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Investigation of the Simultaneous Effect of Flow Rate and Water Salinity on Kaolinite Mobilization in Sand

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Abstract

There are several factors that trigger particle migration of kaolinite in hydrocarbon formations of which two primary factors are high flow rate and low water salinity. Studies on fines migration by low water salinity and flow rate have been conducted separately, but in reality, these factors work together; not in isolation. Hence, this work aims to experimentally study flow rate and water salinity in combination as factors that trigger particle migration in unconsolidated sand. Kaolinite clay obtained from Umulu/Ngwugwo deposit in Ibere, Ikwuano Local Government Area of Abia State in Nigeria was used to study the combined effect of flow rate and water salinity in fines mobilization. The experiments were conducted for flow rates of 1, 3, 5, 7, and 9ml/min and water salinity values of 0, 5, 10, 15, and 20g/l. Experimental results show that the likely critical water salinity value and flow rate that mobilizes clayey fines within the boundaries of this work are 15g/l and 7ml/min respectively. It is speculated that at various stages, one factor could dominate the flow more than the other.

Introduction

Clay minerals are hydrous aluminosilicates that are characterized by crystal sizes less than 2μm in diameter. They can also be described as phyllosilicates characterized by a sheet structure made of layers of Si-O (± Al) tetrahedra, sharing three or four oxygen atoms and alternating with layers of octahedra or some other types of polyhedra cations (such as Fe^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}). Clay minerals are classified based on the number of cations occupying the octahedral sites in the octahedral layer and can either be dioctahedral or trioctahedral, with two trivalent cations or three divalent cations in the octahedral site respectively.

Clay minerals can also be classified into several groups namely Kaolinite, Smectite, Illite, Vermiculite, and Chlorite. Out of all these groups, Kaolinite and Illite are the most common migratory clays while Smectites (Montmorillonite) are swelling clays. The compositions of migratory fines in formations are mainly tiny grains of sand and clays. The different types of clays seldom exist in isolation naturally; they often exist together but in varying percentages. Out of the major types of clay minerals that exist together, Kaolinite is known as the main migratory clay [1] in hydrocarbon formations and is often referred to as fines.

Particle detachment from the rock matrix and subsequent migration through pore spaces in hydrocarbon reservoirs constitutes a serious problem during fluid production in the petroleum industry. This is because it reduces permeability, a very important rock property for fluid flow in porous media, and this can adversely affect productivity. Permeability decline by a factor of 9 – 54 during salinity alteration from typical seawater conditions to deionized water due to kaolinite mobilization in sand packs have been reported [2]. Permeability is reduced mainly because of pore throat blockages from migratory kaolinite clay particles which have relatively larger diameters than some pore throats [3]. In another study, it was stated that Kaolinite blockage of pore spaces and throats result in permeability reduction of about 21.87 – 36.89% after water injection [4]. Such results no doubt stress the need to fully understand how factors that trigger fines migration work together in order to find a lasting solution to the problem. The pick-up, migration, deposition and clogging behavior of fine particles of kaolinite have been studied in two-dimensional micro fluidic models. Results showed that velocity vector and drag forces are responsible for deposition [5].

Mobilization of fines in hydrocarbon formations is triggered by several factors which include low water salinity, high flow rate, pressure depletion, high temperature, wettability, and type of hydrocarbon [6]. Studies have shown that even CO_2-saturated brine has the tendency to mobilize fines such as Illite and Kaolinite [7, 8]. All of these factors contribute together in mobilizing particles in formations; they do not work in isolation, but the extent to which each factor contributes to the problem needs to be studied. In previous experiments, flow rate and water salinity as factors that trigger fines migration have been studied separately, especially in the presence of aluminum oxide nanoparticles [9-13]. In fact, in a certain experimental work, fines migration with flow rate and water salinity were studied but it was done separately, not in combination [14]. But in this work, flow rate and water salinity are studied in combination in the absence of nanoparticles and crude oil. The main objective is to fundamentally investigate how a combination of these two factors mobilizes clayey fines in unconsolidated sand. The application is relevant in kaolinite mobilization in ground water movement, water injection for oil recovery, soil science and environmental fluid disposal strategies. The same study in the presence of crude oil and nanoparticles will be subjects for further research work since the presence of these materials in sands can drastically alter the results.

The effect of flow rate on mobilization of Kaolinite (obtained from The USA) in the presence of nanoparticles has been experimentally studied. Several experiments were conducted where water salinity of 5g/L was injected into the sand at varying flow rates. The reference cases in these experiments (conducted in the absence of nanoparticles) showed that the clayey fines were mobilized at flow rates of 0.2 to 0.6mL/min. It was also reported that a sudden drastic rise in flow rates agitates the sand particles, dislodging them from their initial positions. Even with the use of the best nanoparticles that can attach fines in positions to sand grains, if flow rates are not gradually increased step by step, allowing the fines and sand grains to stabilize at a slightly higher flow rate, particles will dislodge from their positions and will be put into motion. This implies that increasing fluid flow rates gradually enhances the performance of fines trapping agents in sands [9-10, 15]. Study of fines migration due to mechanical particle detachment theory with flow rate has also been conducted and modeled [16]. The effect of high flow rate and low water salinity have been discussed in several publications and methods for militating against these factors to prevent particle dislodgement have also been reported [17].

Two different flow rate experiments of particle migration using kaolinite obtained from Umulu/Ngwugwo deposit in Ibere, Ikwuano local Government Area of Abia State in Nigeria have been studied. In the first set of experiments (termed Flow Rate I), 5% total weight of the prepared sand was the clayey fines and water salinity of 5g/L was continuously injected through the sand packs at specific flow rates until fines break through occurred. In the second set of flow rate experiments (termed Flow Rate II), the clayey fines were dispersed in brine of 5g/L salinity and injected into the sand packs at specific flow rates until fines break through occurred. In both sets of experiments, the flow rates used were 1, 3, 5, 7 and 9mL/min. The reference cases which were conducted in the absence of nanoparticles and which are of interest in this work showed that the kaolinite clay was mobilized almost immediately at all the flow rates except at 1mL/min for the two sets of experiments [9, 11]. The results in both cases were similar and agreed with the fact that high flow rates mobilize fine particles in unconsolidated formations than low flow rates. But practically, there is a limit to which production flow rates can be reduced in the field because it is tied to economics. The importance of this subject has led to modeling of fines migration in porous media triggered by flow rate [18].

The effect of water salinity on mobilization of Kaolinite in the presence of nanoparticles has been experimentally studied. Kaolinite clay obtained from Umulu/Ngwugwo deposit in Ibere, Ikwuano local Government Area of Abia State in Nigeria was used for this study with aluminum oxide nanoparticles. The area of interest from this work is the reference cases where it is reported that about 5 to 20 pore volumes of clean effluent were produced before fines breakthrough occurred for water salinity range of 0 to 40g/L [11]. A study of the results shows that more pore volumes of clean effluent were produced as the water salinity increased, implying that low water salinity mobilizes fines more easily than high water salinity [12]. This finding agrees with results from other sources [19-22]. Earlier experimental studies have shown that low water salinity below its critical salt concentration results in reduction of permeability, the studies postulated that the critical salt concentration of 5000ppm to 15000ppm triggers fines migration in the sand matrix [1]. However, low water salinity has also been reported to enhance crude oil recovery better than high water salinity which might require a compromise during artificial water injection schemes. A model has been developed and used to study permeability decline caused by fines migration triggered by low saline water [23].

Material and Methods

The clayey fines used in this work is the same as the one used in investigating the effect of nanoparticles in militating against the mobilization of clayey fines in sand triggered by water salinity and flow rate [11-12]. The clay was collected from Umulu/Ngwugwo deposit in Ibere, Ikwuano local Government Area on Latitude 5°26′ and Longitude 7°35′E. The chemical and mineral compositions of the clay which have already been determined [24] are presented on Table 1. The sieved sand was mixed together with 5% of the obtained clay because the amount of clay minerals in the Niger Delta hydrocarbon formation is about 2 - 5% [25]. The main mineral composition of the clay is kaolinite which is the main migratory clay in formations. It is assumed that the effect of other clay minerals in the study is negligible since their percentage content in the sample is small.

Table 1. Chemical and Mineral Composition of Ibere Clay

Chemical Composition		Mineral Composition	
Constituent	Composition (%)	Constituent	Composition (%)
SiO_2	52.06	Kaolinite	67
Al_2O_3	27.87	Illite	4.6
Fe_2O_3	3.25	Chlorite	6.0
MgO	1.43	Montmorillonite	3.6
CaO	0.34	Total Clay Content	81.2
Na_2O	0.38	Feldspar	2.0
K_2O	2.92	Free Quartz	13.0
LOI (H_2O)	9.3	-	-
Al_2O_3/SiO_2	0.54	-	-

The materials of interest used in this work are sand, a constant flow rate displacement (Eldex Optos) pump, kaolinite clay and brine of varying salinity values. Collected sand was washed, dried and sieved to the required grain sizes of below 300microns. The clay samples were dried and grinded into powder. Sand plugs just like core plugs were prepared from sand and clay, where the clay served as fines in the plugs. 5% total weight of the prepared sand pack was the kaolinite clay which was homogenously mixed with the sand. The plugs were prepared and weighed dry (W_1), after which they were saturated in brine of 30g/l for 72hours and weighed wet (W_2). The porosity values of the sand packs were determined using Eq. 1.

$$\text{Porosity (\%)} = \frac{(W_2 - W_1)}{W_2} \times 100 \qquad \text{Eq. 1}$$

The required brine salinity was injected through each plug sample at a particular flow rate using the constant flow rate displacement pump. Each brine salinity value was continuously injected through each sand pack at a particular flow rate until fines breakthrough occurred. The experiments were conducted for flow rates of 1, 3, 5, 7 and 9mL/min. and water salinity values of 0, 5, 10, 15 and 20g/L. Each flow rate experiment at a particular water salinity value was conducted at least twice, and the pore volumes of clean effluents produced before the breakthrough of fines were plotted against the flow rates and against water salinity values.

The performance indicator at different stages of the experiments is the number of clean (fine-free) pore volume effluent produced from each sand pack before breakthrough of fines occurred. The number of clean pore volume of effluent was derived from Eq. 2.

$$N = V/P \qquad \text{Eq. 2}$$

Where

N = Number of clean pore volume of effluent produced

V = Volume of clean (fines-free) effluent produced

P = Pore volume of the sand pack

$$P = \text{Net Volume} \times \text{Porosity} \qquad \text{Eq. 3a}$$

$$\text{Net Volume} = \pi r^2 h \qquad \text{Eq.3b}$$

The net volume is the volume of a cylinder where "r" is radius and "h" is height of the cylinder. This is because the sand plugs are shaped like cylinders. Porosity is derived from Eq. 1.

A schematic of the experimental setup is presented in Figure 1. Note that these experiments were conducted in the absence of crude oil and under ambient temperature and pressure.

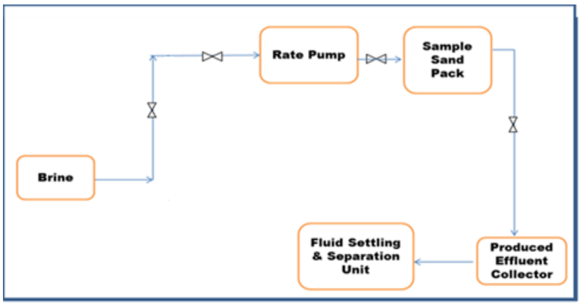

Figure 1 A Schematic of the Experimental Setup

Note that before the combined cases of water salinity and flow rate experiments were conducted, experiments to study the effect of water salinity and flow rate on kaolinite mobilization in sand were first conducted separately. The essence is to first understand and establish the graphical trend of each of the two factors. For water salinity, the concentrations considered were 0-20g/l at a constant flow rate of 3ml/min, while 1-9ml/min flow rate was experimented at a constant water salinity of 30g/l.

Results and Discussions

Figures 2 and 3 are results of water salinity and flow rate effects on kaolinite mobilization in sand respectively. Figure 2 shows that as water salinity increased the tendency for kaolinite mobilization decreased. But in Figure 3, it is clear that as flow rate increases, the tendency for kaolinite mobilization increases. Note that the trend in both graphs are opposite in direction.

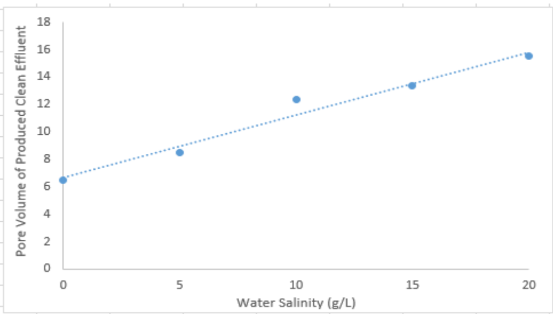

Figure 2 Effect of Water Salinity on Kaolinite Mobilization in Sand.

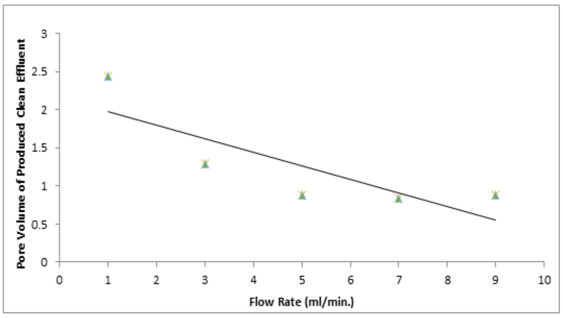

Figure 3 Effect of Flow Rate on Kaolinite Mobilization in Sand.

Results of the effects of combining flow rate and water on fines migration is presented in Figures 5 and 6. The experimental results showing the plots of the number of clean pore volume of produced effluent against water salinity are presented in Figure 5. Generally as expected, the lowest number of pore volumes of fines-free effluent produced occurred at low water salinity values for all the flow rates because low water salinity mobilizes fines.

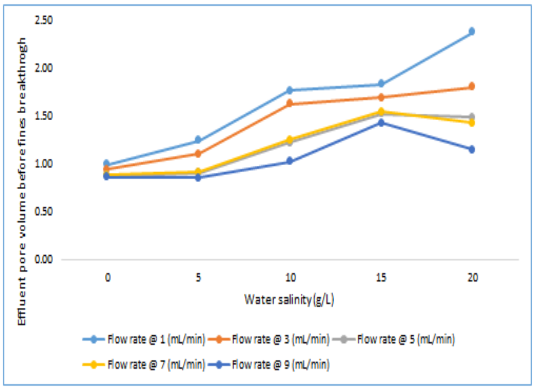

Figure 3 Experimental Results for the Five Flow Rates at Different Water Salinity Values.

There is a notable observation from Figure 3 at 15g/l water salinity. For flow rates of 5, 7 and 9ml/min, there are drops (instead of the usual increase) in the number of pore volumes of clean effluent as the water salinity increased from 15 to 20g/l. In the case of 1 and 3ml/min, there are drops at 15g/l before a slight increase for 3ml/min and a sharp increase for 1ml/min. 15g/l (15000ppm) water salinity therefore seems to be the critical water salinity value in this study. According to Gray [1], the critical salt concentration that triggers fines migration in sand matrix is postulated to be from 5000ppm to 15000ppm (5g/L to 15g/L), which agrees with the value in this study. Probably in this study, the fines are mobilizes by water salinity values of 15g/L and below while fines are not mobilized by water salinity values higher than 15g/L. It is likely then that at higher water salinity values of 15g/L and above, flow rate dominates the flow as a trigger factor to mobilize fines (not water salinity), since fines are not mobilized at high water salinity values. In any case, an area for further research is presented to investigate the trend from 15g/L water salinity to higher water salinity values of 20 – 60g/L still at 1, 3, 5, 7 and 9mL/min flow rates.

The experimental results showing the plots of the number of clean pore volume of produced effluent against flow rate are presented in Figure 6. The results show that generally as expected, the number of pore volumes of clean effluent produced decreased as flow rate increased. The highest pore volumes of fines free effluent produced are at low flow rates for all the water salinity values. However, there are deviations (a sudden increase) at the flow rate of 7ml/min for all the cases, after which the decrease continued at 9ml/min. It is therefore possible that 7ml/min might be the critical flow rate in this study that triggers fines migration in sand.

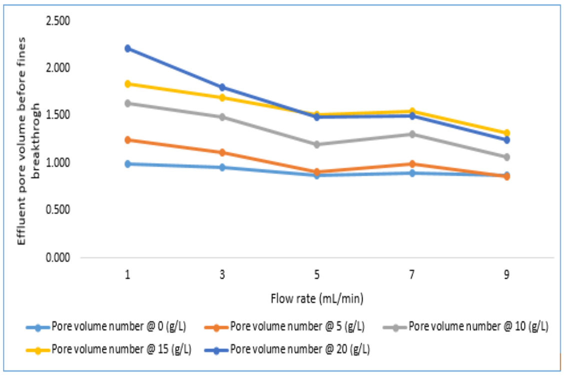

Figure 4 Experimental Results for the different Water Salinity Values at five flow Rates

The presumed critical values that tend to trigger fines migration within the boundaries of this experimental work are 15g/l for water salinity and 7ml/min for flow rate. Water salinity seems to dominate the flow from 0 - 15g/l after which flow rate becomes the dominant factor only for higher flow rates of 5 to 9mL/min. Water salinity may have been the dominant factor at low flow rates of 1 and 3ml/min. Therefore, in order not to mobilize the kaolinite fine particles used in this work, the flow rate needs to be maintained below 7ml/min while the water salinity value should not be less than 15g/l. It is speculated that probably the effect of water salinity dominates kaolinite mobilization at lower flow rates but at higher flow rates, it still dominates until after 15g/L when the effect of flow rate takes control of fines mobilization. The implication is that certain conditions might allow water salinity or flow rate to be dominant.

In actual field situations, several factors contribute together to trigger fines migration. These factors are flow rate, water salinity, temperature, pressure, wettability, type of crude, type of hydrocarbon present in the formation (oil or gas), formation weakness and fatigue. It is important to study these trigger factors separately and in combination because all these factors occur in combination, not in isolation during production from reservoirs. It is also necessary to study each of these factors separately and together so that models that can predict laboratory conditions can be built before such results can be up-scaled to field conditions. Up-scaling these values to field conditions that have the same characteristics as the ones used in laboratory studies is the practical benefit of this kind of study.

Conclusions

The conclusions drawn from this work are listed as follows:

1. Low water salinity mobilizes kaolinite clays in sands more than high water salinity.
2. High flow rates mobilize kaolinite clays more than low flow rates.
3. In this study, the critical water salinity value that mobilizes kaolinite clayey particles is 15g/l and below while the critical flow rate that mobilizes kaolinite clay is 7ml/min and above.
4. When water salinity and flow rate combine together to trigger fines migration in unconsolidated sands, it is possible that at various stages, one particular factor will dominate more than the other.

RECOMMENDATION

To prevent kaolinite particles embedded in unconsolidated sands from mobilization such as in this work, a flow rate below 7ml/min should be maintained and the water salinity should not be less than 15g/l. This is because the clayey particles contained in the sand tend to be sensitive to mobilization at a flow rate of 7ml/min and a water salinity value of 15g/l.

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Conflicts of Interest

There are no conflicts to declare.

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