EXPERIMENTAL STUDIES OF SAND PRODUCTION FROM UNCONSOLIDATED SANDSTONE PETROLEUM RESERVOIRS IN NIGER-DELTA

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Abstract

Production of sand during oil and gas exploration causes severe operational problem for oil and gas explorers especially companies producing from unconsolidated formations. Most reservoirs in the Niger-Delta fall in this category. Production oil and gas from such reservoirs has been limited by rate-dependent sand production and fines migration which resulted in near wellbore formation plugging. To prevent this occurrence, controlling the oil and gas flow rate will be of high importance to the oil and gas companies especially the producers operating in the Niger Delta. A physical model which has capacity for both consolidated and unconsolidated samples has been used to simulate the effect of flow rates, confining pressure, pressure drawdown and fluid viscosity on sand production in the Niger Delta. The model was also used to determine the ability of using the flow rate to control the production of sand. Sand sample from an unconsolidated reservoir in the Niger Delta was used in the model. Light and heavy crude oil with laboratory simulated brine was used as fluids as well. Results from the studies showed that the sand production increased as the following parameters; the flow rates, the confining pressure, the drawdown and the viscosity of the formation fluid are increased. The results also indicates that high sand-free flow rates can be achieved if the sand formation is mechanically confined (compacted). Further investigation revealed that sand production can be controlled by managing the flow rate alone when light oil was used while it is impossible to control sand production by managing the flow rate alone when heavy oil was used.

Keywords: sand production, unconsolidated formation, petroleum reservoir, Niger Delta

1. Introduction

Oil and gas production increases if zero sand production criteria is relaxed and sand production is allowed. The benefits of the increased production need of course not to outweigh the negative consequences of sand production such as risk of well failure, erosion of pipelines and surface facilities, sand separation and disposal. A proper assessment is thus required where the knowledge of the mass and rate of sand production is necessary. Experimental studies for volumetric sand measurement in different sandstones, model development, theoretical and numerical analysis have lead to the development of some prediction models for sand production[1].

Sand production control has become one of the most effective ways to increase well productivity. The oil and gas industry reports increases in the sand free rate up to 44% after sand production. Much attention has thus been focused on how to produce loose sand under controlled conditions[2]. Nigerias Niger Delta province has been identified as one petroleum system - the tertiary Niger-Delta (Akata-Agbada) petroleum system and almost all the petroleum resources currently are produced from the sandstone species within this Agbada formation. Turbidite sand in the upper Akata formation is a potential target in deepwater offshore and currently producing interval onshore. Currently, sand production is considered as one of the major problems in the petroleum industry in the Niger-Delta province. Every year, well cleaning and workover operations related to sand production and restricted production rates cost the industry millions of dollars. Additional expenses associated with sand production include pump maintenance, well cleaning and disposal of dirty sand. Sand production occurs when the induced in-situ stresses exceed the formation in-situ strength. Formation strength is derived mainly from the natural cementing materials that hold (adhere) grain together. According to this strength, the sandstone formations can be classified as consolidated, weak and unconsolidated[3].

2. Establishing a Criterion for the Time of Pore Collapse

A very likely compaction behavior of reservoir weak sandstone is shown in Fig. 1. This figure depicts the reduction in porosity of the sandstone as effective stresses increase[4,5]. The behavior of sandstone, like other geomaterials, is supposed to be highly dependent on the stress history. Therefore a preconsolidation stress hypothesis is also considered to be true in this case. At low stress levels, the sandstone deforms mainly elastically with moderate compaction per amount of applied stress. At higher stress levels, however, it begins to show larger compaction. This phenomenon of very high compressibility is referred to as pore collapse, and the sandstones compaction is divided into the 2 regions of elastic behavior and pore collapse[6]. Compaction in the pore collapse is not recovered when the stress is removed (Fig. 1). If the material is not cemented, it could be assumed that mean pressure at the time of pore collapse coincides with pre-consolidation pressure[7]. But it is hypothesized that material cementation can delay pore collapse to some extent to a mean pressure above the pre-consolidation pressure. Fig. 2 depicts such behavior. As shown in the figure, the material first undergoes mainly elastic behavior that extends up to the pre-consolidation point. At this point, it shows plastic behavior that brings about some small plastic deformation. A further increase in effective stresses due to reservoir depletion will lead to material pore collapse provided that the porosity of the formation is larger than the critical porosity. The difference in pre-consolidation and pore collapse pressures is assumed to depend mainly on the level of cementation of the material[6].

3. Proposed Experimental Study of Sand Production

Experimental studies play an important role in understanding the behavior of the material under different loading conditions and are necessary to determine the parameters required for sand production analyses. Currently, the Unconfined Compressive Strength (UCS) (basically, a triaxial test under zero confining stress) and thick-walled cylinder (TWC) test strength are the most popular laboratory experiments. The objective of our test program is to define the mechanical behavior of the reservoir rock under the test conditions that simulate the stress and fluid saturation that occur in the field. The tests

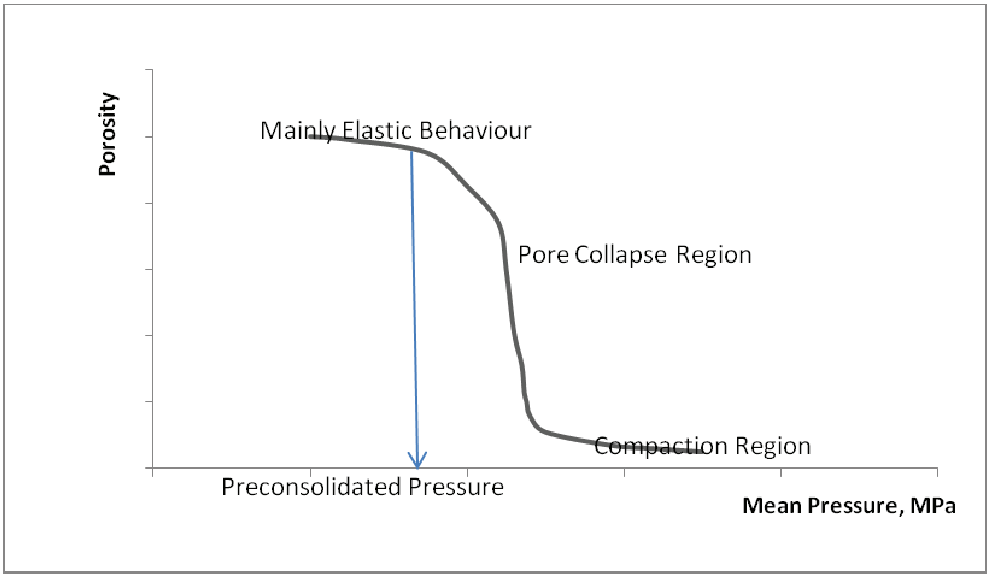

Figure 1: Porosity/stress curve showing elastic and pore-collapse regions.

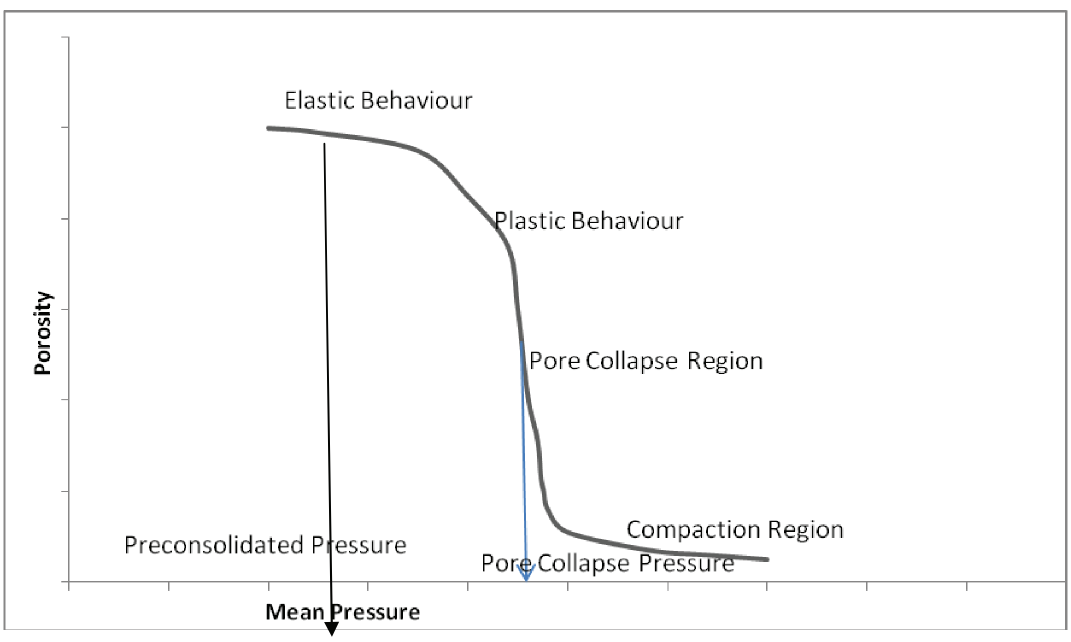

Figure 2: Porosity/stress curve showing elastic and pore-collapse regions and loading and unloading paths.

must subject the rock samples to the stress levels encountered during the producing life of the field. In addition, the manner in which the stress is applied must take into account the nature of the stress environment in the reservoir[8,9]. All rock in the reservoir is surrounded by adjacent rock. There are no free faces in the reservoir, except immediately surrounding the wellbores. So tests to simulate sandstone in the subsurface should be confined tests that prevent the rock from undergoing any lateral deformation[6].

In the test, the sample is first brought to preproduction conditions. The total axial stress is maintained at a constant. Uniaxial strain boundary conditions are established and maintained to prevent additional radial displacement. The pore pressure is reduced at a controlled rate in order to simulate the depletion process. As the pore pressure is reduced, the sample deforms laterally unless the confining pressure is adjusted (reduced). The confining pressure is adjusted through radial Linear Variable Differential Transformers (LVDTs), which constantly measure the radial deformation of the core. Signals from the LVDTs are evaluated continuously by a computer, which activates a confining pressure pump when the radial deformation of the core exceeds a narrowly defined limit[10]. Back pressure is reduced until the material fails. It is expected that at the time of pore collapse, a substantial deformation in the sample will result.

4. Experimental Procedures

In the present work, a sand sample was obtained from a Nigerian oil field (Escravos). In this field, hydrocarbons are produced from a weak and/or unconsolidated sandstone formation with some appreciable sand content. This field suffers a continuous sand production problem. Therefore, a complete research plan was proposed to choose the best sand control method to be applied to the oil field under consideration. The main objective of the plan is presented below. It consists of the following:

(a) Determining the amount of sand produced under different confining pressures and flow rates.
(b) Carrying out part (a) using different crude viscosities.
(c) Conducting sand granulometric analysis before and after each run in part (a) and (b).
(d) Classifying sand control methods according to crude oil and reservoir properties.

The experimental work includes the granulometric analysis of the sand, formulating a porous medium analogous to that of the reservoir under consideration, analyzing the fluid and experimental setting up and test procedures[11]. In order to determine the granulometric analysis of the sand sample obtained from the field, a calibrated ASTM C-136 sieves plus pan has been stacked in series. A 900g of sand sample obtained from a reservoir in Nigeria's Niger Delta was poured into the top sieve. The set of sieves was then placed in a shaker and shake for 30 minutes. After that, the sieves are unloaded and brushed thoroughly. The weight of sand retained on each sieve had been weighed and the percentage values had been calculated. Based on this analysis a mixture of sand with grain size similar to that of the reservoir is used as porous medium in this study[3].

4.1. Displacing and Displaced Fluids

Saline water and various crude oils were used in the study. The saline water was produced by dissolving 5% by weight sodium chloride (NaCl) in distilled water. The crudes were Light crude-oils (API ranges of 28° − 31°), Medium crude oils (API ranges of 22° − 28°) typically produced from Nigerias Niger-Delta fields, and a heavy crude with API of 20° from an abandoned field.

4.2. Sand Production Model Set-Up

The experimental set-up is schematically shown in Fig. 3. It consists of three main parts: Oil and Water tanks, Hoek cell and Confining pressure system[12]. The two steel tanks of oil and water have diameter of 40cm and 65cm respectively. Each tank has three connections, two inlets on the top and one outlet from the bottom. One of the two inlets is used to pressurize the fluid inside the system and the other for producing vacuum. The outlet connection is used to discharge the pressurized fluid. The Hoek cell is equipped with a sand pack, which has the inside diameter of 3.92cm and 10cm long. The sand pack can be subjected to different values of confining pressure. A hand pump is used to supply the confining pressure for the sand pack. Two pressure gauges are installed in the inlet and outlet of the Hoek cell to measure the pressure drop across the sand pack. The fluid and sand produced from the Hoek cell is controlled by a valve. The test procedure is presented in the Appendix.

5. Results and Discussions

Since the sand mixture (porous medium) used in this study had no cementing material, the only effecting parameters were the flow rate, the drawdown, the confining (compaction) pressure and the displacing and displaced fluids properties.

5.1. Effect of flow rate

Figures 4 and 5 show that the sand production from a sand pack at confining pressure of 0 Mpa using light oil, produced a decreasing amount of sand as the production rate increases until some critical production rate is exceeded. Increasing the production rate above the peak rate results in increasing the amounts of sand production as shown in the last point when flow rates was increased to 1.2cc/sec and also there was corresponding increase in percentage of sand in the produced fluid rising to 6%. It was noticed that the sand mass flow rates decreases toward a specific value below peak flow rate, this indicates that the sand production continues at a specific flow rate until a stable sand arch is formed. The arch will then stabilize and no more sand is produced if the flow rate is kept constant. If the flow rate is increased, then the sand arch will become unstable and the sand production will commence. Thus, any further increase in the flow rate will lead to another sand production cycle[13]. Figure 6 shows the corresponding cumulative sand production for the sand pack at confining pressure of 0 Mpa using light oil, the figure showed that cumulative sand production is excessive above the peak rate, thereby validating the above stated theory. Therefore, determining the critical flow rate above which sand production becomes excessive is very important. The cumulative sand production increases with increasing flow rate. Figure 7 shows the grain size distribution of the porous medium and the produced sand from the sand pack granulometric analysis, it was noticed that the produced sands contain higher percentage of smaller grain sizes compared with the porous medium sand distribution.

Figure 8 shows the sand mass flow rates at different periods of production from the sand pack with different draw-downs corresponding to fluid rate below the peak rate using light oil at a confining pressure of 2MPa, the intention was to mimic what really happens in the reservoir during the production of oil and gas from unconsolidated formation. The result confirms our earlier theory of sand arch stability during the flow of fluid through an unconsolidated formation at rates below the peak flow rates. Figure 9 shows the corresponding cumulative sand production for the sand pack at draw-downs (0.2-0.4MPa) which corresponds to fluid flow at rates below the determined peak rate. The result shows that the sand production is converging towards a fixed rate confirming the formation of stable sand arch.

Figures 10 and 11 show the mass flow rate and cumulative mass of produced sand from the sand pack at draw-downs (0.8-1.0MPa) which corresponds to fluid flow at rates above

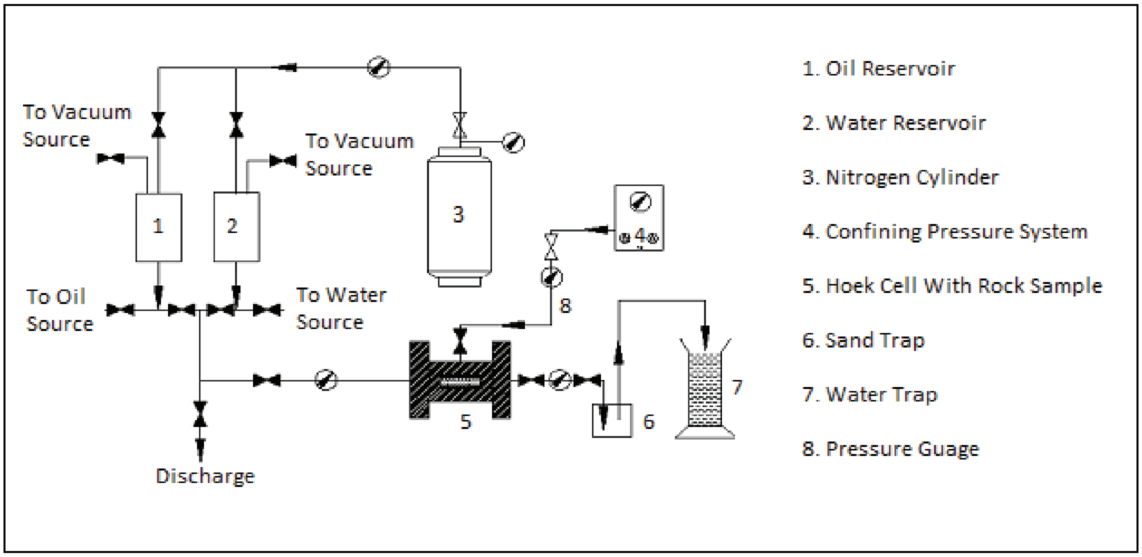

Figure 3: Experimental set-up used in sand production problem study.

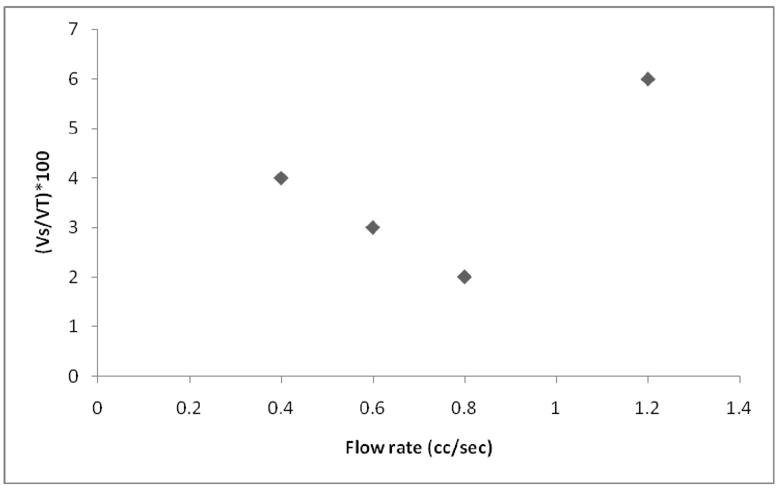

Figure 4: Percentage volume of sand in the produced fluid at different flow rate using light oil at confining pressure of 0MPa.

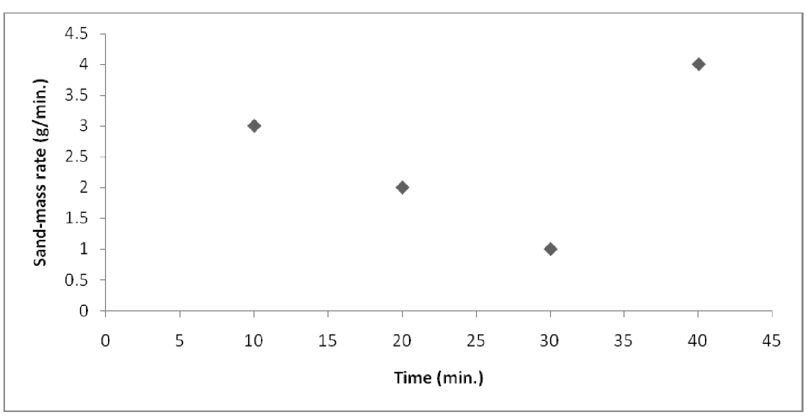

Figure 5: Mass flow rate of produced sand at different periods using light oil at confining pressure of 0 Mpa.

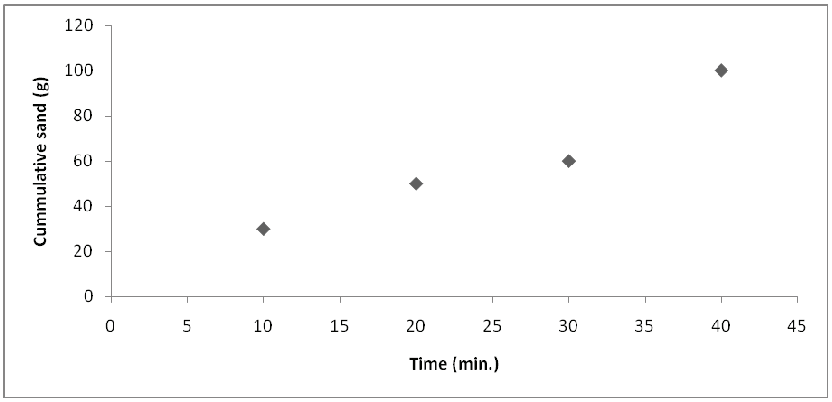

Figure 6: Cummulative sand produced at different time using light oil at confining pressure of 0 Mpa.

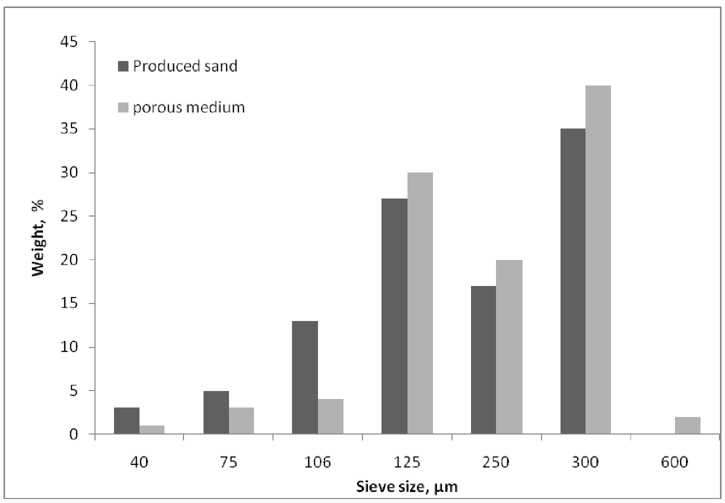

Figure 7: Grain size distribution of sand produced and porous medium at confining pressure of 0 MPa using light oil.

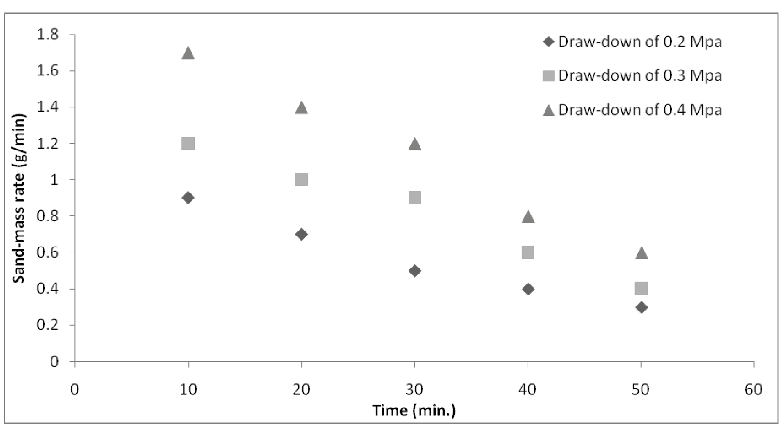

Figure 8: Mass flow rate of produced sand at different draw-downs using light oil at confining pressure of 2 Mpa.

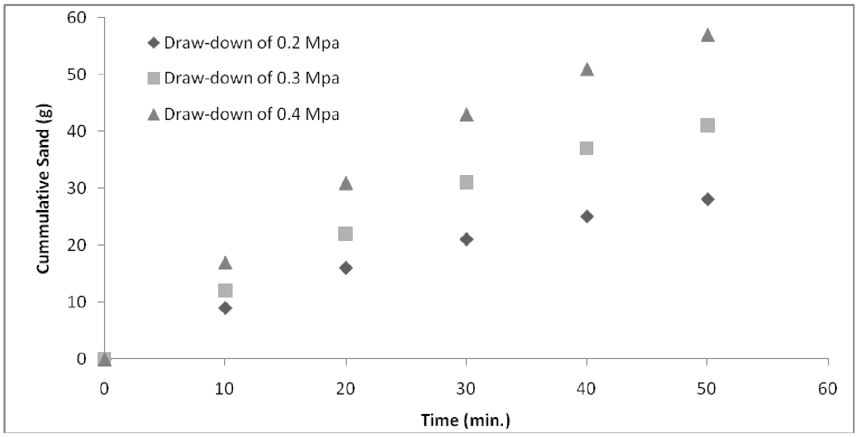

Figure 9: Cummulative sand produced at different draw-downs using light oil at confining pressure of 2 Mpa.

the determined peak rate, the results shows that new sand production cycle is responsible for the sand production at these high rates.

Fig. 12 shows the grain size distribution of sand produced at rates above the peak rate. It was observed that there was more percentage of middle grain sizes in the produced sand when compared with the produced sand grain sizes distribution produced from fluid flow below the peak rate. These confirmed the formation of new sand arch at the rates above the peak rate, which is responsible for the production of relatively bigger grain sizes. By using saline water as the displacing and displaced fluid follow the same pattern as for the light oil but with relatively lower sand production at the same draw-down under same confining pressure. Also when medium grade crudes were used as the displacing and displaced fluid follow the same pattern as for the light oil but with relatively higher sand production at the same draw-down under same confining pressure.

5.2. Effect of confining pressure

It is evident that higher sand-free production rates require higher confining pressures. Due to the absence of cementing material in the tested porous medium, the high confining pressure works as a cementing material by pressing the sand grain to each other. Upon contact, sand grain will hold each other by their apparent cohesion (friction). It is noticed that, unconsolidated formation becomes loose if there is no confining pressure and it carry high overburden loads when it is sufficiently confined. The effect of confining pressure on the critical flow rate (rate at which sand movement was first induced) and on the peak flow rate (rate at which the sand rates become excessive) for different fluid are shown in Figs. 13 and 14. Fig. 13 shows that at high confining pressure high flow rates can be achieved without sand production. It also shows that an appreciable increase in sand critical flow rate is achieved when the confining pressure is increased from 2MPa to 4MPa for the light oil. Even higher percentage increased in critical rate was achieved with water as the displaced and the displacing fluid.

5.3. Effect of pressure draw-down

As expected higher draw-down results in production of higher percentage of sand, this is due to higher drag force separating the fluidized sand from the sand mass leading to sand production. These concepts were validated in Figs. 8-11.

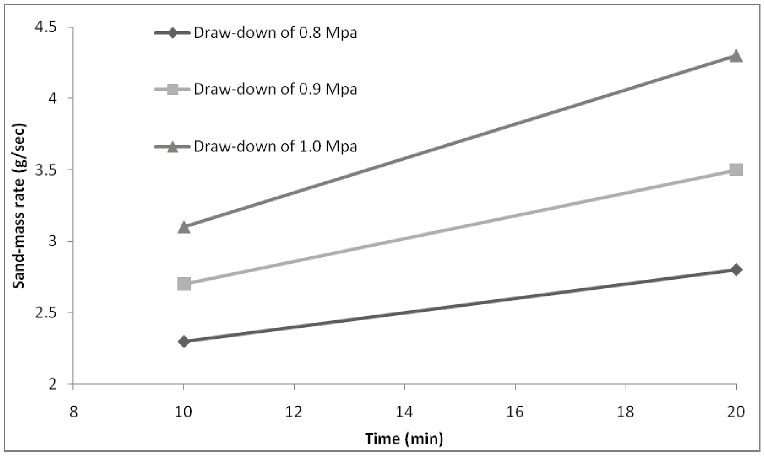

Figure 10: Mass flow rate of produced sand at different draw-downs using light oil at confining pressure of 2 Mpa.

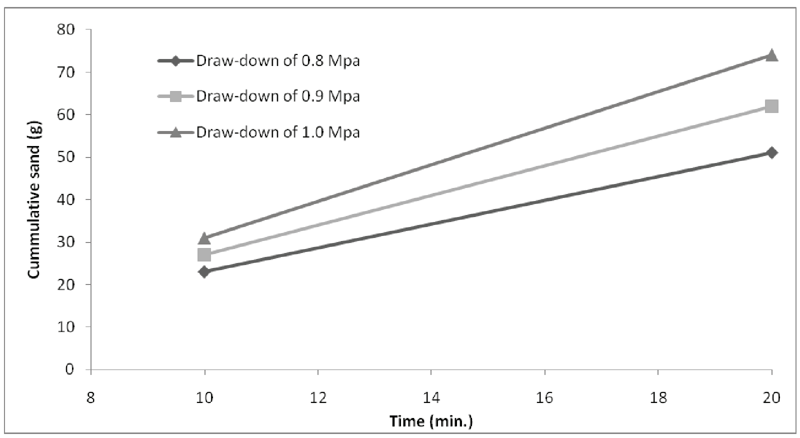

Figure 11: Cummulative sand produced at different draw-downs using light oil at confining pressure of 2 Mpa.

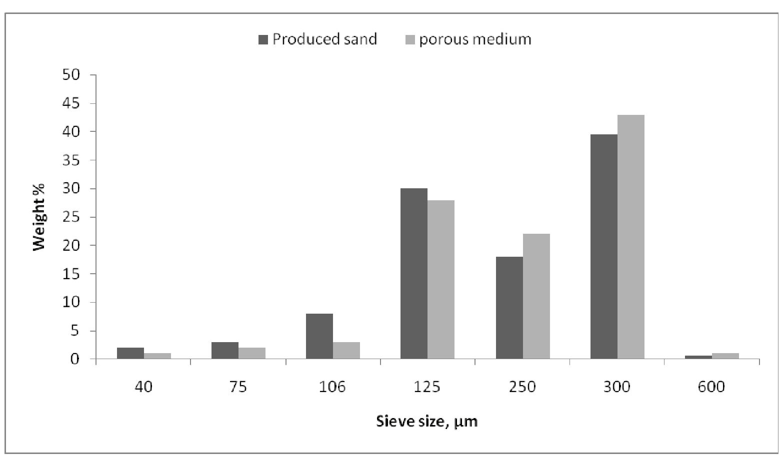

Figure 12: Grain size distribution of sand produced and porous medium at confining pressure of 2 MPa using light oil.

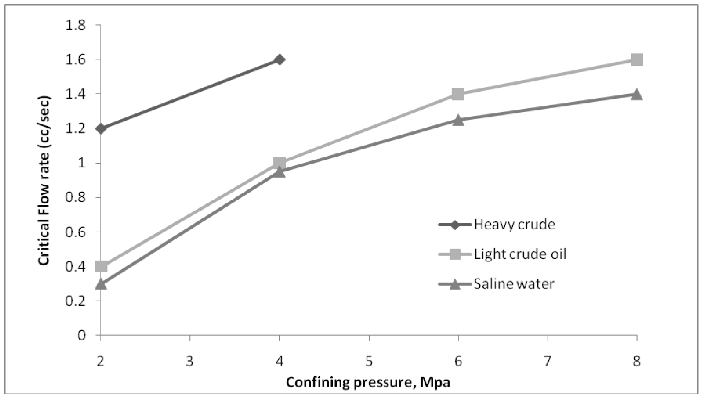

Figure 13: Relationship between critical flow rate and confining pressure.

5.4. Effect of fluid viscosity

The formation fluid type (water, light oil or heavy oil) greatly controls the sand production process. For constant flow rate and confining pressure, sand production using water as a displaced fluid is much smaller if compared to the case when heavy crude oil is used as the displaced fluid, this was confirmed in Fig. 15. The difference is attributed to the effect of higher drag forces generated by more viscous crude oil. Thus, in the case of heavy crude oil, controlling the flow rate is not effective because the arches will collapse immediately after they have been formed. Analyses of the produced sand and porous medium sand showed that the two sands have the same composition as shown in Fig. 16. Hence sand production during heavy oil flow is more of erosion production than sand particles displacement. Also higher lubricating ability of the heavy oil makes the flow of sand in heavy oil to be less dependent on the flow rates of the reservoir fluid. Therefore, the flow control method is not good enough to control sand production in heavy oil formations.

6. Conclusion

The volumetric sand production data from sand samples from Nigerias Niger Delta reservoir in a sand pack apparatus showed that the sand rates could be correlated with the applied drawdown. An increase of the drawdown results in a peak in the sand rate. The magnitude of the peak is larger for a larger drawdown increase. After the peak and under constant drawdown, the sand rate appears to approach a constant value, which depends on the magnitude of the drawdown itself and not on the increase in drawdown. Although the presented volumetric sand data pertain to a limited period of time and many other factors may influence sand production rate, the interpretation shows the influence of drawdown (i.e., the influence in the near well effective stresses and flow rates), on the sand rate. It provides also a way to interpret field sand data and to improve the understanding of sand production in the field for a more reliable sand data collection.

Based on the analysis of the experimental work conducted on sand sample from a Nigeria's Niger-Delta field it was observed that the sand production from unconsolidated sandstone formations is strongly affected by the flow rate as well as the confining pressure. High sand-free flow rates can be achieved if the sand formation is mechanically confined (compacted). The grain size distribution of the produced sand in the laboratory is identical to that of the field sample. At high confining pressure only small sand sizes are produced from the porous medium. In case of water and light crude oil sand production be controlled by managing the flow rate while it

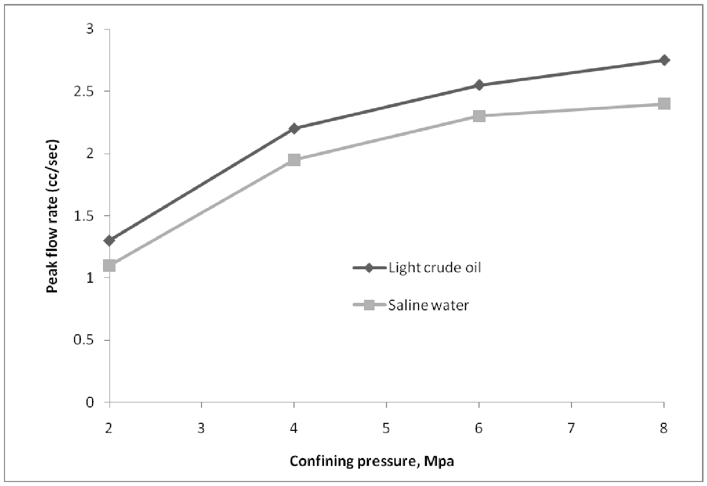

Figure 14: Relationship between peak flow rate and confining pressure.

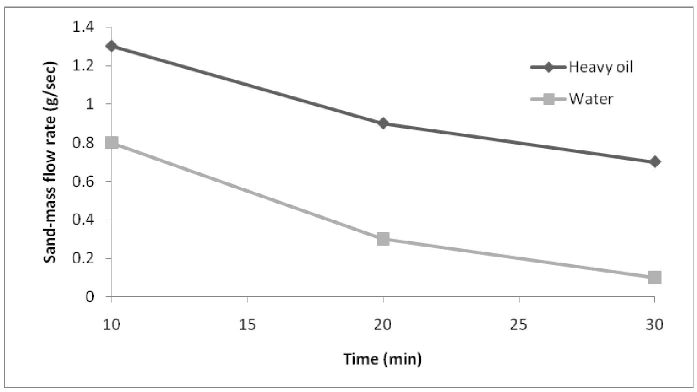

Figure 15: Mass flow rate of produced sand at different period using heavy oil at confining pressure of 2 Mpa.

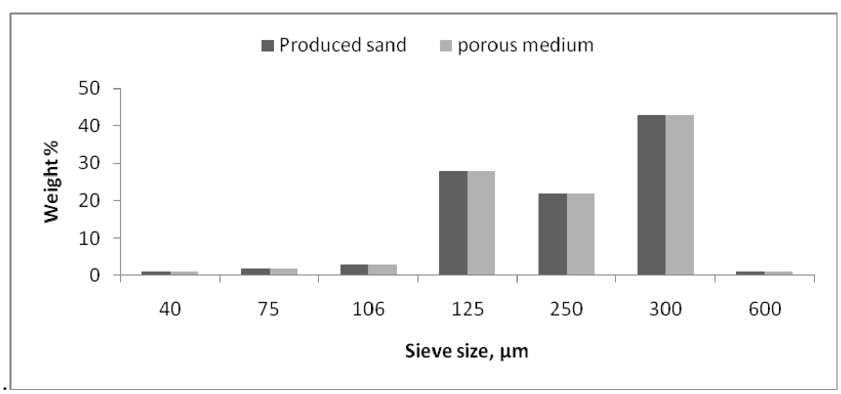

Figure 16: Grain size distribution of sand produced and porous medium at confining pressure of 2 MPa using heavy oil.

is impossible to control sand production from heavy crude oil formation by managing the flow rate alone. For unconsolidated sandstone formation containing heavy crude oil, it is necessary to apply other sand control methods such as down-hole emulsification, gravel packing, or down-hole solidification. According to the confining pressure results, shallow formation results in larger sand production than those in deeper wells.

Finally, producing a reservoir at rates between the critical rate and the peak rate resulted in sand production decreasing towards a certain constant rate. Production at rate higher than the peak rate results in excessive sand production which depends on the flow rate.

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Appendix - Testing Procedures

a. Saline water (5% NaCl by weight) was prepared using magnetic stirrer.

b. Oil and water tanks were filled with their respective fluids.

c. The Hoek cell was cleaned and dried before each experiment.

d. Sand packing began by pouring 15cm^3 of the saline water inside the holder and then adding 30g of sand mixture. A small Hammer was used to tap the surface of the holder to prevent the formation of cavities. The packing was continued carefully until the sand holder was fully packed with sand and saline water.

e. In the case of crude oils, part (d) was repeated using the crude oils in place of the saline water.

f. After fully packing the Hoek cell with the sand and fluid, the weight and volume of the remaining sand and saline water are determined.

g. The porosity of the sand pack was calculated using the following equation:

$$\text{Porosity} = \frac{\text{pore volume}}{\text{bulk volume}} 100$$

where, the pore volume is the volume of the saline used for packing and the bulk volume is the holder volume of the Hoek cell calculated using the cell dimensions.

h. The sand pack was then mounted into the Hoek cell and the Hoek cell was connected to the set-up. The confining pressure was then increased gradually to the desired value.

i. A certain pressure was applied to the displacing fluid tank and the pressure drop across the sand pack is kept constant.

j. At the end of every 10 minutes, the out let fluid was filtered and separated. The separated was then, dried in an oven at 200oC. The volume of the produced sand was then expressed as a function of the produced fluid volume. The mass of the dry sand was then determined.

k. Step (j) was repeated until sand production stops, and the grain size distribution of the cumulative produced sand was determined at the end of the run.

l. Different fluid such as light, medium and heavy crudes were used as the displacing and the displaced crude and the entire procedures repeated.