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Effect of Aluminum Oxide Powder and Nanoparticles on Kaolinite Mobilization in Sand

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ABSTRACT

Al_2O_3 nanoparticles in sand can militate against mobilization of kaolinite, indicating that Al_2O_3 powder could also do same but this has not been investigated. In this work therefore, the capacity of Al_2O_3 powder to militate against clay mobilization in sand is investigated and its performance is compared with the performance of Al_2O_3 nanoparticles at different water salinity values expressed in mass fraction. Experimental results show that the presence of Al_2O_3 powder and nanoparticles in sand can militate against kaolinite migration during fluid flow, but the performance of the nanoparticles is more effective than the ordinary powder. At a mass fraction range of zero to 0.04, the volume of clean effluent produced were 5 – 20 pore volumes, 5 – 28 pore volumes and 10 – 48 pore volumes for the control case, use of Al_2O_3 powder and use of Al_2O_3 nanoparticles respectively. This indicates that significant volumes of kaolinite free effluents can be produced from sand packs containing Al_2O_3 nanoparticles than with Al_2O_3 powder and when Al_2O_3 is completely absent in sands. It is also observed that produced volumes of clean effluent increases as water salinity increases, implying that kaolinite is prone to mobilization at lower water salinity levels. Linear equations derived from the experimental results and expressed in dimensionless parameters are also presented.

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1. Introduction

Factors that trigger and promote fines migration include high flow rate, high temperature, low pressure, wettability, the presence of water and low water salinity [1,2]. 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 migration have also been reported [3–10]. The effect of salt concentrations in stabilization of clays in sands and other methods of clay stabilization in sandstone formations have been investigated [11–16]. The physics of particle mobilization, migration and straining have been studied. It is reported that mobilization of particles in porous media is instantaneous with abrupt change, and it is observed that particles migrate with velocities that are significantly lower than the carrier water velocity [17,18]. Effort has been made to develop analytical models for one-dimensional linear and radial suspension colloidal flows, accounting for detachment, mobilization, migration and straining of natural reservoir fines. It has been observed that significant decline of injection well index occurs due to particle migration during low water salinity injection [19].

Reservoir sands are intercalated with clays and two kinds of clay that cause problems in petroleum reservoirs are Smectites (especially Montmorillonite) because it swells, and Kaolinite because it migrates. One reason why kaolinite migration constitutes a serious problem during oil and gas production is because it impairs permeability by plugging and blocking pore spaces and pore throats in porous media, thereby obstructing fluid flow (as illustrated in Fig. 1) and reducing productivity [20]. Mobilization, transport and deposition of kaolinite and illite in porous media due to flow velocity and pH has been studied and modelled [21].

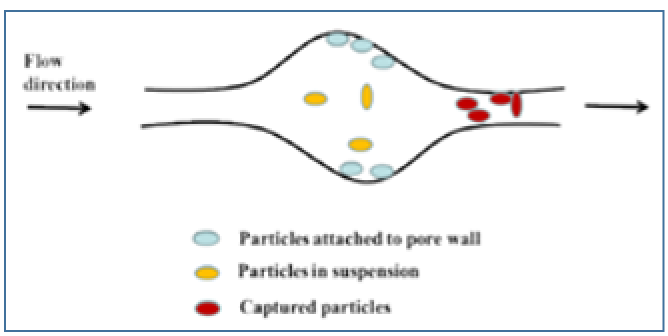

Fig. 1. Particle Migration and Deposition along Pore Spaces and Pore Throats [20].

In studying the low permeability sandstone reservoir of Daqing oilfield for formation damage after water injection, core samples obtained from the reservoir were used in conducting experiments. The formation which contained Illite, Kaolinite, Chlorite and Smectite clays was subjected to X-ray diffraction studies and results revealed that the formation pores were blocked by kaolinite clay after water injection (as presented in Fig. 2). This is because the kaolinite particle sizes are larger than some pore throats, thus plugging fluid passage ways and causing permeability impairment. Figure 3a shows the reduction percentage that occurred while Fig. 3b shows the permeability reduction in different lithology samples after water injection according to the report. It can be concluded that permeability reduced mainly because of pore throat blockages from migratory kaolinite clay particles which have relatively larger diameters than some pore throats [22].

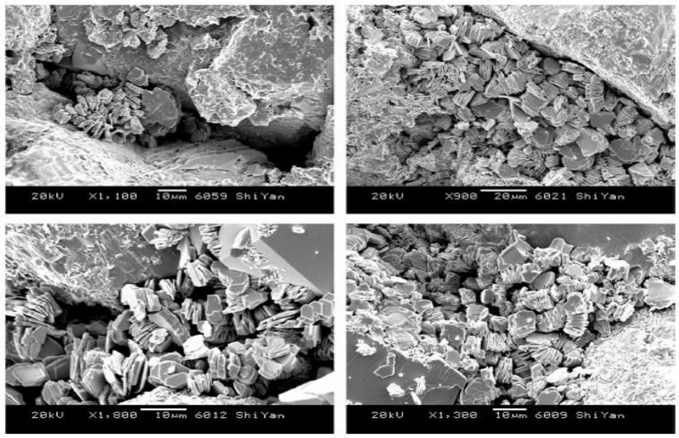

Fig. 2. X-ray Diffraction showing Kaolinite Plugging Pores Spaces after Water Injection [22].

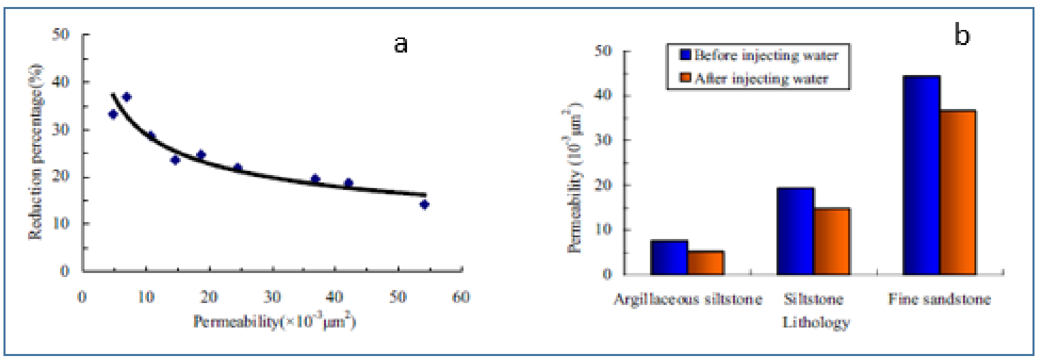

Fig. 3. (a) Permeability Reduction Percentage after Water Injection (b) Permeability Reduction in Different Lithology after Water Injection [22].

The presence of nanoparticles in the environment is gradually proliferating due to advances in nanotechnology and the various industrial uses of nanoparticles. In this work, aluminum oxide (Al_2O_3) nanoparticles is considered along with fine sand grains and kaolinite clay because Al_2O_3 nanoparticle has been recommended as an agent that can prevent the migration of clayey fines in reservoir formations, it traps and attaches migrating clays to the parent rock [23–26]. Transportation of nanoparticles in porous media and models for describing the process are poorly understood and still under investigation. There have been many studies conducted on sand and clay migration in porous media, but the study of nanoparticles migration in porous media is still emerging [27–29].

There are different projects on modeling the transportation and deposition of different nanoparticles in porous media in order to study their future environmental effects. It has been reported that different nanoparticles exhibit widely different transport behaviors [30]. Very few studies have been conducted on the transport and deposition of aluminum oxide (Al_2O_3) nanoparticles in porous media of which it was asserted that Al_2O_3 nanoparticles are mobile through saturated porous media [31]. Reported has shown that mobility of Al_2O_3 nanoparticles increases in porous media under conditions in which the nanoparticles and porous media have like charges and that the total mass retained in the system is independent of concentration. It is reported that aluminum oxide nanoparticle has high mobility and small collector contact efficiency (η_o) in sand. It is also pointed out that its rate of deposition increases with increasing ionic strength and that its breakthrough at pH 4 is higher than at pH 7 [32]. In using three different models, it was observed that the deposition rate coefficients were either under predicted or over predicted relative to experimentally determined values. It was also pointed out that the electrostatic interaction between nanoparticles and sand is negligible under strong ionic strength condition [33]. When the ionic strength is large, the electrostatic force will be small, tending towards zero.

2. Research significance

In controlling particle migration by preventing kaolinite mobilization in porous media, experiments have been conducted with different kinds of nanoparticles and it has been observed and reported that Al_2O_3 nanoparticles is more effective in comparison with some other nanoparticles [17,34]. Some researchers have recommended other types of nanoparticles such as SiO_2 and MgO nanoparticles [35–37] while others have recommended Al_2O_3 nanoparticles [38,39]. Studies have shown that Al_2O_3 powder stabilizes clay by decreasing critical coagulation concentration, clay dispersion and increasing micro aggregation [40]. This implies that Al_2O_3 powder could perform the same task as Al_2O_3 nanoparticles but this has not yet been investigated. In this work therefore, use of Al_2O_3 powder in prevention of kaolinite mobilization in sand is investigated and its performance is compared to the performance of Al_2O_3 nanoparticles in carrying out the same task. It is an experimental work that is conducted under different values of water salinity to derive basic equations that can be used to model the process.

3. Methods

This work is experimental and it involves the use of Al_2O_3 powder and Al_2O_3 nanoparticles to militate against kaolinite mobilization in sand. Sand packs were prepared like core plugs using sand from a river bank in the Niger Delta; the sand was washed, dried and sieved to grain sizes below 300microns. The Kaolinite clay used was obtained from Umulu/Ngwugwo deposit in Ibere, Ikwuano local Government Area on Latitude $5^o26^/$ and Longitude $7^o35^/$E in Umuahia, Abia State in Nigeria. The kaolinite has already been characterized [28] as presented on Table 1; it was dried and grinded into powder before use. The Niger Delta petroleum formation contains about 2 - 5% of migratory clay [29] thus, 5% of the sand used was kaolinite. The kaolinite which served as migratory fines was homogenously mixed with the sand. Al_2O_3 powder was obtained in Nigeria but the Al_2O_3 nanoparticles of 40nm in size with surface area of approximately $60m^2/g$ were purchased from Skyspring Nanomaterials, Inc., Houston, Texas, USA.

Table 1
Chemical and Mineral Composition of Ibere Clay [28].

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	-	-

Three sets of sand packs were prepared and used in this work; the first set was used for control experiments and they consisted of sand and kaolinite only. The second set contained sand, kaolinite and Al_2O_3 powder while the third set contained sand, kaolinite and Al_2O_3 nanoparticles. The quantity of Al_2O_3 powder used was 5% weight of the quantity of kaolinite in the sand, while the quantity of Al_2O_3 nanoparticles used was 0.2% weight of the quantity of kaolinite in the sand. For the second and third sets of sand packs, Al_2O_3 powder and Al_2O_3 nanoparticles were thoroughly mixed with the sand and clay respectively before compaction. The porosity values of all the sand packs were determined and the average value was about 36%. The concentrations of water salinity used were 0, 5, 10, 15 - 40g/l from rock salt mainly composed of sodium chloride. The sand packs were saturated with brine of required water salinity for at least 48hours and required crude was injected into the packs. Two kinds of crude used were light and medium crude of 31^o and 25^o API gravity respectively and 40% of the pore spaces in each sand pack were filled with crude before commencing the experiments.

Water flooding was achieved by continuous injection of required saline water at the rate of 3ml/min until breakthrough of kaolinite occurred in the produced effluents before brine injection was terminated. The pore volumes of produced clean particle free effluents were recorded and this served as the parameter to evaluate the performance of the Al_2O_3 powder and nanoparticles in militating against mobilization of kaolinite. A schematic of the experimental setup is presented in Fig. 4. All experiments were conducted at ambient temperature and pressure and each experiment was conducted at least twice.

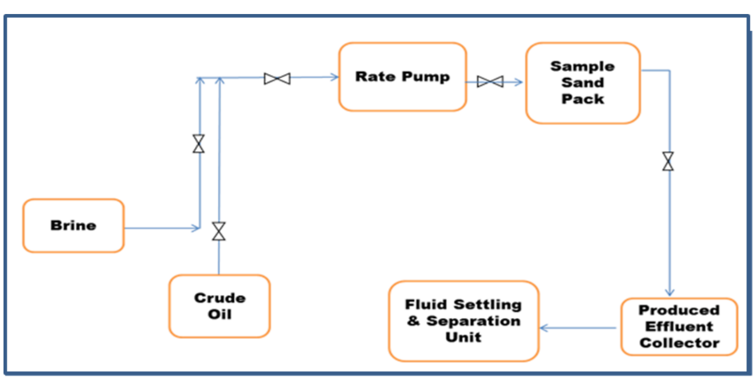

Fig. 4. Schematics of the Flooding Process.

The water salinity concentration used in this work is in grams per liter (g/l) but this unit was converted to mass fraction which is a dimensionless parameter. Mass fraction is the ratio of one substance to the total mass of the substance in a mixture or solution. It can also refer to the ratio of the mass of a solute to the total mass of the same solute in solution, which constitutes the total mass of the solute and solvent. For this work, the mass fraction is the ratio of the mass of the salt to the sum of the mass of the salt and solvent. Mass fraction can therefore be expressed as:

Mass Fraction = Mass of salt / (Mass of salt + mass of solvent)

The number of pore volume of kaolinite free effluent produced from each set of conducted experiments is plotted against mass fraction. Straight line equations that describe the results were generated using Microsoft Excel software.

4. Results

Two sets of experimental results are presented; the first one compares results from three experiments that involve the control case and use of Al_2O_3 powder and Al_2O_3 nanoparticles. The second set of experimental results only compares control cases and use of Al_2O_3 nanoparticles. Linear equations from Microsoft Excel for all conducted experiments are also presented for each set of results.

Presented in Fig. 5 are the first set of experimental results showing the performance of the control experiments, use of Al_2O_3 powder and Al_2O_3 nanoparticles to control kaolinite mobilization in the presence of light crude with an API gravity of 31^o. It can be observed from the results that at a mass fraction range of zero to 0.04, the volume of clean effluent produced are 5 – 20 pore volumes, 5 – 28 pore volumes and 10 – 48 pore volumes for the control case, use of Al_2O_3 powder, and use of Al_2O_3 nanoparticles respectively. Further experiments using Al_2O_3 powder was discontinued because the results of Al_2O_3 nanoparticles are better.

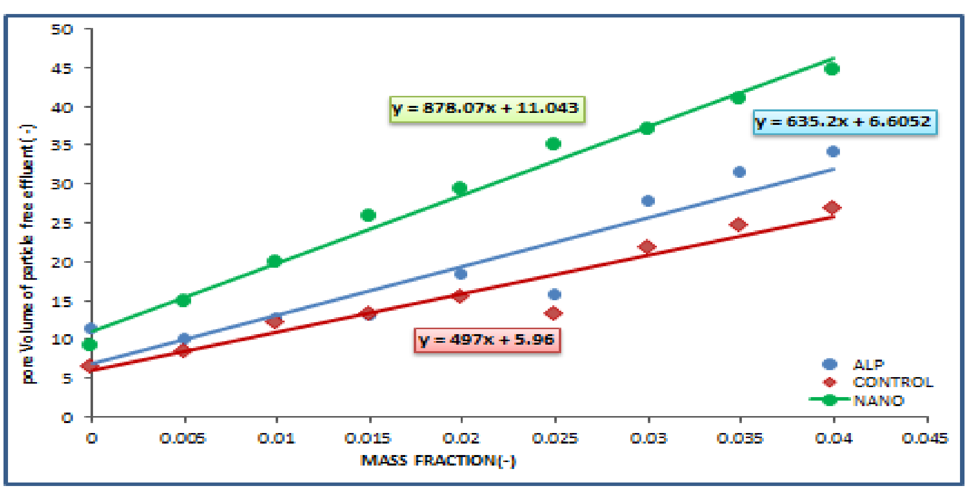

Fig. 5. Experimental Results for Control, Al_2O_3 powder and Nanoparticles Using Light Crude.

The second set of results is presented in Figs. 6 to 7 and they comprise of only the control experiments and Al_2O_3 nanoparticles results for light and medium crude. It is evident that with Al_2O_3 nanoparticles in sands, larger volumes of reservoir fluids can be produced without mobilizing kaolinite particles in the formations.

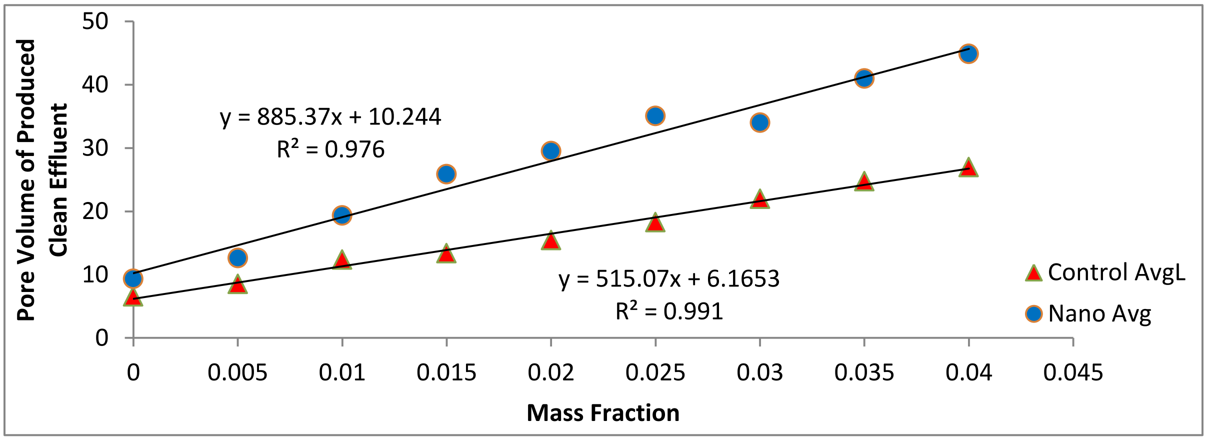

Fig. 6. Results of Control and Nano Experiments with Light Crude.

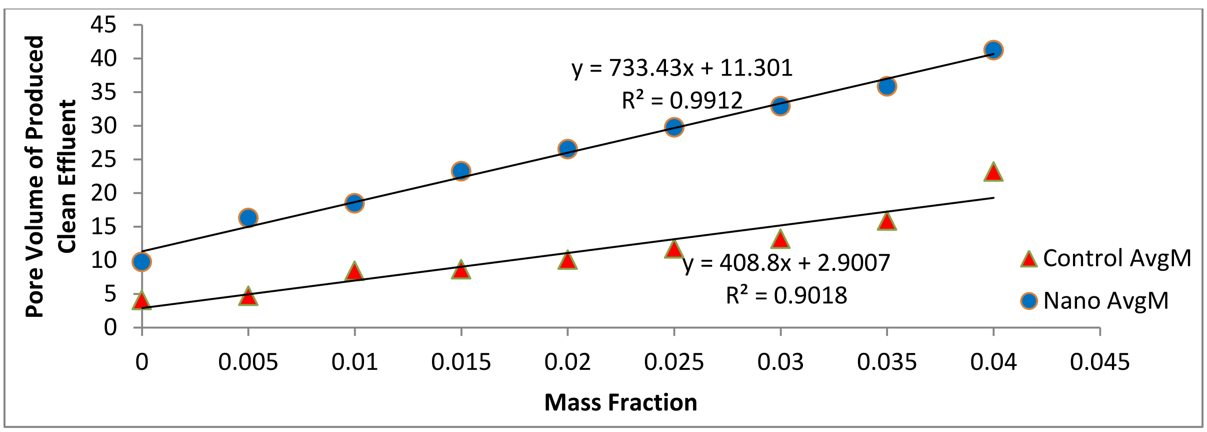

Fig. 7. Results of Control and Nano Experiments with Medium Crude.

The essence of Figs. 8 and 9 is to compare results of light and medium crude oil samples in kaolinite mobilization in sand. In Fig. 8, it can be observed that medium crude mobilizes kaolinite clay faster than light crude in the absence of Al_2O_3 nanoparticles because the volumes of clean effluent produced before the breakthrough of kaolinite particles are comparatively lower. In Fig. 9, it is observed that the effect of crude type in mobilizing kaolinite in sand is less significant in the presence of Al_2O_3 nanoparticles though the case of light crude is slightly better.

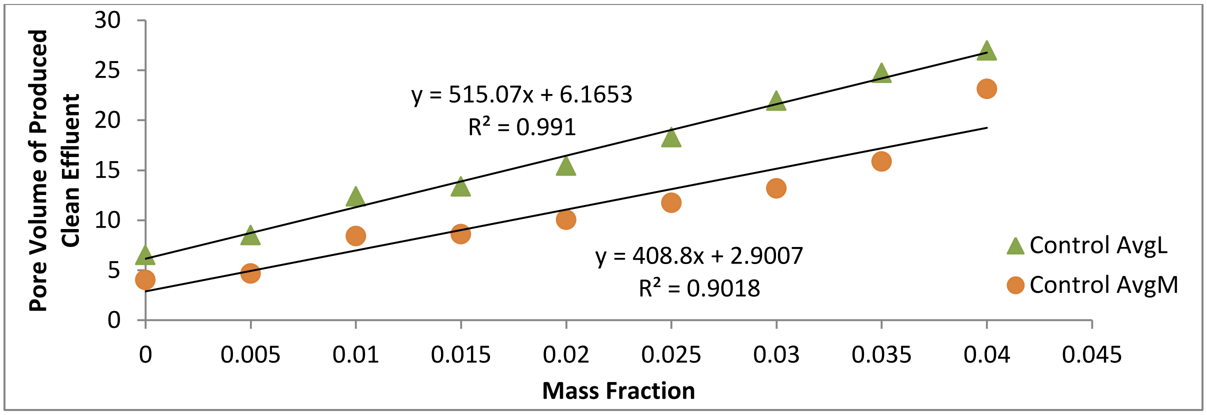

Fig. 8. Comparisons of Control Experiments with Light and Medium Crude.

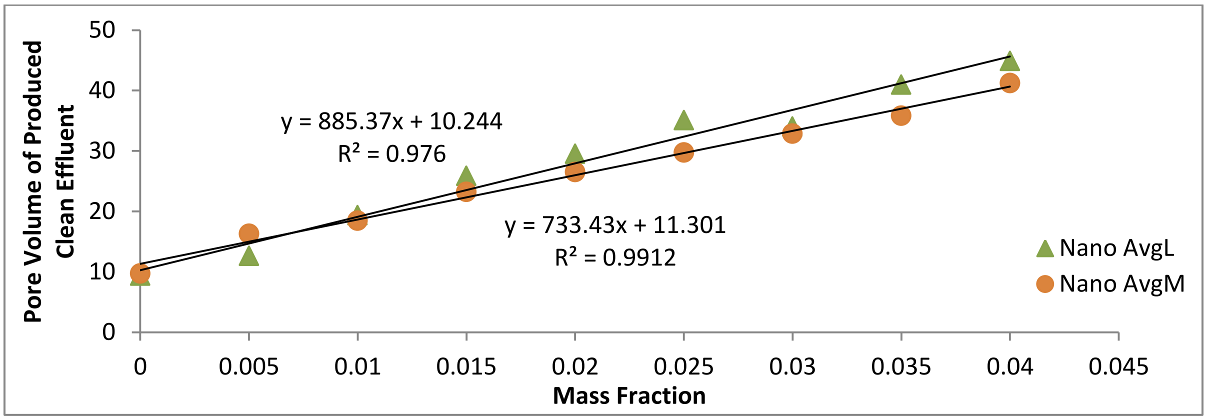

Fig. 9. Comparisons of Nano Sample Experiments with Light and Medium Crude.

Linear equations from obtained experimental results are presented in Table 2. These results can be used as fundamental equations to model the volume of clean effluents that can be produced from sands containing Al_2O_3 nanoparticles before breakthrough of the kaolinite particles occur in produced effluents. Note that the R^2 in all the cases is high, with at least a value of 0.9.

Table 2
Linear Equations of the Control and Al_2O_3 Nanoparticles Results.

	Type of Crude	Line Equations	R^2
Control Cases	Light	Y = 515.07x + 6.1653	0.99
	Medium	Y = 408.8x + 2.9004	0.9
Nano Cases	Light	Y = 885.37x + 10.244	0.98
	Medium	Y = 733.43x + 11.301	0.99

5. Discussion

Results from Fig. 5 clearly showed that the performance of Al_2O_3 nanoparticles (Nano) is better than Al_2O_3 powder (ALP) in trapping kaolinite in sand. It indicates that Al_2O_3 powder can perform the same task as Al_2O_3 nanoparticles but is not as effective as the nanoparticles. It can be deduced from Figs. 6 and 7 that the performance of Al_2O_3 nanoparticles is better as the value of mass fraction increases; generally, the tendency of kaolinite to migrate in sand increases as water salinity (or mass fraction) decreases. Results from Figs. 8 and 9 indicate that in the presence of Al_2O_3 nanoparticles the difference between the performance of light and medium crude in mobilizing kaolinite particles in porous media might be blurred.

Obtained equations from experimental results in Table 2 are straight line equations with parameters expressed in dimensionless forms. Modifying the basic equations derived from these results to capture the rock and fluid characteristics are areas for further research work. Indirectly, these equations can be modified and used to predict mobilization of kaolinite clay in sand with respect to water salinity (expressed in mass fraction) in the absence and presence of Al_2O_3 nanoparticles.

There are important factors to consider in modeling kaolinite mobilization in petroleum reservoirs in the absence and presence of Al_2O_3 nanoparticles. These factors include the percentage of kaolinite in the formation, percentage of Al_2O_3 nanoparticles present, the water salinity level, type of fluid (oil or gas) and if oil, the type of crude oil (light, medium or heavy) in the reservoir. Other key factors that have roles to play in the result output are flow rate, rock geometry, type of rock (sandstone, dolomite or carbonate), rock composition and level of rock consolidation. Developing a robust model that can effectively predict kaolinite mobilization in petroleum reservoirs, taking into cognizance all necessary factors is an interesting area for further research work.

6. Conclusions

This work compares the performance of Aluminum oxide powder and Al_2O_3 nanoparticles in trapping kaolinite clay in sands in the presence of light and heavy crude oil. The effect of water salinity expressed as mass fraction in mobilizing kaolinite in sand is studied and derived equations are presented. Experimental results show that the presence of Al_2O_3 powder and nanoparticles in sand can allow production of larger pore volumes of reservoir fluids without mobilization of kaolinite at various levels of water salinity. However, Al_2O_3 nanoparticles trap kaolinite better in sands than Al_2O_3 powder, resulting in larger volumes of clean effluents from sands containing Al_2O_3 nanoparticles than in sands containing Al_2O_3 powder. The performance of Al_2O_3 powder and nanoparticles in trapping kaolinite in sand is enhanced at higher water salinity levels; in fact low water salinity mobilizes kaolinite clay in sand than high salinity water. It was observed that medium crude oil tends to mobilize kaolinite particles in sands faster than light crude oil. Equations of the effect of water salinity (expressed in mass fraction) in mobilizing kaolinite clay in sand in the absence and presence of Al_2O_3 powder and Al_2O_3 nanoparticles have been presented.

The presence of Al_2O_3 powder and nanoparticles in sands can delay kaolinite mobilization triggered by low water salinity in the presence of light and medium crude oil. However, the performance of Al_2O_3 nanoparticles in militating against kaolinite mobilization in sand is better than the performance of Al_2O_3 powder in carrying out the same task.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

NAO: Conceptualization; TA: Data curation; NAO, TA: Formal analysis; TA: Investigation; NAO: Methodology; TA: Project administration; MOO: Resources; NAO, TA: Software; MOO: Supervision; NAO: Validation; MOO: Visualization; NAO, TA: Roles/Writing – original draft; MOO: Writing – review & editing.

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