SLURRY TRANSPORT AND PARTICLE SETTLING IN ANNULUS IN CUTTINGS REINJECTION PROCESS

RADZUAN JUNIN[1] & KONG WAI MENG[3]

Abstract. The expending interest in cuttings re-injection process has brought into focus on technical problems relating to the flow and stability properties of suspensions. To design a successful injection program, it is necessary to obtain an optimum delivery efficiency of the cuttings into the formation and the problem of annulus plugging must be avoided. This paper presents the results of a laboratory study to investigate the slurry transport and settling velocity of particles in slurry in vertical annulus. Some aspect of the investigation into the effects of particle size, particle concentration, carrying fluid viscosity and slurry flow rate towards the particle velocity were examined. A criterion for assessing the efficiency of particle transport in slurry in a downward vertical annulus flow, using a relative particle velocity (V_p/V_m) measurement, has been established. The results indicate that the gross effect on particle velocity is similar in both static and dynamic condition. An increase in base fluid viscosity and particle concentration lowers the particle velocity, while a greater particle size increases the particle velocity. A prediction of optimum slurry condition based on results from static and dynamic tests has been done and it shows that slurry with base fluid viscosity of 66.7 cp is needed to achieve the optimum condition in carrying 30% by volume of sand particles with the size of 425 μm - 500 μm into the fractured formation.

Keywords: Cuttings reinjection; drill cuttings; slurry transport; partide settling; annulus flow

1.0 INTRODUCTION

With current technology, some high-angle wells can only be drilled safely and economically by use of oil based mud. However, drilling with oil based mud results in oil-contaminated drill cuttings. Extensive drilling operation has resulted in generation of large volumes of oil-contaminated drill cuttings. In addition, ongoing production operations continue to produce large quantities of tank bottoms and produced oily sands. Traditional alternatives to disposal these wastes include transportation to shore for surface disposal or landfills, incineration, soil washing and disposal into salt caverns. These methods are generally more costly and leave the operator susceptible to future environmental and other liability concerns. Besides, loading operations must be suspended when waves are too high, considerable storage space must be available on the drilling platform to allow drilling to continue when off-loading of cuttings is not possible. Other factors include safety when transporting

---

[1] Faculty of Chemical and Natural Resources Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia

[2] Haliburton Energy Services (Malaysia), 50450 Kuala Lumpur

the cuttings to shore and the increasing number of landfill closures. For these reasons, the drilling industry is exploring new methods and approaches to managing the cuttings disposal issue.

The process of cuttings re-injection (CRI) is a means to dispose of accumulated oilfield wastes by deep well injection. This process yields considerable advantages to the operator over conventional disposal methods. Cuttings re-injection provides an environmentally attractive and permanent disposal solution for considerable volumes of non-hazardous wastes, and has minimal impact on surface land use. In addition, it affords a significant reduction of long-term liability to the operator while reducing transportation and disposal costs. Cuttings re-injection has been successfully implemented in Alaska, the Gulf of Mexico, California, the North Sea and Canada. This method provides a permanent disposal solution for terminal oilfield wastes and it is the only on-site disposal method that can comply with the zero percent discharge of oil-contaminated cuttings.

The increased knowledge of the sub-surface aspects of the cuttings disposal process combined with the improved knowledge of slurry handling is important to ensure a successful injection process. Annulus and near wellbore plugging are the common problems faced by the field operators. Annulus management is thus of particular concern and it is evident that the risk of solids settlement must be minimized not only during the injection process itself, but also during any preparatory activities. Transport properties of the slurries should be studied in detail since they give an indication of the ability of the slurry to suspend solid particles. To achieve optimum suspension stability, careful consideration must be given to certain parameters that require optimization; such as particle size, solids concentration, rheological characteristics of fluid, and pump rate (or bulk velocity). Brief discussion on slurry characteristics in relation to downhole disposal have been given by several authors [1 – 2], but very little data is available defining the optimum slurry conditions.

The studies of slurry flow in oil and gas industry are mostly concerned about hydraulic fracturing process, which involved the transportation of solid particles (proppant) down to the oil well and into the fractured formation. There is very little concerning the CRI process, which shared the same flow direction as the hydraulic fracturing process, but with different slurry properties. Particle transport in CRI process has been studied by Radzuan Junin [3], which involved the study of transportation of solids particles in vertical fracture.

The present study is, therefore, undertaken with the aim of improving the understanding of the suspension stability of the solids in the annulus and to identify the parameters that affect the particle settling velocity in the slurry. The effects of base fluid viscosity, particle size, particle concentration and slurry flow rate toward particle settling velocity, and finally to determine the optimum operational condition in the annulus column by using a relative particle velocity were identified in this study.

2.0 EXPERIMENTAL WORK

2.1 Annulus Flow Model

The experimental set-up of an annulus flow model (Figure 1) was designed to investigate the delivery efficiency of slurry as a function of fluid properties, particle size, solids concentration and slurry flow rate. Generally it consists of 3 main components; *i.e.* an annulus flow model, a slurry handlings system, and a pump.

The annulus flow model consists of two concentric tubes with the length of 12 ft (366 cm). The inner tube OD was 4 in (10.16 cm) and the outer tube ID was 5.5 in (13.97 cm), leaving a 0.75 in (1.91 cm) flow gap. This annulus model was specially designed to simulate the actual field condition. It was scaled down to represent the actual annular space for a 13 3/8 in casing and a 20 in casing. To enable the visualization of the slurry flow in the annular space, the outer tube was made of transparent acrylic pipe. The inlet of the annulus was particularly designed to minimize the entrance effects.

A manometer was used to record the pressure differential (ΔP) along the annulus cross-section at the respective height. The velocity profiles along the annulus cross-section was determined to enable the investigation of velocity distribution in the annulus, thus, it helps to confirm the fully development of flow in the annulus.

The concentric position was achieved using a three-radial struts centralizer placed at the height if 4 ft (122 cm) above the exit point. The pressure relief valve at the top of annulus model was to make sure that no air bubbles were trapped inside the annulus.

2.2 Testing Sample and Testing Fluid

Sands from Port Dickson beach were used to simulate two slurry systems of ground, drilled cuttings, which differ in fineness or particle size distribution. Hereafter these two slurry systems will be referred to as the fine (150 μm – 250 μm) and coarse (425 μm – 500 μm) slurry systems. The selection of the particle sizes was according to the usual practice of a cuttings re-injection process. Dry sieving method was used to prepare the testing samples according to its size.

Various concentrations of glycerin solutions were used to provide different viscosity of the carrying fluid ranging from 40 to 120 cp, which represent the common practice in the actual cuttings re-injection process. In this study, annular flow experiment were conducted with solid concentration of 10 to 30% by volume and the flow rate of the slurry were set between 30 to 70 gpm.

2.3   Particle Settling Velocity Tests

2.3.1   Static Test Condition

To study the suspension stability in static condition, the annulus model was filled with test slurry, and the times taken for the solid-particles to travel through a known distance were recorded. The whole processes were repeated at various particle concentrations, particle size and viscosity of base fluid.

2.3.2   Dynamic Test Condition

After knowing the relationship of the pump speed and system flow rate, then the slurry was pumped through the annulus model and allowed to stabilize. The movements of the dyed particles through a known distance were then captured with a high-resolution, high-speed video camera. Later the signal from camera was connected to TV output that enable the slow down of the movement of dyed particles up to 8-times. As a result, determination of the velocity of the dyed particles becomes easier and more accurate. Similar technique was used by some researchers [4, 5] in order to determine the particle velocity in a slurry flow.

In this study, relative particle velocity can be described with the equation below:

$$\text{Relative particle velocity} = \frac{\text{particle dynamic velocity}, V_p}{\text{velocity of slurry mixture}, V_m}$$

3.0   RESULTS AND DISCUSSION

3.1   Particle Settling in Static Condition

In cuttings re-injection process, particles settling velocity in static condition is of particular important due to the fact that the slurry is required to be held inside the annulus section for a period of times. Slurry stability plays a very important role in maintaining the solid particles in suspension. Insufficient suspension stability causes the fast settling velocity of the solid particles, thus contributing to the problems of annulus plugging. Further injection of slurry into the formation will be affected due the blockage of the fracture inlet. Therefore, excessive pressures are required to initiate the disposal fractures and re-opening fractures after a period of no-injection [6].

Ten sets of reading were taken for each test and the average reading are shown in Table 1. The settling velocity recorded is referred as hindered settling velocity (V_t') since high concentration of solid particles was exhibited in the flowing stream. The experimental results were compared with the theoretical results proposed by Richardson & Zaki [7].

Table 1   Static test results

Slurry Condition	Experimental Hindered Settling Velocity, V_t' (cm/s)	Theoretical Results Hindered Settling Velocity, V_t' (cm/s)
120cP + 10% fine sand	0.054	0.008
120cP + 20% fine sand	0.043	0.005
120cP + 30% fine sand	0.032	0.003
80cP + 10% fine sand	0.074	0.012
80cP + 20% fine sand	0.056	0.007
80cP + 30% fine sand	0.049	0.004
40cP + 10% fine sand	0.156	0.023
40cP + 20% fine sand	0.088	0.014
40cP + 30% fine sand	0.067	0.008
120cP + 10% coarse sand	0.112	0.042
120cP + 20% coarse sand	0.076	0.025
120cP + 30% coarse sand	0.063	0.014
80cP + 10% coarse sand	0.177	0.063
80cP + 20% coarse sand	0.124	0.037
80cP + 30% coarse sand	0.097	0.021
40cP + 10% coarse sand	0.323	0.126
40cP + 20% coarse sand	0.203	0.074

The results show that measured data were higher than the calculated results, particularly for the group of fine sand slurry. For the experimental works, the group of fine sand with the particle size ranging from 150 μm to 250 μm was used. Whereas the particle size for the theoretical calculation was set at 200 μm, which represents the average size of the sand particle used in the experimental works. Therefore this could be the reason for the great different between the experimental results and the theoretical results.

3.1.1   Effects of Base Fluid Viscosity on Hindered Settling Velocity

Figure 2 shows the effects of viscosity towards the particles hindered settling velocity at the concentration of 20% sand by volume for fine and coarse sands. It shows that experimental results agreed well with the calculated results, where they both showing the reduction in hindered settling velocity as the viscosity of the base fluid increased. An increase in the base fluid viscosity led to a decrease in the particle inertia and an increase in the drag force on each particle. As expected, the higher viscosity of the base fluid enhanced the suspension stability of the particles, resulting in a lower settling velocity.
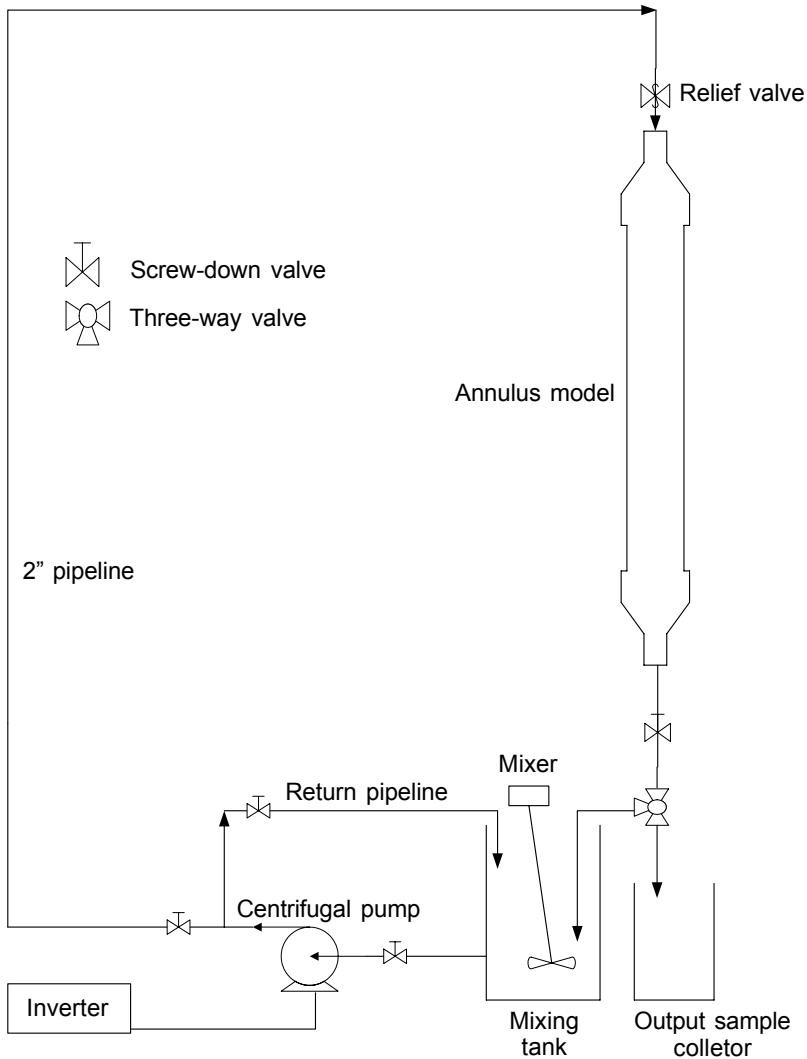
Figure 1   Schematic diagram of experimental rig

3.1.2   Effects of Particle Concentration on Hindered Settling Velocity

Figure 3 illustrates the effects of particle concentration on hindered settling velocity at the base fluid viscosity of 40 cp. As the volumetric concentration of particles increases, it causes interaction and collisions, and momentum transfer between the particles of different sizes. Based on purely geometrical considerations, for sphere at 1% concentration by volume, the inter-particle distance is only 4 diameters. It shrinks to 2.5 diameters at 5% and to 2 diameters at 10% concentration by volume [8]. From this, one might expect hydrodynamic interference, inter-particle collisions and
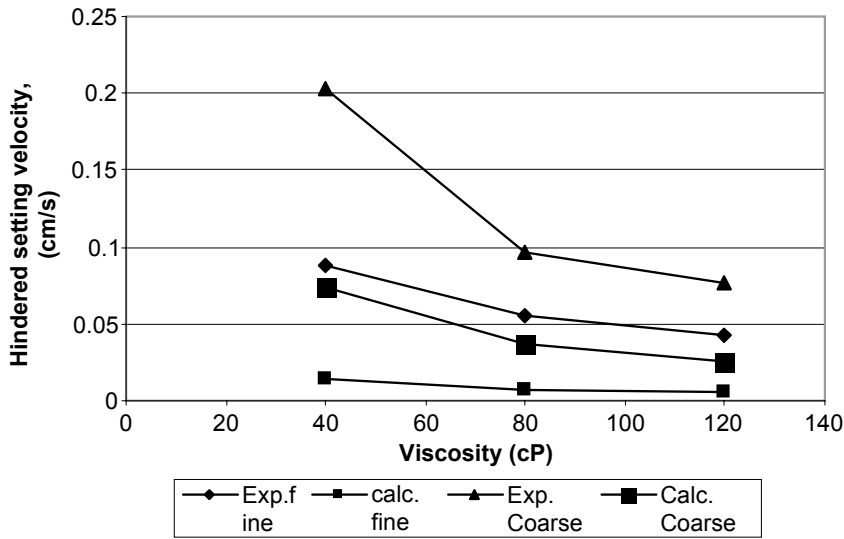
Figure 2 Hindered settling velocity at various viscosity for slurry with 20% by volume fine and coarse sands
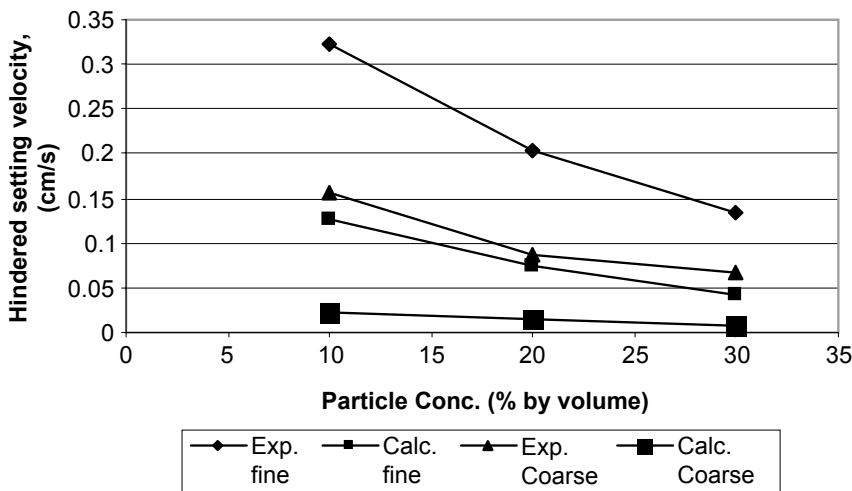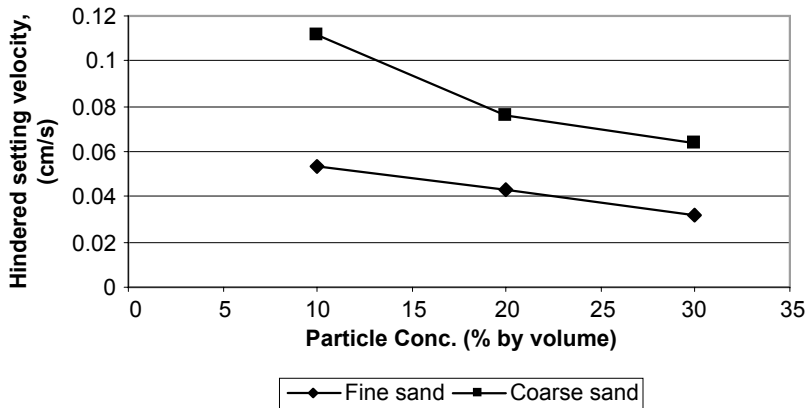

Figure 3 Hindered settling velocity at various particle concentration for slurry with fine sand and coarse sand and base fluid viscosity = 40 cp

interaction to be the rule rather than the exception, and these phenomena cause the reduction in settling velocity. As shown in Figure 3, hindered settling velocity decreases with the increasing of particle concentration. Many researchers had also recorded the same incident, in which they observed a reduction in settling velocity as the particle concentration increased [9 – 10].

Figure 4 Hindered settling velocity at various particle concentration for slurry with fine and coarse sand at base fluid viscosity = 120 cp

3.1.3 Effects of Particle Size on Hindered Settling Velocity

Figure 4 shows the effects of particle sizes on the hindered settling velocity at base fluid viscosity of 120 cp and 80 cp, respectively. Particle density is 2.64 g/cm^3 and base fluid density is 1.24 g/cm^3 for viscosity 120 cp. Due to the density difference between solid particle and base fluid, the particle with higher density is able to settle in the base fluid. Figure 4 shows particle size has a significant effect on settling velocity. Fine sands gave a slower settling rate for the condition shown. As the size is increased, the settling velocity becomes greater. Many other researchers had also recorded the same incident [11 – 12].

3.2 Particle Movement in Dynamic Test Condition

In the actual cuttings re-injection process, slurry is pump through a well annulus which represents a downward vertical flow, to the fractured formation which represents a horizontal flow between narrow parallel plates. The sudden change in flow direction and flow area might cause a disturbance in the transportation of solid particles into the designated area, particularly for the case in which solid particles travel faster than the carrying fluid. Carrying fluid failed to act as a transportation medium to sweep the solid particles into the narrow fracture, causing the accumulation of solid particles in the annulus bottom. Thus, it is a better alternative to keep the relative particle velocity below 1.00, to minimize the annulus plugging during injection period.

3.2.1 Effects of Viscosity on Relative Particle Velocity

Figure 5 and 6 show that relative particle velocity decreases with the increasing of base fluid viscosity. At base fluid viscosity of 40 cp, relative particle velocity is more
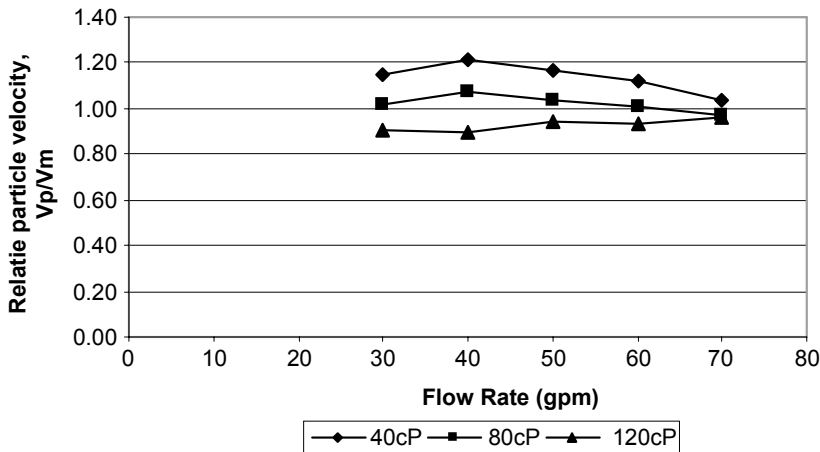
Figure 5   Relative particle velocity for fine sand slurry with particle concentration = 10% by volume
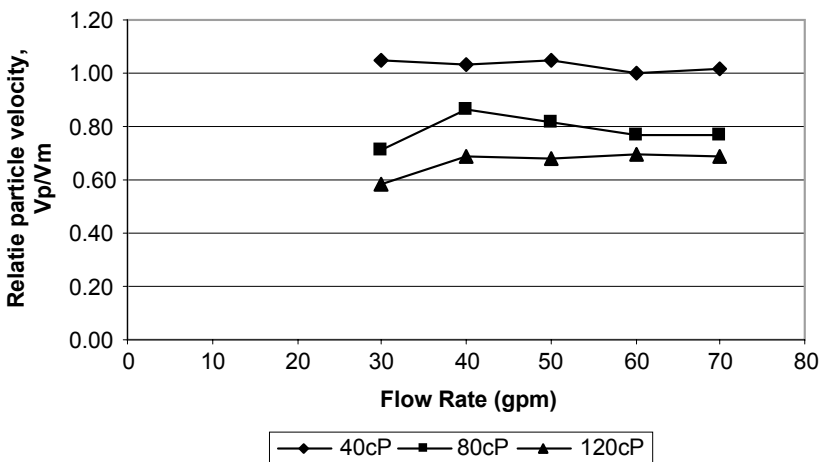

Figure 6   Relative particle velocity for fine sand slurry with particle concentration = 30% by volume

than 1.00, meaning that solid particles in the flow stream travel faster than the carrying fluid. Relative particle velocity for slurry with 10% by volume fine sand approaching 1.00 as the viscosity of base fluid was increased to 80 cp. At particle concentration of 30% by volume (Figure 6), the value of relative particle velocity approaching 1.00 at base fluid viscosity of 40 cp. This is due to the effects of particle concentration. At the base fluid viscosity of 120 cp, the value of relative particle velocity for all slurry conditions are below 1.00, as the velocity of carrying fluid is faster than the velocity of solid particles. Analysis on the coarse sand slurry shows the same trend as those illustrated by the fine sand slurry systems. The increasing of base fluid viscosity

reduces the particle dynamic velocity. This may possibly cause by the complicated particle-particle interaction. Therefore it leads to the decrease of particle relative velocity.

3.2.2 Effects of Particle Concentration on Relative Particle Velocity

Figure 7 and 8 show the effects of particle concentration on relative particle velocity for fine sand slurry at base fluid viscosities of 40 cp and 120 cp, respectively. At the base fluid viscosity of 40 cp, all trend lines are above 1.00. As the viscosity of base
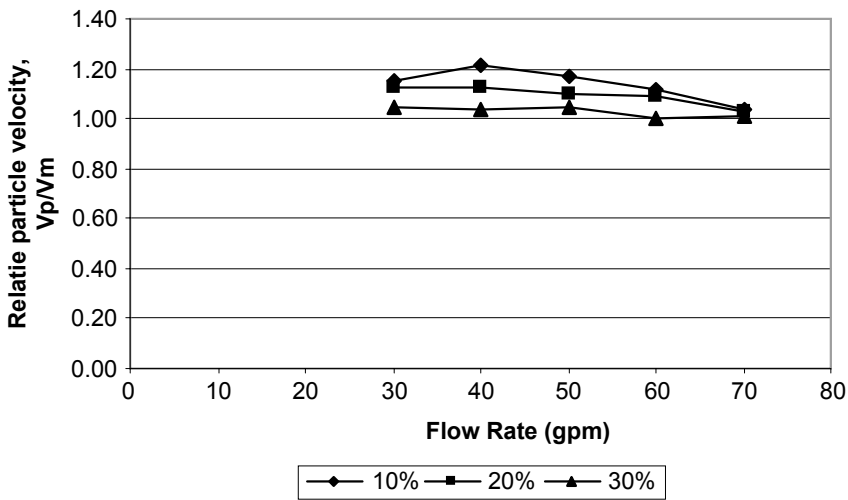

Figure 7 Relative particle velocity for fine sand slurry at base fluid viscosity of 40 cp
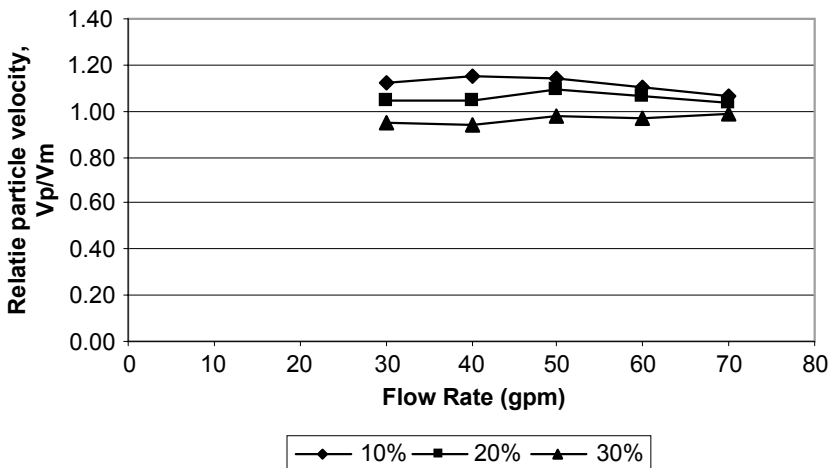

Figure 8 Relative particle velocity for coarse sand slurry at base fluid viscosity of 40 cp

fluid is increased, the overall value of relative particle velocity is reduced and this causes the reduction of overall value of relative particle velocity to below 1.00 for slurry with base fluid viscosity of 120 cp. However, it can be seen that the particle concentration shows the same effects on all slurry condition, in which relative particle velocity is reduced as the particle concentration in the system is increased. Study on the coarse sand slurry shows the similarity with the one demonstrated by the fine sand slurry.

In a slurry system, if the slurry flow rate is kept constant, the reduction of particle dynamic velocity will cause the increasing of in-situ particle concentration. Therefore, one can predict that when the solid particles travel slower than the carrying fluid, the particle concentration exhibited in the annulus space is more than the delivered concentration into the fractured formation.

3.2.3   Effects of Particle Size on Relative Particle Velocity

Larger particle sizes give a greater particle dynamic velocity compared with smaller particle sizes. Therefore, slurry with large solid particles should yield a greater relative particle velocity compared with slurry with small solid particles. Figure 9 shows that relative particle velocity for slurry with particle size of 425 μm – 500 μm is higher than the slurry with particle size of 150 μm – 250 μm. Due to the gravitational and weight effects, the larger particles are allowed to fall faster then the lighter particles.

3.2.4   Effects of Slurry Flow Rate on Relative Particle Velocity

Figure 5 and 6 show the effects of relative particle velocity for fine and coarse sand slurries, respectively. The value of relative particle velocity tends to move to 1.00 as
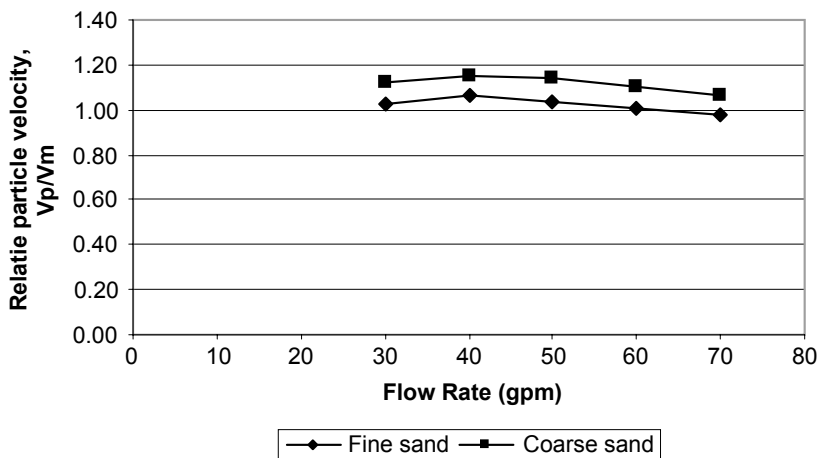

Figure 9   Relative particle velocity for slurry with base fluid viscosity of 80 cp and particle concentration = 10% by volume

the slurry flow rate is increased. At base fluid viscosity of 40 cp as shown in Figure 7 and 8, relative particle velocity for both fine and coarse sand slurries again tend to move to 1.00. Thus it may be concluded that for slurry with low particle concentration and low viscosity, high flow rate causes the slurry flow to become more homogeneous i.e. solid particle and carrying fluid flow at the same speed.

At high flow rate, the high speed carrying fluid might cause interruption to the particle-particle interactions. Particles in the flowing stream might not be able to contact with each other due to the high speed flowing carrying fluid that has the ability to drive down the solid particles to follow its flowing path. This is particularly true for slurry with low viscosity and low particle concentration. As the particle concentration and base fluid viscosity in the system are increased, the effect of particle-particle interactions is dominant. Therefore relative particle velocity is quite stable for all slurry flow rates.

3.3   Optimum Slurry Condition

In the downward annulus flow, attention is given to the ability of slurry to suspend solid particles during no-injection period (static condition), and the ability of carrying fluid to transport solid particles into the fractured formation during injection period (dynamic condition). In static condition, results showed that slurry with 30% by volume of fine sand and base fluid viscosity of 120 cp yield the best suspension, in which the particle settling velocity is 0.032 cm/s. According to Addie, the determination of suspension stability is based on a 62 μm diameter quartz sand grain, which has a settling velocity of 0.15 cm/s in 20 °C water [13]. Higher settling velocities denote bad suspension stability, whereas lower settling velocities denote good suspension stability. Referring to Table 1, most of the slurry conditions are fall into the latter category, with the particle settling velocity less then 0.15 cm/s.

In dynamic condition, optimum slurry condition refers to the state in which the solid particles and the carrying fluid are travel at the same speed. Solid particles that travel faster than the carrying fluid might cause the problem of annulus plugging. Solid particles that travel slower than the carrying fluid lead to an increasing of in-situ particle concentration in the annulus.

The purpose of the cuttings re-injection process is to pack as many cuttings as possible into the fractured formation. Cuttings slurry that is able to hold high volume of solid particles is preferred. Thus attention is given to the optimum rheological condition of the slurry to hold 30% by volume of solid particles. Figure 10 shows that base fluid viscosities of 41.5 cp and 66.7 cp are needed for the fine and coarse sand slurry to achieve its optimum condition.

In the actual field practice, coarser particle size is preferred due to time and cost saving (minimal grinding process). Thus an experiment using 30% by volume coarse sand and base fluid viscosity of 66.7 cp was conducted to confirm the conjecture, and the result is presented in Figure 11. It is clearly shown that the experimental
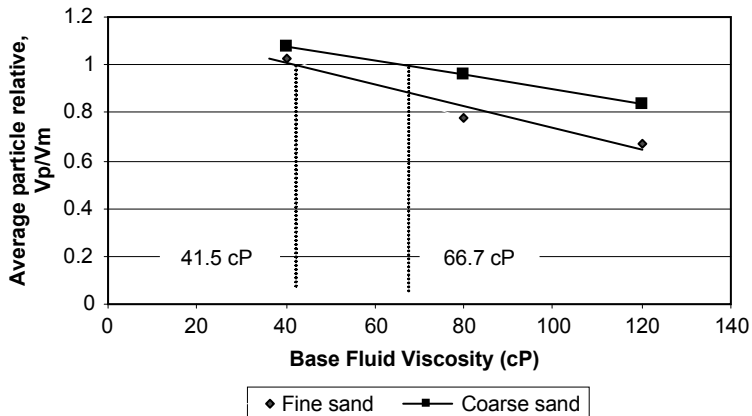
Figure 10   Average particle relative velocity at various base viscosity for slurry with 30% by volume fine and coarse sands
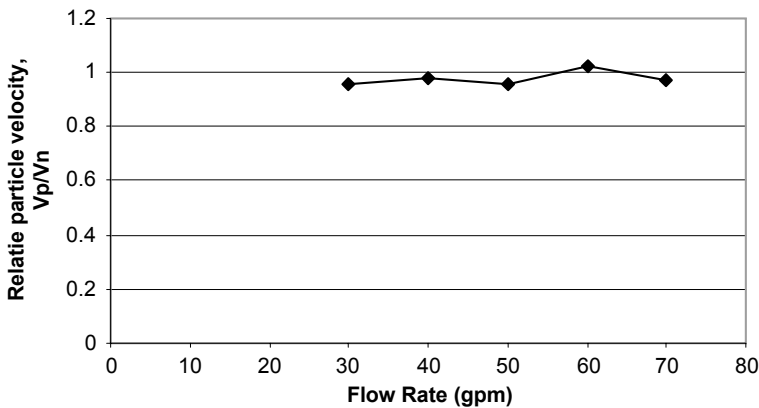

Figure 11   Relative particle velocity for slurry with 30% by volume coarse sand and base fluid viscosity = 66.7 cp

result agreed well with the predicted value. At the base fluid viscosity of 66.7 cp, cuttings slurry is able to perform in its optimum condition. Static test result showed that hindered settling velocity is 0.116 cm/s, a value that represents slurry with good suspension stability.

4.0   CONCLUSIONS

In static conditions, the particle hindered settling velocity is found to depend upon the viscosity of base fluid, particle concentration and the size of solid particles. The increased of base fluid viscosity and particle concentration tend to reduce particle hindered settling velocity. While increasing the particle size leads to the increasing of settling velocity. In dynamic conditions, the increase of particle dynamic velocity is found to be affected by the increasing of particle size, and its value decreases as

the base fluid viscosity and particle concentration are increased. It is possible to use the relative particle velocity (V_p/V_m) as a criterion for assessing the efficiency of the particles transportation in the annulus column. The following conclusions on the change in relative particle velocity (RPV) can be made:

(i)   RPV > 1 : Solid particles travel faster then the carrying fluid and this might cause the problem of annulus plugging.

(ii) RPV = 1 : Solid particles and carrying fluid traveling at the same speed and reaches its optimum condition.

(iii) RPV < 1 : Solid particles travel slower then carrying fluid and caused the increase of in-situ concentration, and worsen the problem of particle settlement during static state.

ACKNOWLEDGEMENTS

REFERENCES

[1]   Minton, R. C. and B. Secoy. 1992. Annular Re-Injection of Drilling Wastes. Paper SPE 25042, *Proc. SPE EUROPEC Conference*. Cannes, France. Nov 16-18: 247-253.

[2]   Siverag, G. and A. Bale. 1993. An Improved Method for Grinding and Re-Injection of Drill Cuttings. Paper SPE 25758 presented at the *SPE/IADC Drilling Conference* held in Amsterdam. Feb 23-25.

[3]   Junin, R. 1996. *Downhole Disposal of Oil-Rig Drill Cuttings*. University of Nottingham: Thesis Ph.D.

[4]   Barree, R. D. and M. W. Conway. 1995. Experimental and Numerical Modeling of Convective Proppant Transport. Paper SPE 28564 presented at the *SPE Annual Technical Conference and Exhibition* held in New Orleans. Sept 25-28.

[5]   Masuda, Y., S. Naganawa, Q. T. Doan, T. Yonezawa, A. Kobayashi and A. M. Kamp. 2000. Experimental Study to Determine Critical Flow Rate of Cuttings Transport During Underbalanced Drilling. Paper SPE 62737 presented at the *2000IADC/SPE Asia Pacific Drilling Technology* held in Kuala Lumpur, Malaysia. Sept 11-13.

[6]   Brakel, J. D., J. B. Davies, G. K. Yule and J. T. O. Thornton. 1997. Cuttings Re-Injection in Brent Reduces Drilled Cuttings Discharge to Sea. Paper SPE 37864 presented at the *SPE/UKOOA European Environmental Conference* held in Aberdeen, Scotland. Apr 15-16.

[7]   Richardson, J. R. and W. M. Zaki. 1954. Sedimentation and Fluidisation. Part I. Trans. Intern. Chem. Engrs. 32-35.

[8]   Abulnaga, B. 2002. *Slurry System Handbook*. Mc-Graw Hill, U.S.A.

[9]   Kirkby, L. L. and H. A. Rockefeller. 1985. Proppant Settling Velocities in Nonflowing Slurries. Paper SPE 13906 presented at the *SPE/DOE 1985 Low Permeability Gas Reservoirs* held in Denver, Colorado. May 19-22.

[10] Dunand, A. and A. Soucemarianadin. 1985. Concentric Effects on Settling Velocities of Proppant Slurries. Paper SPE 14259 presented at the 60th *Annual Technical Conference and Exhibition of the Society of Petroleum Engineers* held in Las Vegas. Sept 22-25.

[11] Govier, G. W. and K. Aziz,. 1972. *The Flow of Complex Mixture in Pipes*. Van Nostran & Reindold Company.

[12] Wasp, E. J., J. P. Kenny and R. L. Grandhi. 1977. *Solid-Liquid Flow in Slurry Pipeline Transportation*. Trans. Clausthal, Germany: Tech. Publication.

[13] Addie, G. R. 1982. *Slurry Pipeline Design Manual*. Georgia: Georgia Iron Works.