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A study of Iraqi shale samples when subjected to different drilling fluids

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ABSTRACT: The interaction between aqueous drilling fluids and clay minerals has been established as a significant factor in the instability of wellbore and shale formation. Previous models of wellbore stability take into consideration the interactions between aqueous drilling fluids and pore fluid but neglect the interactions with shale matrix. This paper provides an understanding of the behavior of shale sample when subjected to water based drilling fluid through laboratory experiments. The gravimetric test method used in the laboratory to acquire a better understanding of water and ion flow into or out of the shale. To avoid shale instability problem, the drilling fluid should be designed in such a way that less water and more ions can diffuse to the shale. In this study, three different salts were added to water base mud to understand which one causes less shale swelling. Shale samples were chosen from two Iraqi oilfields Al-Khabaz and East Baghdad (E.B.) field. These samples were subjected to several steps of drying, immersion, direct and indirect exposure to three chemical solutions namely KCl, NaCl and CaCl2. When E.B. shale was immersed in KCl solution; the shale sample weight increased by just 0.19 % through water diffusion into the shale. KCl solution also increased the sample weight by 0.75 % through the diffusion of ions. As a result, KCl was shown to be more effective in maintaining shale stability compared to NaCl and CaCl2. Al-Khabaz shale sample responded to NaCl drilling fluid better where water increase was approximately zero and sodium cations absorption raised the shale sample weight by 0.62 %.

KEYWORDS: Water activity, Wellbore stability, Gravimetric test, Shale swelling.

INTRODUCTION

Since the beginning of oil and gas industry, one of the main problems has been wellbore instability in shale formation [1]. The undesired effect of drilling fluids on shale formation represent the essential cause of this problem [2]. In reality, 90% of shale collapse problems are due to shale instability [3]. Swelling and scattering of shale can result in several problems including bit balling, sloughing, caving, stuck pipe as well as increased cost, torque, drag, heaving and dispersed drilling activity [4]. The main cause for this instability is shale water absorption and the resulting swelling and sloughing of the wellbore [5]. Such interactions are very complicated including different phenomena like mechanical, chemical, physical, electrical as well as thermal. The overall effects of these interactions are mainly linked to the diffusion of water and ions through the shale. Shale formations properties, such as strength, permeability, elastic modulus, and pore pressure are changed owing to this movement, resulting in shale instability. Two main mechanisms for water movement in shales are the chemical potential difference (i.e., water activity) between drilling fluids and shales, and the hydraulic pressure difference between shale pore pressure and wellbore pressure [6].

The earliest investigation of shale behavior when subjected to water based mud was conducted by Martin E. Chenevert, [7] who studied wellbore instability and the effects of interaction between the shale and drilling fluids. Martin E. Chenevert concluded that clays and montmorillonitic rocks expanded as a result of water and oil adsorbtion. . Fifty shale samples at different depths were collected and studied. The project concluded that all types of shales tested were reactive to fresh water and that the change was no less than 3% of the total weight of the sample. Furthermore, adsorption by confined shale samples generated internal stresses that led to hydrational spalling, vertical fracturing, and compressive strength reduction. The most effective method to increase shale stability is controlling water activity of drilling fluids and reducing pressure difference between shale pore pressure and wellbore pressure through adding additives in drilling mud.

Jianguo Zhang et al. [8] used NaCl, KCl and $CaCl_2$ to study the effects of ion movement between the shale and drilling fluids by chemical (i.e., osmosis, diffusion) and physical (hydraulic pressure difference) processes. Three Arco and three Pierre I shale samples with dimension of 1.0” x 0.75” x 0.5” were immersed separately in three solutions of NaCl, KCl, $CaCl_2$ at controlled relative humidity conditions. The shale samples were then dried using a desiccator and an oven respectively and the weight change was then recorded. The results showed an increase in the weight due to ions movement from the fluids to the shale samples. Therefore, they concluded that chemical osmosis is not the only cause for the transportation of water, however, ion diffusion and capillary effects under zero hydraulic pressure difference also have an important role. Moreover, the water gain and loss is greater in the $CaCl_2$ solution than in those of NaCl, KCl due to the different characteristics of these solutions as Ca^+ ions have different dehydration and hydration diameters [9].

Emadi et al. [4] compared shale swelling behavior after the interaction with oil base and water base mud. The oil base mud resulted in less swelling compared to water base mud containing 7 % KCl. Emadi et al. [4] also concluded that the direction of drilling affects the direction of swelling. In their paper, they also suggested that drilling of shale formation should be perpendicular to its bedding direction where it’s possible. Another paper by Akhtarmanesh, S. et al. [5] showed the use of a nanoparticle additive in drilling mud in order to reduce fluid penetration to shale formation. In this paper, the stability of Gurpi shale, located in Iran, was increased by this method to reduce the pressure penetration to reach 97%. Pore plugging test which needs special apparatus and is relatively an expensive test was used in this paper. Zhang et al. [8] developed Gravimetric-Swelling Test (GST) to quantify ion and water migration during the interactions between drilling mud and shale formation. This method is very simple and may run in the site of well drilling and does not require special equipments to evaluate water and ions movement.

Ions and water movement mechanisms

Convection and chemical activity are the major mechanisms that drive water and ion movement. The hydraulic pressure difference between a drilling mud in the wellbore and fluids present within shale formation pores drives the flow of water and ions movement. Water activity is the principal chemical property responsible in this flow, although the literature often refers to various mechanisms such as ionic diffusion, capillary effects and chemical osmosis, as chemical effects [9].

Chemical Osmosis

The concept of water activity effect on wellbore and shale stability was introduced and studied by Chenevert [10]. His paper revealed that the shale’s hydrational status and ability to absorb water are indicated by shale water activity. Experimentally, it is obtained by measurement of the relative aqueous vapor pressure of the atmosphere above the shale.

In order to describe the chemical potential of a material, the aqueous vapor pressure ratio *(p/Po)* is usually used. This ratio is parallel to the relative humidity and is frequently referred to as water activity, a_w *[7]*

$$a_{w,shale} \cong \frac{P}{P_O} \tag{1}$$

The direction of chemical osmosis flow is from a higher water activity media to a lower one [11]. Hence, if water activity of shale is more than that of a drilling fluid, the water moves out of the shale thus lowers the near wellbore pore pressure and water content [5]. This may result in a shrinkage of the shale. On the other side, if water activity in the shale was less than that of the drilling fluid, the water moves into the shale and raises the water content as well as the pore pressure near the wellbore wall. This water introduction to shale, forces the shale to swell. Low and Anderson [12] derived an equation to establish the osmotic pressure that could develop between the drilling fluid and shale. Nonetheless, few studies [9] have shown that a shale does not act as a perfect semi-permeable membrane when in contact with drilling fluid hence a membrane efficiency term is introduced to correct for the non-ideality.

Diffusive Flow

The diffusion of ions and associated water is dominated by a concentration gradient that is expressed by using Fick's law [13]:

$$J = -D_{si} \left(\frac{C_{i,shale} - Ci,mud}{\Delta X} \right) \quad (2)$$

Where J is mass flux of i^{th} ion, $C_{i,shale}$ concentration of i^{th} ion in pore fluid, $C_{i,mud}$ concentration of i^{th} ion in mud, D_{si} the diffusion coefficient of the i^{th} ion and Δx length of shale. Simply, the direction of diffusive flow for specific ion is from high concentration to low concentration media. If the ion concentration in the drilling mud is greater than its concentration within shale formation fluid, then the ion will enter the shale. This phenomenon increases the formation pressure [5]. On the other hand, rapid crack formation in the shale may result when the pore pressure of the shale drops due to a highly salty drilling fluid which in turn causes the water in the shale pores to flow to the wellbore [3].

Convective Flow

Convective flow is studied by Darcy's equation, which explains that the flow is a result of a gradient between the formation pore pressure and hydraulic drilling fluid pressure. This small flow can be neglected because of the fact that most drilling fluids are designed to operate with low pressure gradient, this is in addition to the extremely low permeability of shale [9].

METHODOLOGY

There are multiple methods to calculate the diverse effects of drilling fluids on shale formation properties since there is no constant composition for drilling fluids. In this research, we used a test called gravimetric test **[8]** to calculate the main factors that can cause ion exchange in shale-fluid system interaction. The immersion of shale into the fluids changes the chemical composition of the shale due to ion movement, thus its physicochemical and mechanical properties are altered. The samples have been taken from two different Iraqi fields; Khabaz and East Baghdad (E.B.) oil fields. Khabaz oil field is about 20 Km to the North-West of Kirkuck city in the North-East of Iraq. It is located between Jambur and Bai-Hassan structures and the South-West of baba-dome. Al-Khabaz complex (tertiary & cretaceous reservoir) has an asymmetrical elongated anticline (about 15 km length and 5 km width) it also has a NW-SW axis and faulted mainly on its west flank by reverse. [14] E.B. Field in the Rashdiah region contains many reservoirs; most importantly are Tanuma, Khasib and Zubair, which have different grades of crude oil 21 – 23, and 35 API in Zubair formation. The geological structure of East Baghdad oil field is complex because of the presence of many faults and the fact that the field lies in treated agricultural and urban regions. [15]

Gravimetric Test

The main goal of this test is to simulate the conditions that drilling fluid encounters in shale formation. Firstly, the shale sample must be filled with the native water formation or some equivalent water activity fluid. Secondly, the shale sample must be immersed in the drilling fluid to see the interaction between them. Experimental steps to study the flow of water and ions into or out of shale were performed in this study. Preparation was done prior to the testing procedure. The samples were cut and trimmed to the specific dimensions and then placed in an oven at 200 ºF until their water content is evaporated.

Step 1: Three cylindrical E.B. and three Al-Khabaz shale samples with the dimensions of 2.5 cm diameter and 2.6-2.5 cm length were placed in a controlled relative humidity environment of 85% (a_w = 0.85) desiccator containing potassium chloride, weighed and recorded until equilibrium (constant weight) is achieved. In the desiccator, ions do not diffuse through the shale as does the water [1] In order to make a valid comparison between data, the samples should be brought to the same water level [16].

Step 2: The above samples were then immersed into separate containers of 0.85 a_w NaCl, 0.85 a_w KCl, and 0.85 a_w $CaCl_2$ solutions for 24 hours, and were then removed, weighed, and their new weights is recorded. This step represents the conditions at which the drilling fluid interact with the shale formation in reality.

Step 3: The last step comprises of drying them in a 93 ºC using an oven for 24 hours. Their dried weight is then also recorded.

The four weights recorded earlier are represented graphically in figures (1), (2) which show the changes taking place in different immersion solutions in different samples.

RESULTS AND DISCUSSION

The results of the experiment is tabulated according to the steps in which they were obtained relative to the initial (after preparation) results in which the water/ion content was zero as shown in table 1 and table 2 for Al-Khabaz and East Baghdad fields respectively.

Table 1. Results for Al-Khabaz Field Gravimetric Tests

Step Number	Al-Khabaz Field		
	Sample K1	Sample K2	Sample K3
Native Wt. (after preparation) (gm)	34.10	33.60	38.60
Step 1. Controlled relative humidity desiccators placement (gm)	34.50	33.91	39.20
Step 2. Immersion in $CaCl_2$ for K1 Immersion in KCl for K2 Immersion in NaCl for K3	34.76	34.23	39.43
Step 3. Drying by Oven at 93 °C (gm)	34.27	33.82	38.84

Table 2. Results for E.B. Field Gravimetric Tests

Step Number	E.B. Field		
	Sample R1	Sample R2	Sample R3
Native Wt. (after preparation)	31.70	32.00	33.40
Step 1.Controlled relative humidity desiccators placement	32.10	32.20	33.50
Step 2. Immersion in $CaCl_2$ for R1 Immersion in KCl for R2 Immersion in NaCl for R3	32.38	32.50	33.75
Step 3. Drying by Oven at 93 °C	31.89	32.24	33.52

In step 1, a 0.3 % wt increase was noticed in the E.B. shale samples. In this step, owing to the gaseous osmosis, the equilibrium was established. Under these conditions, there was no contact of E.B shale sample with liquid water, therefore water molecules moved through vapor phase. Equilibrium was reached between the solution by their vapor pressure and the shale. After Step 1, the samples were put in a 0.85 aw NaCl solution as part of step 2. An increase of 1.05 wt % was noticed. This weight increase resulted from ions and water movement, essentially because of the diffusion phenomenon. After the second step, water molecules were eliminated from the sample using an oven to complete step 3. After the drying step, it was observed that its weight has increased by 0.36 % in comparison to the dried native weight thus, it can be concluded that ions have entered the shale.

When testing the E.B. shale samples in KCl solution there was a difference in the values of the absorbed and lost water/ion values between the KCl and NaCl solution. For KCl, the weight increment in step 1 was 0.63 % and the weight lost in step 3, which is 0.75 %, compared to a weight reduction of 0.3 % in step 1 and 0.36 wt % in step 3 for NaCl. In comparison with the previous results gathered from testing the same shale samples in both NaCl and KCl solutions. The sample tested in CaCl2 solution have the largest weight change. In figure (1), step 1 shows that the sample recorded 1.26 % wt change and this change increased significantly when the samples immersed in $CaCl_2$ solution reaching a value of 2.15 % which is the largest among the three E.B. shale samples. In addition, at the end of the test in step 3, the dried sample witnessed the largest loss in water compared to the other two samples.

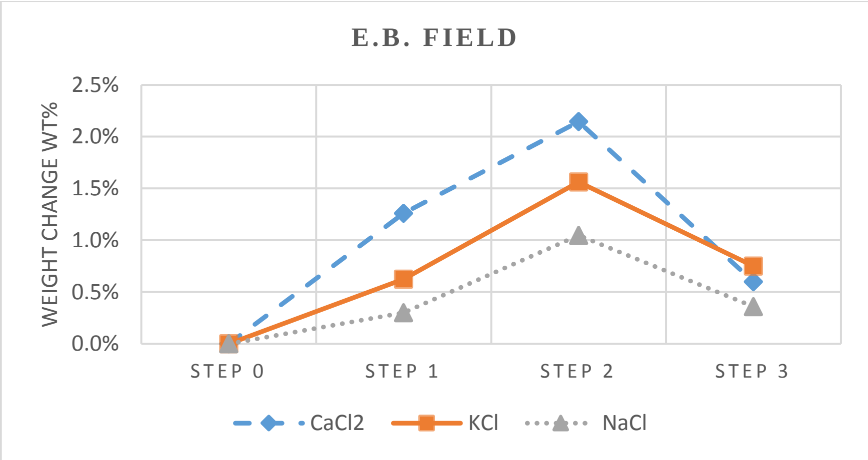

Figure 1. Gravimetric test for E.B.field samples in three solutions; $CaCl_2$, KCl, NCl.

In order to examine the weight change of water and ions during each step of the experiment; it was important to determine the initial water content in E.B. and Al-Khabaz shale samples. This was achieved through drying three separate native pieces of shale in a 93 ºC until their water content became zero. Below is the change in weight percent for each sample of E.B. field showed graphically in figure (1). Tests similar to the above E.B. tests were performed for Al-Khabaz shale samples. The results are shown in figure (2). The three Al-Khabaz shale samples gained water after they were equilibrated in 0.85 a_w atmosphere. Water and ion movement calculated by using gravimetric test that was published initially by Zhang et al. [8] and the results are graphically showed in figure (3) and figure (4) for Al-Khabaz and E.B. field respectively.

Al-Khabaz field water movement: It's clear from figure (3) that the samples immersed in KCl and $CaCl_2$ obtained more than 0.2 wt % water. So, as more water absorbed, shale swelling increased as there is a relation between water content and shale strain [3, 17].

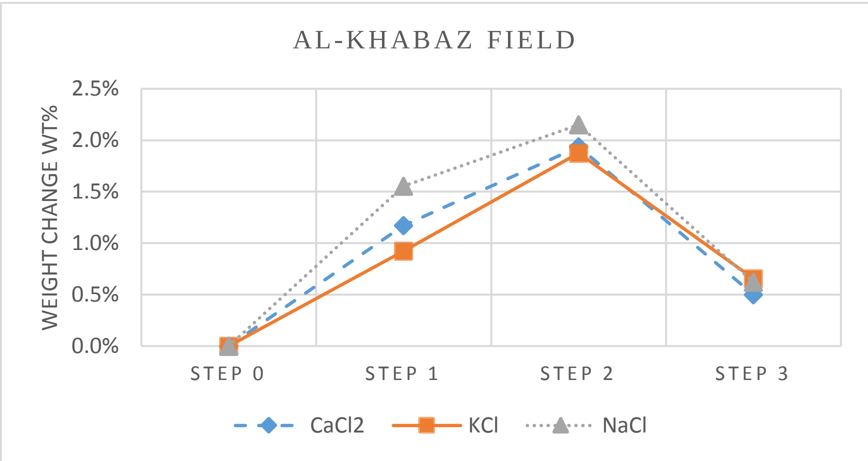

Figure 2. Gravimetric test for Al-Khabaz field samples with three solutions; $CaCl_2$, KCl, NaCl.

In contrast, NaCl solution resulted in a reduction in water content in shale sample as seen in figure (3). The value for water change is negative. That means the shale sample did not gain water from the NaCl solution, but also lost a little amount of its native water. As a result of this behavior, the shale will be more stable, i.e. when shrinkage occurs instead of swelling.

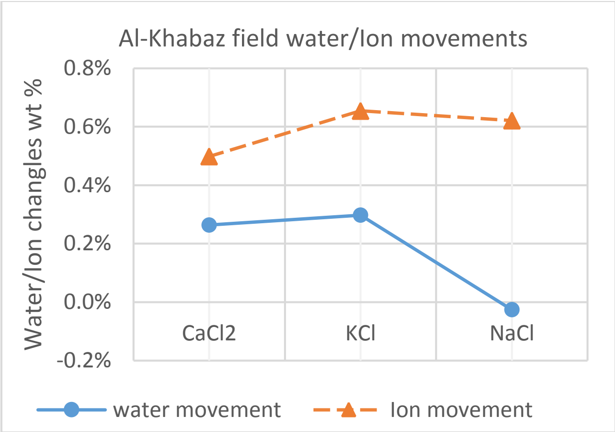

Figure 3. Water and ion movement during the immersion of Al-Khabaz shale samples in three different solutions; $CaCl_2$, KCl, and NaCl.

Al-Khabaz field ion movement: It is interesting to know that the overall electric charge of the platelets in the shell is negative, which makes them unstable because of the repulsion forces among the like charges. If the cation size is small enough to enter between the platelets, it can adhere to the parallel plates thus preventing water molecules from entering the shale structure. In other words, as more cations enter the shale, the latter becomes more stable. As can be seen from figure (3), the absorption of Na^+ and K^+ cations is more than 0.6 wt %. This means that both of these solutions can be used to increase shale stability of Al-Khabaz oil field. On the other hand, Ca^{2+} cations are less absorbed resulting in smaller increase in weight percentage compared to the two other solutions. It should be noticed that the electric charge density plays a critical role in maintaining platelets strength. This is due to the fact that electrostatic attraction among the platelets increases as the charge density increases. This will in turn cause the attraction energies of the clay to stabilize it. [18]. Nonetheless, charge densities of the platelets are heterogeneous [19] therefore; it's impossible to have a proper judgment about the effectiveness of electrical charges densities, especially, without examining the platelet components of the clay.

E.B. field water movement: E.B. shale samples absorbed less water when immersed in KCl solution compare to the $CaCl_2$ and NaCl. The absorbed water resulted in 0.19 wt % increase, which will not result in significant swelling. The water absorption of NaCl solution for E.B. sample is more than that of Al-Khabaz field sample. Therefore, NaCl solution is not proper selection for E.B. field unlike is for Al-Khabaz field.

E.B. field ion movement: The main cation absorbed in the E.B. shale sample is potassium with a value of 0.75 wt % increase. This absorption will increase the attraction between shale platelets and reduces its instability. Calcium cations are also absorbed with 0.6 wt % increase thus improving shale stability. The sodium cation in NaCl solution caused an increase by 0.39 wt % and this value is the smallest when compared to $CaCl_2$ and KCl solution in E.B. shale sample. Hence, the effect on the stability of the shale is smaller in the case of NaCl when compared with KCl and $CaCl_2$.

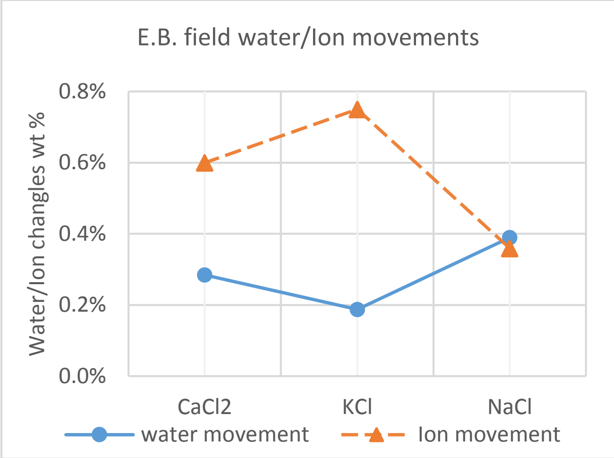

Figure 4. Water and ion movement during the immersion of E.B. shale samples in three different solutions; $CaCl_2$, KCl, and NaCl.

CONCLUSIONS

1- The gravimetric test is used in this research to calculate water and ion migration in the shale samples of Al-Khabaz and E.B. oil fields in Iraq.

2- The most convenient drilling fluid in this paper for Al-Khabaz oilfield is NaCl when compared to $CaCl_2$ and KCl solutions as the former resulted in a loss of 0.03 wt % from the shale sample native water formation. Therefore, no shale swelling resulted. On the other hand, ion diffusion caused an increase in wt% by 0.62, which is relatively high regarding to other experimented drilling fluids. This makes the attraction between the shale platelets stronger and thus more stable.

3- For E.B. shale sample, the most effective solution used was KCl because the weight of water absorbed by shale is only 0.19% of the sample weight. This value is actually very small therefore no swelling issues will result. The experiment shows that KCl solution increased the weight of the E.B. shale sample by 0.75 % through ion movement. Potassium cations that were introduced parallel to platelets with negative charges will increase the attraction forces. This will improve shale stability by reducing swelling resulting from water absorption

4- In the future, it is necessary to identify shale platelet compositions and water activity of native formation water to design the most proper drilling fluid.

REFERENCES

[1] A. Alsubaih, Shale Instability Of Deviated Wellbores In Southern Iraqi Fields. 2016.

[2] A.A. Alwassiti, M.A. Al-Bidry, and K. Mohammed, "Experimental study of Zubair shale stability of east Baghdad oil field using different additives in water-based mud", Journal of Petroleum Exploration and Production Technology, Vol. 10, No. 3, Pp. 1215-1225, 2020.

[3] Q. Zhang, A review of the shale wellbore stability mechanism based on mechanical–chemical coupling. 2015.

[4] H. Emadi, "An experimental study of the swelling properties of unconventional shale-oil rock samples using both water-based and oil-based muds and effects of invasion on rock mechanical properties. in SPE/IADC Drilling Conference and Exhibition", Society of Petroleum Engineers, 2015.

[5] S. Akhtarmanesh, M.A. Shahrabi, and A. Atashnezhad, "Improvement of wellbore stability in shale using nanoparticles", Journal of Petroleum Science and Engineering, Vol. 112, Pp. 290-295, 2013.

[6] M.A. Jarrett, "Improved competence in water activity measurement", in AADE (American Association of Drilling Engineers) Technology Conference, Houston, Texas. 2004.

[7] M.E. Chenevert, "Shale alteration by water adsorption", Journal of petroleum technology, Vol. 22, No. 09, Pp. 1141-1148, 1970.

[8] J. Zhang, "A new gravimetric-swelling test for evaluating water and ion uptake in shales", in SPE annual technical conference and exhibition. Society of Petroleum Engineers, 2004.

[9] J. Carlos, D.E. Clark, and J. Zhang, "Stressed shale drilling strategy-water activity design improves drilling performance. in SPE Annual Technical Conference and Exhibition", Society of Petroleum Engineers, 2006.

[10] M. Chenevert, "Shale control with balanced-activity oil-continuous muds", Journal of Petroleum technology, Vol. 22, No. 10, Pp. 1309-1316, 1970.

[11] S. Koteeswaran, "Characterization of shale–fluid interaction through a series of immersion tests and rheological studies", Journal of Petroleum Exploration and Production Technology, Vol. 8, No. 4, Pp. 1273-1286, 2018.

[12] P.F. Low, and D.M. Anderson, "Osmotic pressure equations for determining thermodynamic properties of soil water", Soil Science, Vol. 86, No. 5, Pp. 251-253, 1958.

[13] J. Wei, Y. Cheng, and C. Yan, "Two-Dimensional Pore Pressure Distribution Model to Evaluate Effects of Shale Semipermeable Membrane Characteristics", Journal of Energy Resources Technology, Vol. 142, No. 1, 2020.

[14] N. Amin, and A.A. Alhaleem, "Analysis of Stuck Pipe Incidents in Khabaz Field", Iraqi Journal of Chemical and Petroleum Engineering, Vol. 19, Pp. 47-53, 2018.

[15] A. Alrazzaq, "Development of East Baghdad Oil Field by Clusters of Horizontal Wells", Iraqi Journal of Chemical and Petroleum Engineering, Vol. 20, Pp. 75-79, 2019.

[16] M.N. Al-Awad, and B. Smart, "Characterization of shale-drilling fluid interaction mechanisms related to wellbore instability", Journal of King Saud University-Engineering Sciences, Vol. 8, No. 2, Pp. 187-214, 1996.

[17] C. Yan, J. Deng, and B. Yu, "Wellbore Stability in Oil and Gas Drilling with Chemical-Mechanical Coupling", The Scientific World Journal, Pp. 720271, 2013.

[18] I. Shainberg, N. Alperovitch, and R. Keren, "Charge Density and Na-K-Ca Exchange on Smectites1", Clays and Clay Minerals - Clays Clay Miner, Vol. 35, Pp. 68-73, 1987.

[19] O. Talibudeen, and K.W. Goulding, "Charge heterogeneity in smectites", Clays and Clay Minerals, Vol. 31, No. 1, Pp. 37-42, 1983.