of vibrating wave swabbing. It can help obtain more accurate information about the effect of VWS on various characteristics of the reservoir, to develop more accurate predictions about its performance, and to optimize the VWS process.

Scientific research on this topic is important because CLR is a significant reserve of oil and gas, but their extraction is complicated by low permeability. VWS could become a promising method of intensification of fluid inflow to wells from CLR because traditional production methods do not always give the expected result.

Such studies are needed in practice as they could define a more economical and environmentally oriented method of hydrocarbon extraction.

2. Literature review and problem statement

In [1], the results of studies of low-frequency oscillations, amplitude, and duration of fluid inflow are reported. It is shown that there are optimal excitation parameters that maximize the extraction of hydrocarbons. But the issues related to the influence of the viscosity of oil and water on the effectiveness of vibrating wave swabbing, the influence of the heterogeneity of the reservoir on the process of mobilization of oil plugs remained unresolved.

In experiments [2] with loams, vibration waves can be a useful tool for studying its various properties, such as density, viscosity, and elasticity. The objective difficulties analyzed in [3] associated with the change in vibration may indicate the presence of pores in the material under study. An option to overcome the relevant difficulties may be to increase the amplitude of pressure fluctuations, which helps increase the efficiency of the vibration wave action, since the permeability of the reservoir increases more intensively. And an increase in the frequency of oscillations, on the contrary, reduces it because the depth of the effective zone of vibrational action decreases [4]. The generated pulses (shocks) described in [5] destroy mechanical crusts and increase the permeability of the formation. A depression is created on the formation, the pore channel of the reservoirs is cleaned, the blocking effect of residual gas, oil, and water is eliminated, and the filtration of fluids in low-permeability reservoirs is initiated.

Work [6] shows that low-frequency vibration can significantly increase the permeability of low-permeability reservoirs. But the issues related to the mechanism of the vibration effect on the structure of the reservoir and the effect of the viscosity and density of the extracted fluid remained unsolved.

The reason for this may be the objective difficulties associated with the study of the dynamics of multiphase flows in porous media and the measurement of flow parameters at the microscopic level. To solve this problem, possible solutions can involve:

– the use of numerical modeling methods,

– devising new experimental research methods;

– the use of a combined approach, i.e., a combination of laboratory studies with numerical modeling and analytical calculations.

This is the approach used in works [7, 8]; however, the authors did not take into account the influence of some important factors, such as the amplitude of pressure fluctuations and the frequency of fluctuations. The results of the work have not been verified on real objects.

All this gives reason to assert that it is expedient to carry out a study aimed at determining vibrating wave swabbing under the operating conditions of low-permeability reservoirs.

Therefore, the challenge is to develop simpler, more cost-effective designs that will allow for a shorter timeframe to get the fluid flow.

3. The aim and objectives of the study

The purpose of our research is to determine the effect of vibrating wave swabbing on the functioning processes of carbonate low-permeability reservoirs. This will make it possible to evaluate the effectiveness, optimize the parameters, and expand the understanding of the mechanisms of impact of vibrating wave swabbing.

To achieve the goal, the following tasks were set:

– to reveal the regularities of VWS influence on various characteristics of the reservoir;

– to determine the dependence of the frequency of oscillations on the volume of the sampled liquid;

– to establish the dependence of the permeability coefficient of the reservoir on the amplitude of oscillations.

4. The study materials and methods

The object of the current study is to determine the effect of vibrating wave swabbing on the functioning processes of carbonate low-permeability reservoirs.

The main hypothesis of the research assumes that vibrating wave swabbing could significantly affect carbonate low-permeability reservoirs, namely:

– to increase the permeability of CLR;

– to increase the oil yield of CLR;

– to change the physical and mechanical properties of CLR;

– to influence the electrical characteristics of CLR.

This hypothesis is based on the fact that VWS can generate vibration waves that destroy mechanical crusts and increase the permeability of the formation. It can also initiate the filtration of fluids in low-permeability reservoirs and can affect the structure and properties of the rock, which could lead to changes in its physical, mechanical, and electrical characteristics.

In order to test the hypothesis, a set of laboratory studies on VWS in CLR will be conducted and their results will be worked out using multiple regression [9, 10]. To this end, the software package «Statistica 10» (Oklahoma, USA) will be used.

5. Results of investigating vibrating wave swabbing in low permeability carbonate reservoirs

5. 1. Identifying patterns of influence exerted by vibrating wave swabbing on various characteristics of the reservoir

To establish the regularities of WVS influence on various characteristics of the reservoir, we shall use the results of laboratory studies given in Table 1.

Table 1

Input data for statistical analysis

Observation	Oscillation frequency f, Hz	Reservoir permeability coefficient K, Darcy	Amplitude of pressure fluctuation A, mm	Volume of sampled fluid V, ml
1	2.85	$8.4{*}10^{-12}$	0	20
2	2.41	$1.26{*}10^{-11}$	150	30
3	1.88	$3.9{*}10^{-11}$	165	95
4	0.85	$4.2{*}10^{-11}$	173	100
5	0.66	$4.8{*}10^{-11}$	181	115
6	0.55	$5.03{*}10^{-11}$	295	120
7	0	$8.82{*}10^{-11}$	423	210

We process the obtained results with the help of multivariate analysis and the software package «Statistica 10».

As a result of the analysis, we obtained a graphical dependence (Fig. 1) and equation (1) of the volume of the sampled liquid on the amplitude of pressure fluctuations:

$$A = 10.3094 + 1.9056 \cdot V. \tag{1}$$

Correlation coefficient r=0.9181. Fisher's criterion is equal to 26.82, and the value of $F_{critical}$=19.25.

Since $F_p > F_{critical}$, the null hypothesis is rejected, and the constructed regression equation is accepted as statistically significant. The hypothesis about the adequacy of the model was confirmed.

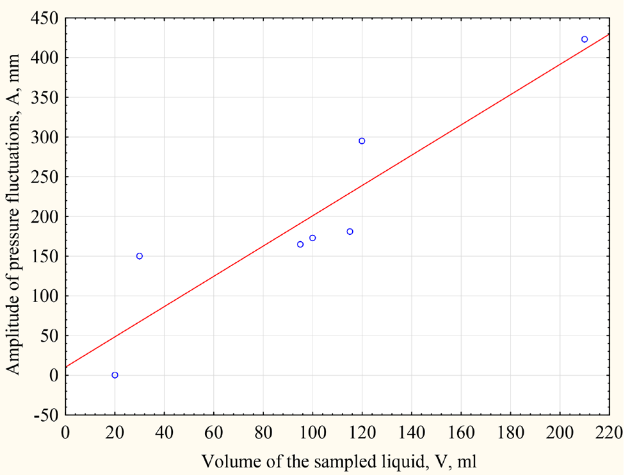

Fig. 1. Graphical dependence of the volume of the sampled liquid on the amplitude of pressure fluctuations

Fig. 2 demonstrates that the correlation coefficient will be 91.81 %. This suggests that the amplitude of pressure fluctuation depends on the volume of the sampled liquid.

Fig. 2 shows the graphical dependence and equation (2) of the volume of the sampled liquid on the permeability coefficient of the reservoir:

$$K = -1.699 \cdot 10^{-13} + 4.1984 \cdot 10^{-13} \cdot V. \tag{2}$$

Correlation coefficient $r=0.999$. Fisher's criterion is equal to 3171.19, and the value of $F_{critical}=225.0$.

Since $F_p > F_{critical}$, the null hypothesis is rejected, and the obtained regression equation is accepted as statistically significant. The hypothesis about the adequacy of the model was confirmed.

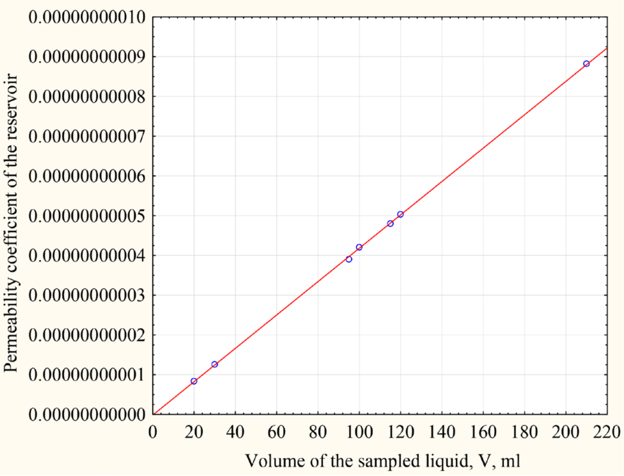

Fig. 2. Graphical dependence of the volume of sampled liquid on the permeability coefficient of the reservoir

As can be seen from Fig. 3, the correlation coefficient will be 99.9 %. This suggests that the permeability coefficient of the reservoir depends on the volume of the sampled liquid. Almost all points lie on a straight line.

Fig. 3 shows the graphical dependence and equation (3) of the volume of the sampled liquid on the frequency of oscillations:

$$f = 2.8401 - 0.0155 \cdot V. \tag{3}$$

The correlation coefficient $r=-0.9180$. Fisher's criterion is equal to 27.38, and the value of $F_{critical}=19.25$.

Since $F_p > F_{critical}$, the null hypothesis is rejected, and the constructed regression equation is accepted as statistically significant. The hypothesis about the adequacy of the model was confirmed.

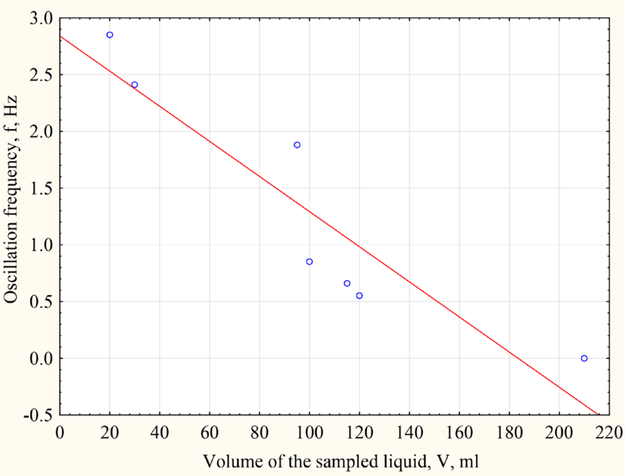

Fig. 3. Graphical dependence of the volume of sampled liquid on the frequency of oscillations

Fig. 4 demonstrates that the correlation coefficient will be 91.8 %. This suggests that the variables move in opposite directions. That is, with an increase in the frequency of oscillation, the volume of the sampled liquid will decrease.

Fig. 4 shows the graphical dependence and equation (4) of the permeability coefficient of the reservoir on the frequency of oscillations:

$$K = 7.1311 \cdot 10^{-11} - 2.29 \cdot 10^{-11} \cdot f. \tag{4}$$

Correlation coefficient $r=-0.9197$. Fisher's criterion is equal to 27.42, and the value of $F_{critical}=19.25$.

Since $F_p > F_{critical}$, the null hypothesis is rejected, and the constructed regression equation is accepted as statistically significant. The hypothesis about the adequacy of the model was confirmed.

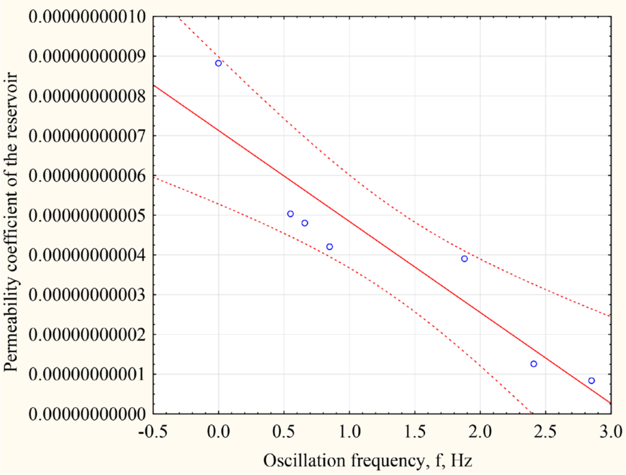

Fig. 4. Graphical dependence of the reservoir permeability coefficient on oscillation frequency

As can be seen from equation (4), the correlation coefficient will be 91.97 %. This suggests that the variables move in opposite directions. That is, with an increase in the frequency of oscillation, the coefficient of permeability of the reservoir will decrease. To confirm our conclusions, it was decided to use logarithmic analysis.

5. 2. Determining the dependence of the frequency of oscillations on the volume of sampled liquid

Our analysis of the dependence of the oscillation frequency on the volume of the sampled liquid is illustrated in Fig. 5 and equation (5).

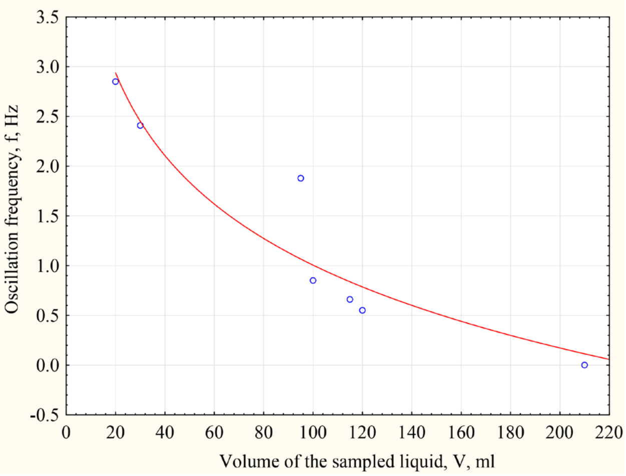

Fig. 5. Graphical logarithmic dependence of oscillation frequency on the volume of liquid

As a result, the regression equation and the value of the correlation coefficient are obtained:

$$f = 6.5388 - 2.77 \cdot \log 10(V). \quad (5)$$

The coefficient of determination is $R^2=0.81$. The coefficient of determination indicates the possibility of applying such a regression dependence.

Our analysis of the dependence of the amplitude of pressure fluctuations on the volume of sampled liquid is illustrated in Fig. 6 and equation (6).

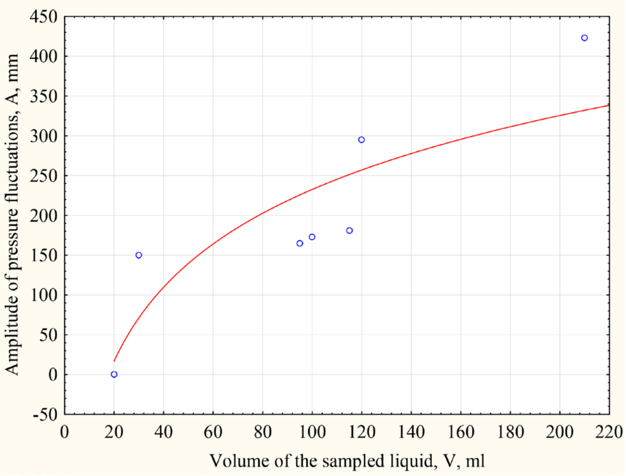

Fig. 6. Graphical logarithmic dependence of the amplitude of pressure fluctuations on the volume of sampled liquid

As a result, the regression equation and the value of the correlation coefficient are obtained:

$$A = -384.6858 + 308.6556 \cdot \log 10(V). \quad (6)$$

The coefficient of determination is $R^2=0.92$ The coefficient of determination indicates the possibility of applying such a regression dependence.

As a result of the analysis of logarithmic dependences, the preliminary conclusion about the inverse relationship between the permeability coefficient of the reservoir and the frequency of oscillations was confirmed. For greater clarity, 3-D dependence plots were constructed using the method of least squares.

Fig. 7 shows the 3-D dependence of oscillation frequency on the volume of the sampled liquid and on the permeability coefficient of the reservoir.

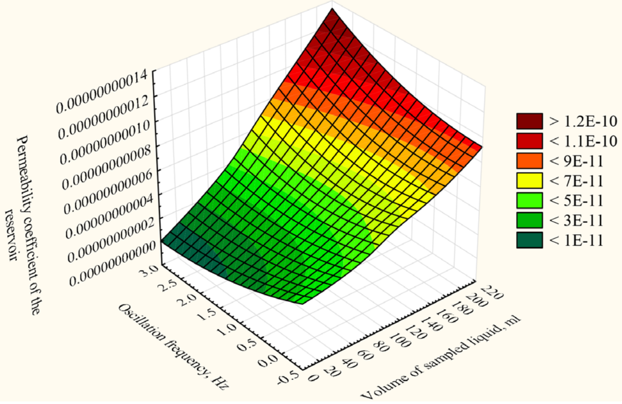

Fig. 7. 3-D dependence of oscillation frequency on the volume of sampled fluid and on the permeability coefficient of the reservoir

Analyzing the change in the aforementioned parameters, we can conclude that the increase in the amplitude of pressure fluctuations contributes to the increase in liquid selection, since the permeability of the reservoir increases more intensively.

5. 3. Determining the dependence of permeability coefficient of the reservoir on the amplitude of oscillations

Our analysis of the dependence of permeability coefficient of the reservoir on the volume of sampled liquid is illustrated in Fig. 8 and equation (7).

As a result, the regression equation and the value of the correlation coefficient are obtained:

$$K = -8.8566 \cdot 10^{-11} + 6.8729 \cdot 10^{-11} \cdot \log 10(V). \quad (7)$$

The coefficient of determination is $R^2=0.81$. The coefficient of determination indicates the possibility of applying such a regression dependence.

Our analysis of the dependence of permeability coefficient of the reservoir on the frequency of oscillations is illustrated in Fig. 9 and equation (8).

As a result, the regression equation and the value of the correlation coefficient are obtained:

$$K = -3.8758 \cdot 10^{-11} - 5.3717 \cdot 10^{-11} \cdot \log 10(f). \quad (8)$$

The coefficient of determination is $R^2=0.84$. The coefficient of determination indicates the possibility of applying such a regression dependence.

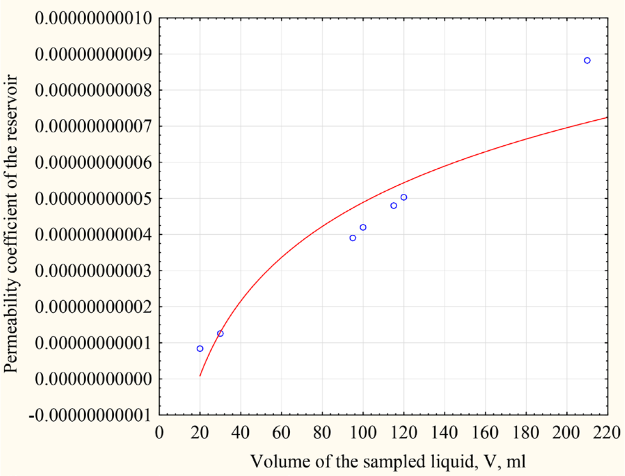

Fig. 8. Graphical logarithmic dependence of reservoir permeability coefficient on the oscillation frequency

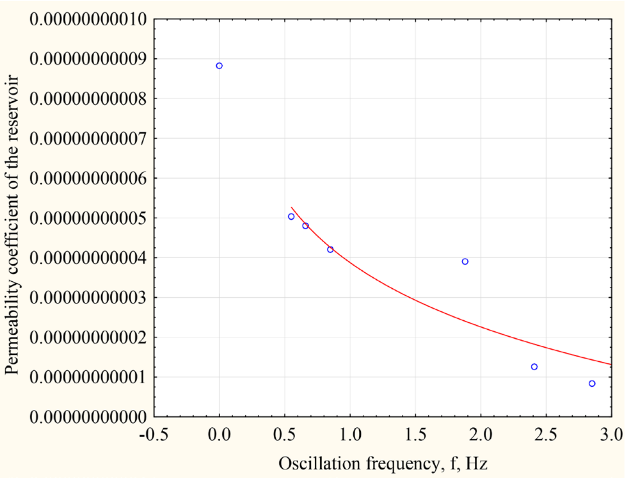

Fig. 9. Graphical logarithmic dependence of oscillation frequency on the reservoir permeability coefficient

For clarity of the result, in Fig. 10 we plotted the 3-D dependence of the amplitude of pressure fluctuations on the volume of sampled liquid and on the permeability coefficient of the reservoir using the method of least squares.

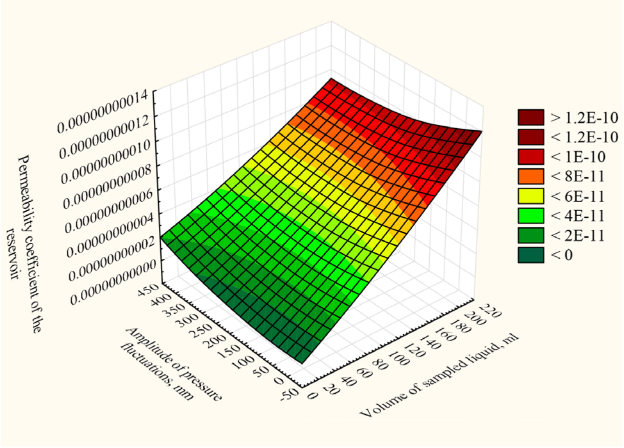

Fig. 10. 3-D dependence of the amplitude of pressure fluctuations on the volume of the sampled fluid and on the permeability coefficient of the reservoir

Analyzing such parameters as the amplitude of pressure fluctuations, the coefficient of permeability of the reservoir, we can draw the conclusion that an increase in the frequency of oscillations, on the contrary, reduces the selection of liquid because the depth of the effective zone of vibration treatment decreases.

6. Discussion of results of investigating vibrating wave swabbing in low-permeability carbonate reservoirs

As a result of our study of the vibration wave injection, the interaction between the frequency of oscillation, the coefficient of permeability of the reservoir, the amplitude of the pressure fluctuation and the volume of the sampled liquid was established (Table 1). There is an optimal frequency of oscillation, which varies from 0.6 to 1.0 Hz, the amplitude of pressure oscillation (165–250 mm), and duration of vibration, at which the maximum effect of VWS is observed. With these values, a rather large value of the reservoir permeability coefficient is observed. These parameters are interrelated and must be selected taking into account the properties of the reservoir and the type of fluid.

Unlike low-permeability reservoirs, high-permeability reservoirs [1, 2] respond better to vibrational influence. This is due to the better spread of vibration in the reservoir. Under the operating conditions of CLR, the result of the impact is achieved by adjusting such parameters as the amplitude of pressure fluctuations and the frequency of fluctuations.

Increasing the amplitude of pressure fluctuations destroys mechanical crusts more intensively and cleans pores. This leads to an increase in the permeability of the reservoir, as a result of which the selection of liquid increases, which is shown in Fig. 4–8, and equations (3) to (6).

Increasing the frequency of oscillation reduces the depth of vibration penetration into the reservoir. This leads to a decrease in the effective zone of vibrational action, as a result, the selection of liquid decreases, which is shown in Fig. 9–11, and equations (7), (8).

Therefore, as a result of the statistical processing of the data on laboratory studies of VWS, it can be concluded that the purpose of research into VWS has been achieved. After all, the influence of VWS on the filtration capacity characteristics of CLR was investigated, the regularities of the influence of VWS in CLR were revealed, and the obtained data can be used for the development of methods of intensification of oil and gas production from CLR.

Therefore, it is possible to define the following restrictions:

– research on laboratory models cannot always be accurately scaled to the real conditions of the deposit. This is due to the heterogeneity of the layers, the non-ideal geometry of the well;

– the influence of vibration on the viscosity, density, and other properties of fluids has not been fully studied, which may lead to inaccuracy in the modeling and forecasting of flow dynamics;

– limitations on the frequency, amplitude, and duration of the vibration effect that can be generated under real conditions.

A comprehensive approach combining laboratory studies, numerical simulations, and field tests is necessary for the success of vibrational swabbing research.

It may take a long time to get the final results of a vibrating wave swab test.

It is important to continue the research into the vibration effect on the functioning processes of carbonate low-permeability reservoirs in order to better understand the mechanisms of swabbing, to devise effective methods of its application, and to evaluate its economic and ecological effect.

The following can be attributed to the disadvantages of VWS:

– laboratory studies are carried out on small samples of reservoirs. This can lead to inaccuracy of the results during statistical processing since the data are not representative of the actual field conditions;

– carbonate reservoirs have a complex geological structure and significant heterogeneity. Therefore, the results obtained on laboratory samples will not correspond to the results obtained in real wells;

– statistical processing gives only a quantitative assessment of the impact of vibrating wave swabbing. Additional research is needed for more detailed analysis and interpretation of the results.

Therefore, in order to more accurately determine the impact of vibration wave action on CLRs, it is recommended to conduct additional studies with a wider range of parameters of the vibration wave effect, optimization of VWS parameters for various types of CLRs, and conducting research under field conditions. Based on the results of research, practical recommendations can be devised regarding the optimal parameters of vibration wave influence for various types of reservoirs and fluids.

7. Conclusions

1. The study of the effect of vibrating wave swabbing has made it possible to reveal the regularities of the effect on the filtration and capacity characteristics of the reservoir. It has been established that VWS can significantly increase the permeability of CLR. This is due to the destruction of mechanical crusts, cleaning of pore channels, and initiation of filtration of fluids under the influence of vibration waves. Our study showed that VWS can increase the oil and gas yield of CLR. This is due to increased permeability and mobilization of residual oil, gas, or condensate under the influence of vibration. Also, the effect of vibration waves can change the physical and mechanical properties of CLR, such as strength, cracking, porosity, and specific surface area. These changes can affect the filtering characteristics of the reservoir.

2. Increasing the amplitude of pressure fluctuations from 0 to 500 mm during vibrating wave swabbing more intensively increases the permeability of the reservoir, respectively, from $8.4*10^{-12}$ to $8.82*10^{-11}D$ and contributes to a greater selection of liquid, which will amount to 210 ml. An increase in the amplitude of pressure fluctuations leads to more intensive destruction of mechanical crusts, cleaning of pore channels, and initiation of fluid filtration. This, in turn, leads to a significant increase in the permeability of the reservoir and contributes to a better flow of liquid to the wellbore, respectively, and to an increase in flow rate.

3. Increasing the oscillation frequency to 2.85 Hz leads to a decrease in the vibration wavelength. This leads to a decrease in the depth of penetration of vibration into the reservoir, correspondingly to a decrease in the effective zone of vibration wave action, and to a decrease in the permeability of the reservoir, liquid selection, as well as oil and gas condensate return. Therefore, it is necessary to use the optimal frequency of oscillations in the range from 0.6 to 1.0 Hz, at which the maximum effect of vibrating wave swabbing is observed.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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