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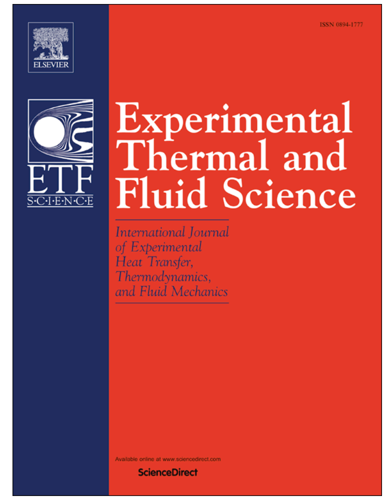

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Viscosity effects on sand flow regimes and transport velocity in horizontal pipelines

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ABSTRACT

Solids transport in multiphase systems is one of the issues under the umbrella of ‘‘flow assurance.’ But unlike issues such as waxes and hydrates, solids transport has received relatively little interest to date. The overall aim of this research was to investigate the fluid viscosity effects on sand particle transport characteristics in pipelines. Investigations were conducted using a 3-inch test facility for oil and a 4- inch flow loop for water and CMC experiments. Three oil viscosities were used including 105 cP, 200 cP and 340 cP. The sand used had a density of 2650 kg/m^3 and a median diameter of 0.2 mm. The sand loadings were 50 lb/1000 bbl and 200lb/1000bbl. Based on the King *et al* (2000) sand minimum transport condition definition, the sand transport velocity for water, CMC solutions and oil (105 cP, 200 cP and 340 cP) were determined by visual observation and camera . The observed sand/oil flow regimes were compared. For oil/sand tests, it was observed that the dominant regime when approaching the critical sand transport velocity was the sliding sand bed, sand dunes were notably absent. However, for water and 7 cP CMC solution, sand dunes and sliding sand bed regimes were observed when approaching the sand transport velocity. For 20cP CMC solution, it was observed that the sand particles in the region between the main dunes were very active compared to those within the dunes.

NOTATIONS

C_v sand volume fraction, lb/1000bbl (v/v)
D: pipe diameter, m
d_p: particle diameter, m
s: particle density/ liquid density, kg/m^3
u_t: Terminal settling velocity, m./s
V_{SL}:superficial liquid velocity m/s
μ: viscosity, cp.
ν: kinematic viscosity, m^2/s
ρ_g: gas density, kg/m^3
ρ_l: liquid density, kg/m^3
ρ_p: particle density, kg/m^3

1 INTRODUCTION

Products from oil reservoir are sometimes accompanied by small quantities of solid such as sand or fracturing materials. Solids transport in multiphase systems is one of the issues under the umbrella of flow assurance. Sand deposition in the flow lines can cause many problems such as reduced production rates, corrosion, erosion and blocking the passage of pigs. Setting up gravel packs, screens and scraping are some of the common practices to prevent sand deposition or to remove the settled sand. As these are expensive to maintain and also require lot t of design considerations, it is important to understand the behaviour of sand particles in oil flow in pipelines in order to establish the sand transportation flow regimes and the critical sand transport velocity for pipeline design.

1.1 Sand transport flow regimes

Flow regimes for solids transport can be classified according to solid/liquid and solid/liquid/gas systems. However, in this paper we are focused on solid/liquid flow regimes in the pipeline. In the literature, solid/liquid flow regimes are obtained mostly for solid/water flows with high sand concentration as found in slurry transport. There is very little reported work on low concentrations and high liquid viscosity as found in heavy oil pipelines. The flow of sand and water in pipelines can adopt a number of configurations or flow regimes as illustrated in Figure 1.

- Stationary bed: At very low liquid velocities, a stationary bed is formed with sand particles at the bottom and no grains move at all. With an increase in the velocity, a stable bed height is reached where the particles at the top are transported further downstream the upper surface of the bed is flat at very low velocity but becomes wavy as the. At higher liquid velocity the height of the stationary bed decreases. An equilibrium bed is reached when the shear at the upper surface of the bed transports sand downstream at a rate equal to the sand inflow rate.
- Moving dunes: If the liquid velocity is increased further the bed breaks up and the particles arrange themselves into moving dunes in which the grains on the upper surface of the dune roll along from back (upstream) to front (downstream). The grains then fall into the sheltered region at the front of the dune. The dune passes over these particles until they are once again on the top. The motion of the dunes is similar to sand dunes in the desert and to snow drifts. Smaller dunes move faster than larger ones and a given length of stationary deposit will break up into a number of dunes, each with a characteristic length and velocity.
- Scouring: As the velocity is increased further the grains roll along the top of the dunes with sufficient momentum that they escape from the sheltered downstream region and are swept away as individual scouring grains. Dunes can still survive in this erosion environment by replenishment from upstream particles.
- Dispersed: At high liquid velocities the dunes are dispersed. The sand particles now move in the produced fluid in an erratic pattern. However, a strong concentration gradient across the pipe is usually observed.

1.2 Review of sand/liquid transport velocity in pipeline

Hydraulic slurry transport had been experimentally investigated for many decades by many researchers, beginning with the work of Blatch (2) followed by several extensive research efforts performed by Durand and Condolios (3), Durand (4), Newitt *et al*. (5), Cairns *et al*. (6), Hughmark (7), Thomas (8, 9 and 10), Wicks (11), Babcock (12), Oroskar and Turian (13), Davies (14), Salama (15), ,Kokpinar and Gogus (16) Al-Mutahar (17),Papavinasam *et al*.(18) and Al-Lababidi *et al*. (19). Table 1 summarises the experimental variables for the slurry systems studied including solids concentration, pipe diameter, particle mean diameter, carrier liquid density and viscosity. From this table it can be concluded that the majority of the work used water as the carrier liquid. Only limited published work, Sinclair (20), Shook *et al*. (21) and Wani *et al*. (22) and Gillies *et al*. (23) used kerosene (1.2 cP), ethylene glycol (38cP) and oil 78 cP respectively other than water as the liquid carrier, Table 2.

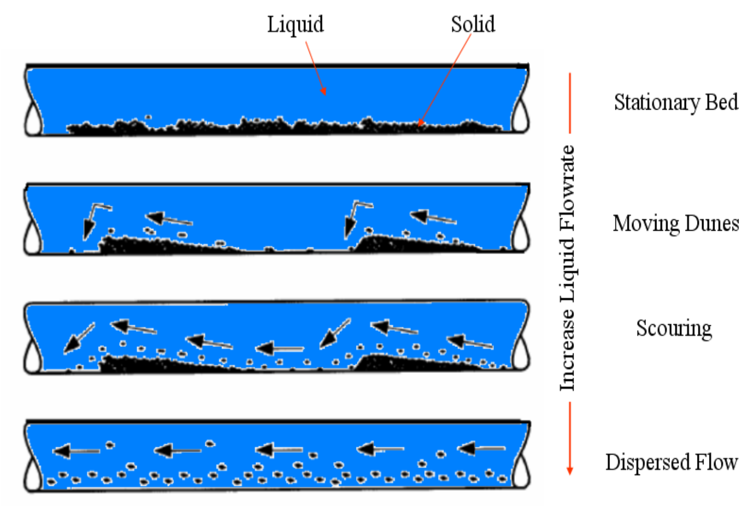


Figure 1: Liquid/sand Flow Regimes in Horizontal Pipelines (1)

1.3 Critical transport velocity models

In the early 70s, Wicks (11) developed a model for the "solids critical transport velocity". Initially, the model was developed for slurry flow and it assumes that a particle will only be transported if a sufficient force is applied to it to move it out of contact with two other particles. Based on the force balance acting on a single particle, two terms S (Wicks' dimensionless group) and Ψ (dimensionless liquid flow rate) are found in the expression containing the variables that depend on the particle Reynolds number Re_p, particle diameter d_p to pipe diameter D ratio, sand transport rate Φ , and the particle and liquid physical properties. As a result, the relationship between the two terms, $\Psi = f(s)$ was then used to predict the critical velocity for the formation of a sand bed.

$$V_C = 1.289 d_p^{0.179} D^{0.3435} \nu^{-0.015} \left(\frac{2g(\rho_p - \rho_l)}{\rho_l} \right)^{0.51} \quad (1)$$

Wasp *et al*. (30) modified Durand's (4) relation to adequately represent the effect of the sand volume concentration and the mean particle size. Wasp reploted the dimensionless coefficient F_L as a function of the sand volume concentrations using the results of different sand concentration, however the minimum sand volume concentration considered in the study was 1%. Oroskar and Turian (13) developed a correlation at which solids start to form a sliding bed. The correlation was derived based on the fluid-particle energy balance model to describe the sand critical transport condition by "remaining suspension in the turbulent core". This correlation was obtained by conducting several sand slurry experiments, thus the sand concentration term is only included.

$$\frac{V_c}{\sqrt{g d_p (s-1)}} = 1.85 C_v^{0.1536} (1-C_v)^{0.3564} \left(\frac{d_p}{D}\right)^{-0.378} \left(\frac{D \rho_l \sqrt{g d_p (s-1)}}{\mu_l}\right)^{0.09} x^{0.30} \quad (2)$$

Based on the experimental data, Oroskar and Turian (13) found x to be close to unity (> 0.95). Cairns *et al.* (6) derived a dimensionless empirical correlation which can be used to predict settling velocity (inferred as the velocity at which particles drop out from suspension).

$$\frac{V_c^2}{gD} = 9.8 C_v^{0.3} \left[\frac{D V_c \rho_l}{\mu_l}\right]^{0.3} \left[\frac{(\rho_p - \rho_l)}{\rho_l}\right]^{0.6} \quad (3)$$

Kokpinar and Gogus (16) proposed an empirical equation to predict critical velocity. They defined critical velocity as the velocity below which deposits will occur but above which no deposits in the pipeline will be encountered. Kokpinar and Gogus (16) used their data and data from other researchers including Durand (4), Wicks (11) and Sinclair (20), and came up with the relation:

$$\frac{V_c}{\sqrt{gD}} = 0.055 \left(\frac{d_p}{D}\right)^{-0.6} C_v^{0.27} (s-1)^{0.07} \left(\frac{\rho_l u_t d_p}{\mu_l}\right)^{0.30} \quad (4)$$

Al-Mutahar (17) developed a mechanistic model for critical deposition velocity, defined as the minimum flow stream velocity needed for keeping sand particles in suspension in pipe flow to prevent sand deposition, based on a force balance and turbulent theory approach used by Davies (14) and Oroskar and Turian (13). Al-Mutahar developed his model in three steps. In the first step, the required turbulent velocity fluctuation necessary to keep the particles in suspension is calculated and then the turbulent velocity fluctuation generated by the flow is evaluated. Finally, with the assumption that required and produced turbulent velocity fluctuations should be equal in order to keep the particles in suspension, he presented his final form of the critical deposition velocity, V_c,

$$V_c = 5.66 \left[f(C_V) \sqrt{d_p g (s-1)}\right]^{8/7} \left(\frac{D \rho_l}{\mu_l}\right)^{1/7} \left(\frac{1}{\Omega}\right)^{8/7} \quad (5)$$

Where $\Omega = \frac{1}{1+3.64 C_V}$, for higher concentrations (>>1%) (Proposed by Davies), and $\Omega = \frac{1}{0.5(1+3.64 C_V)}$, for concentration around 1% and lower (proposed by Al-Mutahar (7)).

Salama (15) presented several correlations for predicting sand erosion rate and "sand settling velocity". The approach taken was based on turbulence theory, considering the kinetic energy dissipated from turbulent eddies that is required to prevent the sand deposition. In his model, Salama (15) introduced the mixture velocity of two-phase air/water flow into Oroskar and Turian (13) and Davies (14) models. He considered the mixture velocity of the two-phase air/water flow is the velocity required to prevent the accumulation of the sand particles on the bottom of the pipe.

$$V_{mix} = \left[1.3\left(\frac{V_{SL}}{U_{mix}}\right)^{0.53}\right] d_p^{0.17}\left(\frac{\mu_l}{\rho_l}\right)^{-0.09}\left(\frac{\rho_p - \rho_l}{\rho_l}\right)^{0.55} D^{0.47} \quad (6)$$

Where V_{mix} is the minimum mixture velocity to avoid sand settling (m/s).
Sinclair (20) showed in his studies that the limit deposit-velocity for any systems depends on the particle-fluid system, particle diameter, pipe diameter, and the transport concentration of solids. However, in his correlation, Sinclair (20) did not include the fluid viscosity parameter in the correlation,

$$\frac{V^2{}_{max}}{g d_p (s-1)^{0.8}} = f_3\left(\frac{d_p}{D}\right) \quad , \quad f_3\left(\frac{d_p}{D}\right) \quad (7)$$

The form of the function f_3 can be explained to some degree in terms of boundary layer theory. V_{max} is the maximum value of the limit deposit velocity (ms^{-1}).
Shook *et al*. (21) developed a correlation for the critical transition velocity from stationary bed to moving bed differentiating Durand (4) pressure drop equation,

$$V_C = \frac{2.43C^{1/3}}{C_d^{1/4}}[2gD(s-1)]^{0.5} \quad (8)$$

Gillies *et al.* (23) found a three-layer model which appears to be useful to describe turbulent slurry flow in the presence of a stationary deposit. The model assumes that the velocity in the region above the deposit scales as the square root of the hydraulic equivalent diameter of the region above the deposit. The experimental data showed that the Meyer-Peter *et al*. (31) equation is useful for the prediction of the sand critical velocity for particles of diameter greater than 100 micron; however, for a very fine particle the equation was inappropriate. Danielson (32) carried out experiments to study the critical condition of sand flow under different fluid conditions using a 3-inch (ID=0.07 m) inner pipe diameter flow-loop with 215 m length. Sand was injected into the flow loop as a slurry of sand in liquid (approximately 30% by volume) using a peristaltic pump. Two-phase gas\liquid with sand experiments were performed, water and oil (Exxsol D80) were used for the liquid phase and air was used as the gas phase. The sand used in the experiments had a median diameter of 280 and 550 microns.

$$V_C = 0.23\nu^{-1/9} d_p^{1/9} [2gD(s-1)]^{5/9} \quad (9)$$

1.4Research objectives

Unlike issues such as waxes and hydrates, Solids problems have received relatively little interest to date; this is especially true for solids transport in high-viscosity oils. Understanding the behaviour of Oil and Sand mixture (slurry) is important to develop the slurry treating processes.
The work reviewed above are for particle concentrations a lot higher and the carrier liquid viscosities used are much lower than commonly found in oil

pipelines. Thus, the effects of viscosity on the low concentration sand transport warrants further investigation. The focus of this research was to investigate the viscosity effects on sand transport conditions and sand flow regime for different fluid viscosities that ranged from 1cP (0.001 kg/m.s) up to 340 cP (0.340 kg/m.s). The sand transport velocity is based on the definition proposed by King at al. (24) as the mean stream velocity required to prevent the accumulation of a layer of sliding particles on the bottom of a horizontal pipe. The obtained sand transport velocity for different fluid viscosities will be compared with selected correlations from the review presented above.

2 EXPERIMENTAL SETUP

Investigations were conducted using the 3-inch and 4-inch test facilities in the laboratory of the Department of Process and Systems Engineering, Cranfield University. Flow regimes for solids transport detected by

- Visual observation.
- Videos captured using HD camcorders (SONY HANDYCAM HDR-CX550VE, 12.0 megapixels).

2.1 4-inch Test Facility

The 4-inch sand transportation test facility was designed to operate under different multiphase flows including two-phase air/water, two-phase air/oil and three-phase air/water/oil with and without sand. For the experimental investigations conducted, water and carboxy methyl cellulose (CMC) were used as the test fluid with sand, see Figure 2. The test section is made of 4-inch (ID = 0. 1m) steel pipe (316 L) and is 40 m in length. The 40 m length is divided into 20 m outward flow pipeline, U shaped bend, and a 20 m return flow pipeline. The test section pipeline is supported on a steel structure and different inclinations can be achieved using an A-frame and lifting chain blocks. Both the beginning and the end of the test section pipeline are fixed using a pivot to allow the pipeline to be tilted at different angles including 5, 10 and 20 degrees, as illustrated in Figure 3. Two 1.2 m long Perspex windows (viewing sections) are installed in the outward and return legs to facilitate visual observations of the sand particles in the flow. Water is stored in a tank of 4.4 m^3 capacity. The water is pumped by a variable speed progressive cavity pump (PCP) to the test section through an approximately 8 m long 3-inch (ID = 0.075 m) line. The water pump has a maximum capacity of 0.025 m^3/s and a maximum discharge pressure of 5 barg. The water flow from the pump is also controlled by means of a by-pass line with the fluid from the pump outlet being recycled back to the water tank via a valve. The water flow to the test pipeline is metered using an electromagnetic meter, Endress+Hauser PROMAG 50W DN 80, with range of 0 m^3/s to 0.05 m^3/s. The electromagnetic flow meter has a 4-20 mA HART output that can be connected to the data acquisition system. A sand injection point is installed after the mixing point of water and air. The sand feeder unit consists of a cylindrical stirred vessel (0.8 m diameter by 0.5 m high), with a 0.365 m diameter axial flow impeller, and a variable speed progressive cavity pump (PCP) with a capacity of $8.33*10^{-05}$ m3/s and 5 barg maximum discharge pressure.

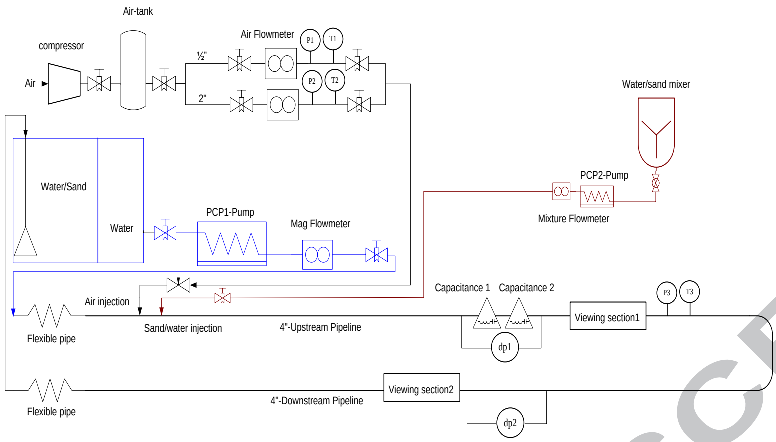


Figure 2: 4-inch test facility

Figure 3:4-inch test facility tilted at 5, 10 and 20 degrees

2.2 3-inch test facility

Figure 4 shows the 3-inch (ID = 0.075 m) test facility. Oil was stored in a tank of 15.3 m^3 capacity at the ground floor level. The oil was pumped by a progressive cavity pump (PCP) through a 3-inch pipe. The oil progressive cavity pump has a maximum capacity of 0.025 m^3/s and a maximum discharge pressure of 5 barg. Azolla 100 oil (hydraulic type oil) was used for the test programme. The inlet oil flow was metered by a Coriolis mass flow meter, Endress+Hauser Promass 83I DN 80. The Coriolis flow meter has three outputs i.e. mass flow rate, density and viscosity. To investigate the oil viscosity effects on sand transport behaviour and mechanism, Azolla 100 oil was heated in the main oil tank to obtain the desired dynamic viscosities at which tests were performed. These viscosities are:

A. Viscosity=340 cP (0.340 kg/m.s) at 16^{o}C and density = 884 kg/m^3.
B. Viscosity = 200 cP (0.200 kg/m.s) at 25oCand density = 880 kg/m^3.
C. Viscosity = 105 cP (0.105 kg/m.s) at 35^{o}C and density = 875 kg/m^3.

A sand/oil injection point was installed in the 7 m Perspex flow line. The sand feeder unit consists of a stirred vessel with an axial flow impeller and a 2.50*10-4 m3/s slurry pump. A known amount of sand is mixed with the oil in the stirred vessel and injected at the appropriate rate to give the correct sand concentration in the 3-inch line. The average sand diameter is approximately 200 micron with a density of 2650 kg/m^3: The sand settling tests carried out were with sand loadings of 50lb/1000bbl (5.38E-03 vol. %) and 200lb/1000bbl (2.15E-02 vol. %).

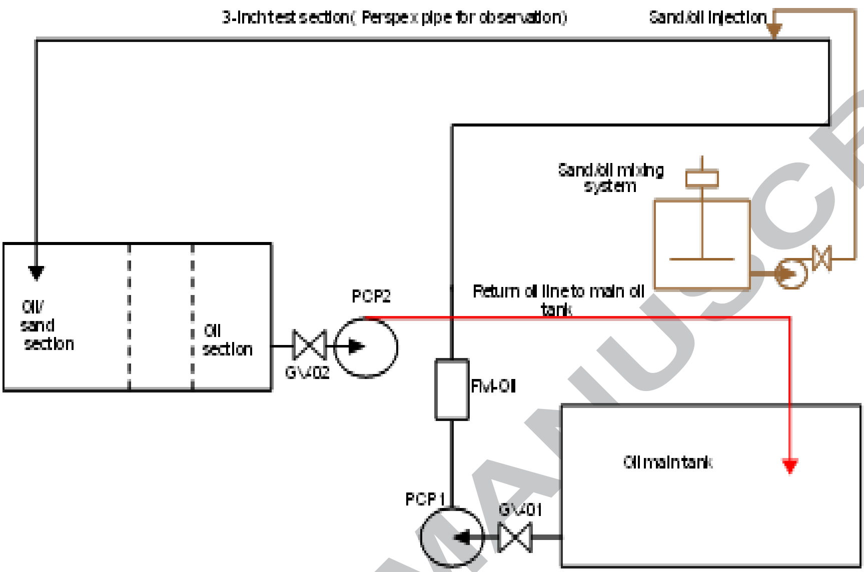
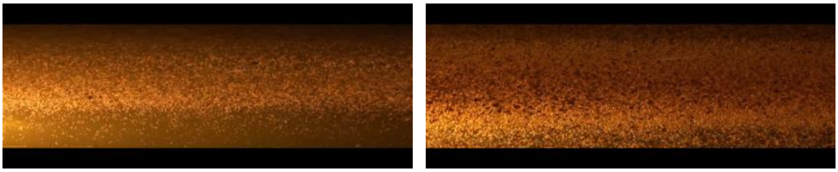


Figure 4: 3-inch test facility

3 RESULTS AND DISCUSSION

3.1 Sand/oil flow regimes in 3-inch pipeline

Sand particles movement and behaviours were observed for oil with 340 cP at 16^{O}C, 200 cP at 25^{O}C and 105cP at 35 ^{O}C. The oil viscosity, density and mass flow rate were measured using Coriolis flow meter. From the visual observations of the sand particles in the 3-inch pipe, the oil/sand flow regimes were obtained when approaching the sand transport velocity for 50 lb/1000 bbl and 200 lb/1000bbl as illustrated in Figures 5 and 6 for 340 cP. Using the definition by King *et al*. (24), the sand transport velocities were observed to be between 0.07 m/s and 0.15m/s for 50 lb/1000 bbl and between 0.2 m/s and 0.25 m/s for 200 lb/1000 bbl. The dominant oil-sand regime, when approaching sand transport velocity, was sliding sand bed. Moreover, the sand bed appeared to get more compact at oil velocities lower than the velocity at sand transport conditions. No sand dunes were observed. At an oil viscosity of 340 cP, the bulk flow at sand minimum transport condition was laminar.

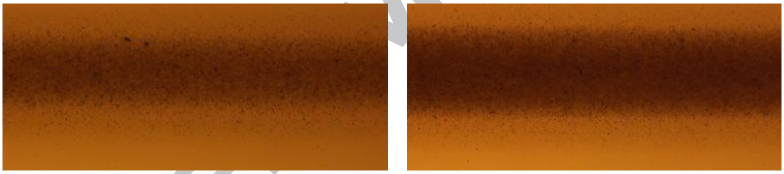


V_{Oil}=0.35m/s for 50 lb/1000 bbl V_{Oil}=0.07 m/s for 50 lb/1000 bbl

Figure 5: Sand transport condition for oil (340 cP at 16 ^{O}C) and for 50 lb/1000 bbl (Bottom view)

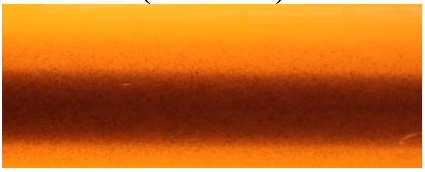
Figure 6: Sand transport condition for oil (340 cP at 16 ^{O}C) and for 200 lb/1000 bbl, V_{Oil}=0.25 m/s (Bottom view)

To obtain a viscosity of 200 cP, the Azolla 100 was heated to approximately 25 ^{O}C in the oil tank. From the visual observation of the sand particles in 200 cP oil (density =880 kg/m^3), it was concluded that the sand transport velocities for 50lb/1000bbl was between 0.25 m/s and 0.3 m/s (Figure 7), and at these velocities the bulk flow was laminar. For 200 lb/1000 bbl, (Figure 8), it was found the sand transport velocity was between 0.3 m/s and 0.35 m/s. Again no sand dunes were observed at 200 cP. A sand bed was observed at sand transport velocity, this bed was enlarged at oil velocities lower than the transport velocity. The flow at sand transport condition was laminar and the Reynolds number was between 102 and 120.



V_{Oil}=0.30 m/s V_{Oil}=0.25 m/s

Figure 7: Sand transport behaviour in 200 cP oil at 25 ^{O}C for 50 lb/1000 bbl (Bottom view)



V_{Oil}=0.35 m/s

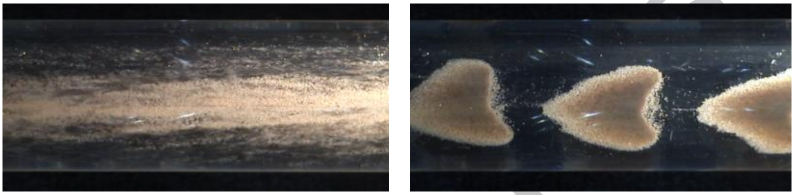
Figure 8: Sand transport behaviour in 200 cP at 25 ^{O}C for 200 lb/1000 bbl (Bottom view)

The Azola oil was heated to approximately 35 ^{O}C to obtain 105 cP oil viscosity. The same sand settling procedures were repeated and the sand/oil flow regimes when approaching the sand transport velocity were noted for 50 lb/1000 bbl and 200 lb/1000 bbl. For 50 lb/1000 bbl and 200 lb/1000 bbl, it was found that by decreasing the oil viscosity from 200 cP to 105 cP, the required velocity to approach the sand transport condition was increased and with the absence of sand dunes formation. The sand transport velocities for 50 lb/1000 bbl and 200lb/1000bbl were approximately 0.35 m/s and 0.45m/s respectively and the bulk flow type was laminar flow.

3.2 Sand/water flow regimes in 4-inch pipe

Based on the experimental observations of the sand behaviours in water experiments with sand, it was found that reducing the water flow rate from the sand transport conditions, V_{Water} = 0.5 m/s, the sand transport regimes changed eventually to sand dunes on the bottom of the pipe when the liquid velocity was reduced to V_{Water}= 0.3 m/s as shown in Figure 9.

It was observed that the sand patterns in water flow changed with sand concentrations. When the sand concentration was 200 lb/1000 bbl, sand particles were transported in the form of a sliding bed while the particles were moving in streaks when the sand concentration was equal to 50 lb/1000 bbl.



a) Water velocity at V_{Water}= 0.5 m/s b) Water velocity at V_{Water}= 0.3 m/s

Figure 9: Sand flow pattern in water flow with sand (Top view)

3.3 Sand/CMC solution flow regimes in 4-inch pipe

For 50 and 200 lb/1000 bbl sand concentration in a CMC solution of 7 cP, the sand transport velocity was observed to be 0.7 m/s and 0.75 m/s respectively. The bulk flow condition was turbulent and the Reynolds number was approximately 10000. When approaching the sand transport velocity at 0.65m/s and Re= 9350 dunes were formed as shown in Figure 10.

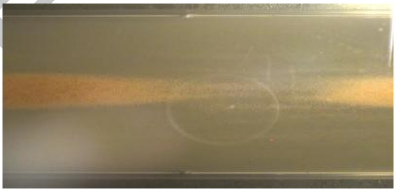


Figure 10: Sand dune at CMC solution of 7cP, V_L= 0.65 m/s, Re= 9350 (Bottom view)

For 50 and 200 lb/1000 bbl sand concentration in a CMC solution of 20 cP, the sand transport velocity was observed to be 0.75 m/s and 0.8 m/s respectively. The Reynolds number was 3750 and the bulk flow was in the transition region. When approaching the sand transport velocity at 0.7 ms^{-1}, the sand dunes were observed to be very concentrated and connected with each other and the Reynolds number was equal to 3524, see Figure 11. Also, it was observed that the sand particles in the region which connected the main dunes were active compared to those within the dune body.

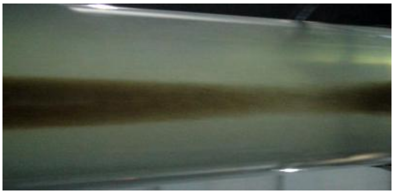


Figure 11: Sand dune at CMC solution of 20cP, V_L= 0.7m/s, Re=3524 (Bottom view)

3.4 Viscosity effects on sand transport velocity in pipe

Table 3 and Table 4 listed the comparisons between sand transport velocity flow regimes for sand concentrations of 50 and 200 lb/1000 bbl.

Table 5 compares the sand minimum transport velocities from this study with a number of selected correlations of previous studies. It was found that the majority of correlations failed to predict the sand concentration effects on the transport velocities. Salama (15), Danielson (32) and Wicks (11) correlations do not account for the sand concentration factor, whereas the other correlations including the sand concentration effect did not predict well for both sand concentration. For viscosity effects, it can be concluded form Table 5 that:

- Salama (15), Kokpinar and Gogus (16) correlations grossly under- predicted the sand transport velocities.
- Wicks(11) correlation over-predicted the sand transport velocities,
- The majority of the selected correlations under-predicted the sand transport velocity when fluid viscosities were at 7 cP and 20 cP. But Wicks [11] correlation slightly over predicted the sand transport velocity.
- For 200 cP, Oroskar and Turian (13), Al-Mutahar (17) and Danielson (32) correlations predict well the sand transport velocity. However, these correlations then over predicted the transport velocity when the fluid viscosity was 340cP.

4 CONCLUSIONS

Experimental investigations were conducted on sand particle behavior and sand transport velocity for different fluid viscosities in 3-inch and 4-inch test facilities. Water and CMC solutions were used as carrying fluids in the 4-inch facility, while Azolla 100 oil(340 cP at 16 ^{O}C) was used in the 3-inch the tests. To study the viscosity effect CMC solutions (of 7cP and20 cP) and the Azolla 100 was heated to obtain 200 cP and 105 cP. The sand particles used had a 0.2mm median diameter and sand concentration of 50 lb/1000 bbl and 200 lb/1000 bbl were used. It was found that the sand minimum transport condition was influenced by fluid viscosity and the sand/liquid flow regimes at transport conditions were different. With high viscosity, because of the lack of turbulence energy, the sand movement is mainly via shear force and no sand dunes were observed. In addition there no observed change on the sand flow regime as sand concentration increased from 50 to 200 lb/1000 bbl.

The CMC solution (7 cP and 20 cP) and Azolla oil (340 cP at 16 ^{O}C, 200 cP at 24.7 ^{O}C and 105 cP at 34.7 ^{O}C) were used instead of water in 4 inch pipeline and 3 inch pipeline, respectively. It was found that the sand MTC increased slightly as the fluid viscosity increased (from 1 to 20 cP). However, when the flow become laminar (viscosity higher than 105 cP), the MTC decreased as the fluid viscosity increased.

The transport velocity seemed to decrease at high fluid viscosity. Obviously further analysis and more detailed experiments would be required to give more definitive explanation and prediction. In general, correlations from previous studies failed to predict the observed sand transport velocities. Therefore, new correlation would be also required to better account for fluid viscosity.

5 ACKNOWLEDGEMENT

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Table 1: Review of range of experimental variables for sand/water in pipes

Researcher	Solids Conc. (vol. %)	Pipe Diameter (m)	Particle mean diameter x10-3 (m)	liquid density (kg/m3)	Liquid viscosity x10-3 (kg/ms)
Blatch (1906)	5.35	0.025	0.190 and 0.580	1000	1
Durand (1953)	2 to 30	0.038 and 0.686	0.200 and 2.470	1000	1
Howard (1939)	10 to 40	0.102	0.382	1000	1
Spells (1955)	2 to 33	0.076 and 0.300	0.080 and 0.820	997.7	1
Thomas (1962)	1 to 15	0.013 and 0.813	0.190 and 3.800	999.7	1
Sinclair (1962)	5 to 20	0.025	0.495	997	1
Weisman (1963)	0.2 to 33	0.013 and 0.610	0.013 and 2.000	998	1
Zandi and Govators (1967)	5.25 to 33	0.025 and 0.610	0.100 and 1.270	1000	1
Smith (1973)	12.29	0.154	3.785	1000	1
Smith (1973)	8.3	0.269	0.029	1000	1
Shook et al (1973)	5.36	0.052	0.2105	993.6	1
Kokpinar and Gogus (2001)	1 to 30	0.025 and 0.076	0.230 and 5.340	1000	1
Al-lababidi et al (2007)	0.05	0.052	0.2	1000	1

Table 2: Review of range of experimental variables for viscous fluids as a liquid carrier

Researcher	Solid/Liquid	Solids Conc. (vol. %)	Pipe Diameter (m)	Particle mean diameter x10-3 (m)	liquid density (kg/m3)	Liquid viscosity x10-3 (kg/ms)
Shook et al (1973)	sand/ethylene glycol	5.42	0.052	0.2105	1096	5.79
Shook et al (1973)	sand/ethylene glycol	5.3	0.052	0.2105	1116.8	14
Shook et al (1973)	sand/ethylene glycol	5.3	0.052	0.2105	1116.8	14
Shook et al (1973)	sand/ethylene glycol	5.24	0.052	0.2105	1132.6	38.1
Shook et al (1973)	sand/ethylene glycol	5.18	0.052	0.718	1121	21.4
Shook et al (1973)	sand/CaCl2 brine	5.42	0.052	0.2105	1150	1.8
Shook et al (1973)	sand/CaCl2 brine	5.42	0.052	0.2105	1250	2.91
Shook et al (1973)	sand/CaCl2 brine	5.42	0.052	0.2105	1350	5.6
Shook et al (1973)	iron/kerosense	5 to 20	0.025	0.495	779	1.238
Sinclair (1962)	sand/kerosene	20	0.025	0.833, 0.208	779	1.238
Smith (1973)	potash/brine	30-50	0.052	0.3 to 0.4	1140 to 1200	1.14 to 1.2
Wasp et al (1970)	iron/kerosense	1 to 18	0.0254	0.138	900	1.9 to 2.0
Gillies *et al (1997)*	sand/oil	41-55	0.052	o.2, 0.1, 0.01	872	78

Table-3: Sand transport velocity and flow regimes for 50 lb/1000 bbl

Fluids	Liquid Viscosity(kg/m.s)	Transport velocity (m/s)	Pipe Diameter (m)	Re	Sand/oil flow regimes
Water	0.001	0.5	0.1	50000.0	sand dunes
CMC solution (7cP)	0.007	0.7	0.1	10000.0	sand dunes
CMC solution (20cP)	0.02	0.75	0.1	3750.0	connected-sand dunes
Oil 105cP	0.105	0.35	0.0776	226.33	sliding sand bed
Oil 200cP	0.200	0.25	0.0776	85.36	sliding sand bed
Oil 340cP	0.340	0.07	0.0776	14.11	sliding sand bed

Table-3: Sand transport velocity and flow regimes for 200 lb/1000 bbl

Fluids	Liquid Viscosity cp (kg/m.s)	Transport velocity (m/s)	Pipe Diameter (m)	Re	Sand/oil flow regimes
Water	0.001	0.7	0.1	70000.0	sand dunes
CMC solution (7cP)	0.007	0.75	0.1	10714.2	sand dunes
CMC solution (20cP)	0.02	0.8	0.1	4000.0	connected-sand dunes
Oil 105cP	0.105	0.4	0.0776	291.00	sliding sand bed
Oil 200cP	0.200	0.3	0.0776	102.4	sliding sand bed
Oil 340cP	0.340	0.2	0.0776	40.31	sliding sand bed

Table 5: Comparisons between sand transport in this work with selected correlations for 200lb/1000bbl

Liquid viscosity (cP)	Minimum Transport Velocity, MTC (m/s)							
	Experiment	**Oroskar and Turian (1980)**	**Salama (2000)**	**Turian et al (1987)**	**Kokpinar et al. (2001)**	**Al-Mutahar (2006)**	**Wicks (1970)**	**Danielson (2007)**
1	0.7	0.65	0.36	0.87	0.43	0.51	0.92	0.54
7	0.75	0.54	0.31	0.87	0.13	0.39	0.90	0.44
20	0.8	0.49	0.28	0.87	0.07	0.33	0.88	0.39
105	0.4	0.42	0.24	0.86	0.02	0.28	0.87	0.31
200	0.3	0.39	0.22	0.86	0.01	0.25	0.86	0.29
340	0.2	0.37	0.21	0.85	0.01	0.23	0.85	0.27

*Highlights 2

- Experimental investigations were conducted on sand particle behavior and sand transport Velocity.
- Water and CMC solutions were used as carrying fluids in the 4-inch facility, while Azolla 100 oil was used in the 3-inch the tests.
- It was found that the sand minimum transport condition was influenced by fluid viscosity and the sand/liquid flow regimes at transport conditions were different.
- the sand transport velocity is increasing as viscosity is increased from 1 cP to 20 cP and then decreases