Particle Settling in non-Newtonian Drilling Fluids

by

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Abstract

Particle settling is relevant for several aspects of drilling and completion operations, and is directly related to safety and operational efficiency. The primary function of particles added to drilling fluids is to provide density stabilizing the wellbore and hinder influx of fluids and gas, causing a kick situation. Keeping the particles suspended in the fluids is also critical to avoid problems such as stuck down hole equipment, poor cementing of casings, lost circulation and avoid formation damage.

The main objective of the present work is to improve the understanding of particle settling in non-Newtonian drilling fluids. The work focuses on identifying parameters critical for particle settling which are directly relevant for everyday handling and use of drilling and completion fluids. To identify these parameters, laboratory techniques have been developed that allow continuous monitoring of the particle settling process in a fluid. The majority of the parameters identified have previously not been studied by the oil industry. This includes parameters such as the composition of the internal brine phase of oil based drilling fluids, added shear energy during preparation of these and the effect of particle morphology on settling. Operational parameters, such as vibrations during drilling, and the efficiency of solids removal equipment have also been discovered to have significant impact on the particle settling rate.

Throughout this work the complexity of particle settling in the fluids has clearly been demonstrated. Conventional settling models have shown not to predict the effect of this phenomena accurately. The complexity of the sag phenomena requires the development of significantly improved practical equipment to optimize and monitor the sag stability of drilling fluids at the rig site.

Acknowledgement

The work presented has been carried out as a part of my position at Statoil where I have been fortunate to have been employed since December 2000. Much of the work has been carried out in co-operation with my colleagues within the drilling fluid and R&D department, and I would like to thank them all for their patience, contributions and support.

The majority of the laboratory work presented in this dissertation has been carried out at the University of Stavanger. An excellent group of students have contributed with studies as part of their BSc or MSc thesis work. The Department of Petroleum Technology has likewise provided excellent working conditions making it possible for me to conduct this work. In particular, Helge Hodne has contributed with both practical assistance, contributions to articles and review of this dissertation.

Without my supervisor Prof. Arild Saasen, professor at the Department of Petroleum Technology and advisor at Det Norske oljeselskap ASA, this work would not have been possible to conduct. Professor Saasen was the main initiator of this work in 2003/04, and has ever since been very supportive and patient in following up the work. I wish to express my sincere gratitude to him for both mental support and guidance throughout these years.

I have also had the great pleasure of having Prof. Per Amund Amundsen, professor at the University of Stavanger, as co-supervisor for my work. I truly admire his capacity for translating physics into mathematical expressions, and I would like to thank him for all of his contributions for getting this work finalized.

Finally I would like to thank my family and especially my wife Mari for her support and patience throughout these years. Without her support I would never have started nor finished this long-term project.

List of papers and Contributions

The papers are referred to in the following review by their Roman numerals and copies of papers [I] to [X] are enclosed subsequently in the appendix. The majority of the content of this thesis is based on these first ten publications. However, there are several findings relevant for particle settling in drilling fluids in publications [XI] to [XXI] and [XXXI]. In these publication, the contributions from the author are varying from providing minor input to being an active partner in the investigations. Furthermore, students have made important contributions in our particle settling investigations. References [XXII] to [XXXI] refer to experimental work performed by bachelor or master students where undersigned have been supervisor or co-supervisor.

I Omland, T.H., Øvsthus, J., Svanes, K., Saasen, A., Jacob, H., Sveen, T., Hodne, H. and Amundsen, P.A.: "Weighting Material Sag", Ann. Trans. Nordic Rheology Soc., vol. 12, pp. 115-122, 2004.

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III Omland, T.H., Albertsen, T., Taugbøl, K., Saasen, A. Svanes, K. and Amundsen, P.A.: "The Effect of the Synthetic and Oil-Based Drilling Fluid's Internal Water Phase Composition on Barite Sag", SPE Drilling & Completion, no. 2, vol. 21, pp. 91-98, June 2006.

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VII Omland, T.H., Saasen, A., van der Zwaag, C., Amundsen, P.A.: "The Effect of Weighting Material Sag on Drilling Operation Efficiency", SPE 110537, SPE Asia Pacific Oil& Gas Conference and Exhibition, Jakarta, Indonesia, 30 October-1 November 2007.

VIII Dahl, B., Saasen, A. and Omland, T.H.: "Successful Drilling of Oil and Gas Wells by Optimal Drilling Fluid Solids Control: A Practical and Theoretical Evaluation", SPE Drilling & Completion, no. 4, vol. 23, December, pp. 409-414, 2008.

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X Omland, T.H., Hodne, H., Saasen, A., Mjølhus, S., Amundsen, P.A.: "Drilling Fluid Weight Material Sedimentation- Part II Sedimentation of suspensions", accepted for publication in Petroleum Science and Technology, Taylor & Francis Inc, December 2009.

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XI Paulsen, J.E., Omland, T.H., Igeltjørn, H., Aas, N., Solvang, S.A.: "Drill Cuttings Disposal, Balancing Zero Discharge and Use of Best Available Technique", SPE/IADC 85296, SPE/IADC Middle East Driling Technology Conference and Exhibition, Abu Dhabi, UAE, 20-22 October 2003.

XII Fimreite, G., Askø, A., Massam, J., Taugbøl, K., Omland, T.H., Svanes, K., Kroken, W. and Saasen, A.: "Advanced Invert Emulsion Fluids for Drilling Through Narrow Hydraulic Windows", SPE/IADC 87128, IADC/SPE Drilling Conference, Dallas, Texas, 2-4 March 2004.

XIII Saasen, A., Svanes, K., Omland, T.H., Mathiassen, E., Vikane, O.: "Well Cleaning Performance", IADC/SPE 87204, IADC/SPE Drilling Conference, Dallas, Texas, U.S.A., 2-4 March 2004.

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XVI Datta, B.K., Ratnayake, C., Saasen, A., Omland, T.H.: "Hole Cleaning and Pressure-Loss Prediction From a Bulk Transport Perspective", SPE 96315, Offshore Europe, Aberdeen, Scotland, United Kingdom, 6-9 September 2005.

XVII Berg, E., Sedberg, S., Haarigstad, H., Omland, T.H., Svanes, K.: "Displacement of Drilling Fluids and Cased-Hole Cleaning- What Is Sufficient Cleaning?", IADC/SPE 99104, IADC/SPE Drilling Conference, Miami, Florida, U.S.A., 21-23 February 2006.

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XXXI Nguyen, T., Miska, S., Yu, M., Takach, N., Ahmed, R., Saasen, A., Omland, T.H., Maxey, J.: "Combined Effects of Eccentricity and Pipe Rotation on Dynamic Barite Sag- Analysis the Different Impacts of Pipe Rotation in a Flow loop & Rotation in a Modified Rotational Viscometer on Barite Sag", part of PhD thesis and presented at AADE National Technical Conference & Exhibition, New Orleans, LA, U.S.A., 2009.

Supervision of student work

XXII Arnesen, S.: "The Effects of zeta potential on the performance of water based drilling fluids", MSc Thesis, University of Stavanger, June 2003.

XXIII Albertsen, T.: "The Effect of the Synthetic and Oil-Based Drilling Fluid's Internal Water Phase Composition on Barite Sag", MSc Thesis, June 2004.

XXIV Lønning, P.: "Investigation on How Particle Size Distribution in a Drilling Fluid Influence Rheological Properties and Sag Behavior", BSc Thesis, University of Stavanger, May 2005.

XXV Bjørnsen, L., Søbye, E.: "Rheological properties of oil based drilling fluid during vibrations", BSc Thesis, University of Stavanger, June 2005.

XXVI Gjerde, A.: "Characterization of weighting materials and influence of electrolyte strength on sag stability.", BSc Thesis, University of Stavanger, June 2005.

XXVII Fard, A.: "Shale Shaker's Effect on Drilling Fluids Rheological Properties", MSc Thesis, University of Stavanger, June 2007.

XXVIII Mjølhus, S.: "Saganalysis using an Atmospheric Consistometer", BSc Thesis, University of Stavanger, June 2008.

XXIX Kartevoll, M.: "Drilling problems in depleted reservoirs", MSc Thesis, University of Stavanger, June 2009.

XXX Egeland, C.: "Investigation of structural breakdown of drilling fluids by imposed vibration", BSc thesis, University of Stavanger, June 2009.

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Contents

Chapter 1

Introduction

Particles settling in fluids cause significant challenges in numerous situations. This ranges from suspending herbs in vinegar to causing problems transporting nuclear waste [1]. Within the petroleum industry one often experience challenges for instance when transporting cuttings out of a borehole or when suspending weighting material in a drilling fluid [2]. Weighting material settling is termed sag by the petroleum industry, and appears as a density variation in the fluid column that causes operational problems. The phenomenon of particle settling in fluids has many facets, but the fundamental settling mechanisms are often more alike than one would expect. In this work the primary focus is on settling of weighting material in non-Newtonian drilling fluids, but other related situations, where particle settling influence the drilling operation, are also discussed.

The first section in this chapter gives an introduction to drilling and completion fluids while Sect. 1.2 describes the history of the scientific investigations of particle settling and illustrates the importance of the topic using studies of field cases. Sect. 1.3 gives a description of other operational aspects that are influenced by particle settling.

1.1 Drilling and Completion Fluids

During drilling and completion operations, various fluids are used to achieve the set goal for the well. In the drilling phase, the drilling fluid serves several functions such as transporting drilled formation out of the wellbore, controlling the formation pressure, avoiding loss of fluid to the formation etc. (Fig. 1.1).

To achieve this, the drilling fluid must be properly designed. Often one needs to compromise between various fluid properties. For example, solids are added to the fluid to hinder fluid loss to the formation, which on the other hand can lead to increased viscosity and subsequent excessive pump pressures due to higher flow resistance. If the formation can not withstand this increased pressure, a loss situation can occur where the drilling fluid flows into generated

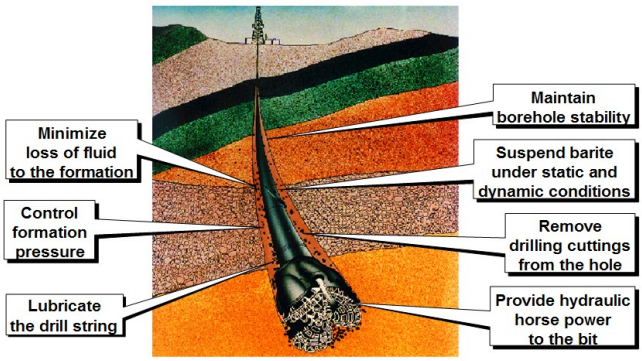


Figure 1.1: *The main functions of a drilling fluid. Courtesy: MISwaco.*

fractures in the formation. Complementary requirement is that the wellbore pressure must be higher than the pore pressure, in order to hinder influx of gas or liquid into the wellbore. These limits of fracturing and pore pressure results in an operational pressure window as shown in Fig. 1.2. The total pressure

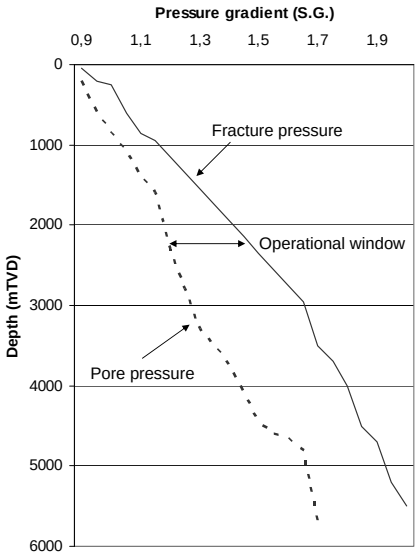


Figure 1.2: *The pressure exerted on the formation from the drilling fluid, must be kept below the fracturing pressure to hinder loss of fluid to formation and above the pore pressure to hinder influx into the wellbore.*

must be kept within this window. The pressure given by the static fluid column is described in terms of equivalent static density (ESD), while the total sum of the pressures, that includes frictional pressure loss during pumping, makes up the equivalent circulating density (ECD).

To provide density to the drilling fluid, various weighting materials are normally added. These are high density solids, such as barite, ilmenite, hematite or manganese tetraoxide. For the fluid to provide a linear pressure increase as a function of vertical depth, the solid phase needs to be kept in suspension to provide a constant pressure gradient. For conventional drilling operations, this is one of the crucial functions of a drilling fluid. Otherwise, the consequences could be a wellbore blowout as shown in Fig. 1.3.

Figure 1.3: *Stratification of the weighting material (sag) in the wellbore causing a dramatic blowout. Source: Maritime-connector.com*

During the final stage for getting a well ready for production, the *completion phase*, ones also faces challenges with particle settling. In many cases this will impair production complementary to having an impact on safety.

Due to the seriousness of density stratification, both during drilling and completion operations, this work focuses on elements that has an impact on the sag phenomenon. The subsequent sections describe briefly the history of sag investigations in the petroleum industry. These sections also describe in more detail the challenges arising from particle settling for specific drilling and completion operations.

1.2 Scientific investigations of particles settling in drilling fluids

Sag has long been recognized as one of the most significant challenges to be dealt with in drilling and completion operations. It has caused numerous incidents of lost circulation, stuck-pipe, casing/liner running problems and even blowouts. Significant dark figures for failed operations caused by sag most certainly exist. A detailed study [VII] of the impact of sag on drilling operations clearly

Table 1.1: *Selection of eleven field cases with sag occurring over a two year period and time elapsed for remedial work [VII].*

Operation Type	Fluid	Initial MW (SG)	Delta MW (SG)	Consequences	NPT (hrs)
Drilling	OBM	1.82	-0.35	Well control situation	224
Drilling re-entry	OBM	1.64	-0.33	None	5
Drilling	OBM	1.61	-0.20	Hole collapse=>sidetrack	240
Drilling	OBM	1.58	-0.08	Cavings, hole instability	20
Drilling/liner	OBM	1.58	-0.10	Excessive circ. time	29
Run 7" liner	OBM	1.58	-0.11	Hole instability=> stidetrack	377.5
Run 7" liner	OBM	1.60	-0.08	Losses during cmt.	7.5
Run 7" liner	OBM	1.67	-0.07	Hole instability=> re-drill	4.5
Run 9 5/8" csg.	OBM	1.70	0.32	Hole instability=> re-drill	7
Run 9 5/8" csg	OBM	1.70	-0.06	Excesive circ. time	22
Run 9 5/8" csg	OBM	1.70	-0.09	Losses during cementing	18

demonstrates its severeness. Table 1.1 shows a selection of eleven North Sea operations over a two year period where sag incidents have occurred. In these field cases, sag is identified as the root cause for non-productive time (NPT) or at least as an element with a significant impact on the operational efficiency. The study shows the wide range of operational issues that are related to sag.

The first incident investigated resulted in a serious well control situation. The density of the oil based drilling fluid fluctuated to such a degree that it could no longer balance the wellbore pressure. This resulted in a $39\,\mathrm{m}^3$ rapid gain of drilling fluid at the rig before the well was shut-in. For the subsequent wells at this field, a brine based drilling fluid was therefore used [3]. This fluid has less settling potential due to its nearly solids-free composition, but has also certain disadvantages, including settling of the material used in the fluid for filtration control, high price and chemical reaction with the formation. Therefore normal weighted drilling fluids using particles for density control is likely to continue to be the preferred solution also in the near future. For all sag incidents investigated throughout this work, totalling over 50 incidents, no common causes such as specific operational conditions, fluid properties etc. have been identified. This shows the complexity of the sag phenomenon and why it is subjected to significant research work.

The first years after realizing the importance of sag in the early 1980s were mostly dedicated to relating already established fluid properties measured in accordance with industry standards, to the fluid's sag stability [4]. One of the first discoveries in these early investigations was that sag is not only a "static" phenomenon, occurring only during pump stops. Most sag incidents actually occur during slow circulation, logging or casing running operations. It was also recognized that sag tends to be more severe in inclined wells, and when using oil

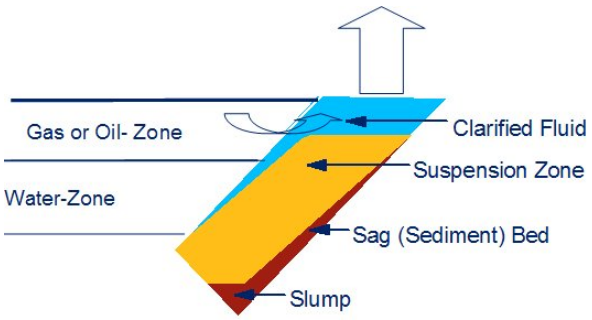


Figure 1.4: *Initial weighting material settling creates a pressure imbalance resulting in a further enhanced settling rate.*

or synthetic based drilling fluids [5]. The phenomenon of accelerated settling, which is observed in inclined wellbores, was discovered much earlier by the physician A.E. Boycott. He reported in 1920 that blood corpuscles settle faster in inclined test tubes than in vertical ones [6]. Fig. 1.4 shows schematically how the Boycott effect results in slumping of a particle bed to the bottom of the borehole. This causes a pressure imbalance in the fluid column which further accelerates the settling in a well. This can result in formation fluids or gas entering the well bore, leading to a well control situation.

These early observations resulted in emphasis on identifying operational parameters influencing sag [7, 8], as well as a search for additional fluid properties that could provide information of a fluid's sag stability [9, 10, 11]. More fundamental research was also performed to link other more basic descriptions of fluid properties to sag performance [12, 13]. With the current knowledge it is recognized that there are many other elements that influence a fluid's sag tendency, some which will be discussed in this work.

1.3 Particle settling and its impact on other aspects of drilling or completion operations

Particle settling is relevant in several aspects during drilling or completion operations, and influence critical elements for performing safe and efficient operations. In the following sections some of these aspects are discussed illustrating the importance of particle settling in drilling and completion fluids. It must be noted that this list of operations affected by particle sedimentation is far from exhaustive.

1.3.1 Particle composition and wellbore strength

Drilling through depleted reservoirs is particulary challenging, since the operational pressure window becomes small or negative [XXIX]. Various techniques have been proposed to maintain the original fracture strength as the pore pressure depletes. One such technique is based on fracturing the borehole wall with small fractures and then fill these with impermeable particles to stop further propagation of the fractures (see Fig. 1.5).

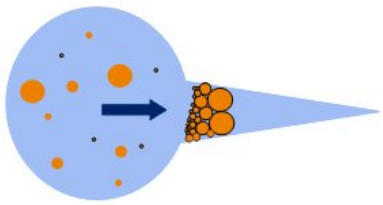


Figure 1.5: *Particles added to the drilling fluid enters small fracture and making a particle bridge. Courtesy: P. Horsrud.*

As the fractures are kept open by propping them with particles, the formation strength increases as the hoop stresses around the wellbore increase. A wide variety of particulate materials are used to obtain this effect, including calcium carbonate ($CaCO_3$), graphite, dolomite, walnuts or various rubber types. The weighting material and drilled solids particles are also known to influence the formation strength. This may be the reason for why solids-free systems have higher potential for losses than conventional systems, once a fracture has been initiated.

The above idea for maintaining formation strength is discussed by Messenger [14] and Morita et al. [15]. Fuh et al. [16] were of the first to suggest this method to prevent lost circulation during drilling. A proposal for material selection and treatment were subsequently refined by several others [17, 18, 19, 20, 21, 22, 23, 24]. All of these studies conclude that the impact from particle addition on wellbore strength is important.

There are several relationships between this approach of added particles for enhanced formation strength to particle settling. The mechanism for formation strengthening in wellbores is closely related to the phenomenon of *arching* in dry powder handling. Arching in pipes and conical sections has been subjected to significant research for more than a hundred year within powder technology [25, 26, 27], and is discussed in most textbooks on soil and powder mechanics [28].

Plugging or arching of silos and transport lines is a consequence of particles having a size distribution (PSD) optimal for plugging of an opening. There are several reasons for this occurring, but particle settling is of significant importance as the PSD changes due to this phenomenon. Another practical aspect, adequate for our drilling fluids and the use of particles for formation strength maintenance, is the deterioration of the PSD in the bulk transport chain. This

result in not having the ideal PSD for use as an additive to drilling fluids for loss prevention, as is a pre-requisite for true application of formation strength enhancement.

The last aspect relating particle settling to formation strength is that these particles are equally subjected to the forces of gravity, buoyancy etc. as are the weighting material particles. Operational experiences confirm this, since settling of relatively small quantities (100-200 kg/m^3) of added calcium carbonate particles to brine based drilling fluids, have caused stuck-pipe incidents due to particle settling.

1.3.2 Formation damage

The last phase of the drilling operation is to drill into the reservoir itself using so-called drill-in fluids, which subsequently are displaced by a completion fluid. Both of these fluid types need to be designed to prepare for highest possible production from production wells and to get good sampling data for exploratory wells [29]. This forms the background for numerous studies on formation damage mechanisms [30].

The particle content is of outmost importance for avoiding formation damage. Hindering fines or unwanted fluids from migrating into the formation requires good filtration properties. This filtration is influenced by several properties, of which PSD and particle content are of the most important ones. Several rules of thumb exist for optimal PSD to obtain good filtration properties, which are necessarily not mutually consistent. Abrams' rule states that particle bridging can occur when the particle diameter is about 1/3 to 1/6 of the opening size [31]. The ideal packing theory states that full particle size range is required

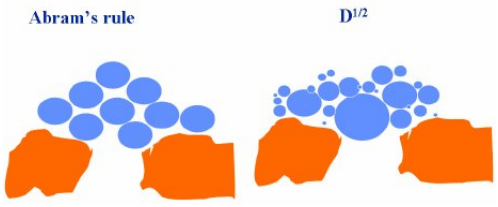


Figure 1.6: *Different rules of thumb to obtain optimal particle size distribution exist. Abrahams' rule states that bridging can occur when the particle diameter is 1/3 to 1/6 of opening size. From Ideal Packing Theory ($D^{1/2}$), a full particle size range is required to plug the fracture [33].*

to plug all voids, including the openings between particles plugging the formation [32]. This theory prescribes a linear relationship between the square root of the diameter and the cumulative particle volume. Control of PSD throughout the drilling or completion operation is therefore of high importance.

Another aspect of particle settling and production impairment, is for wells run with completion solutions where the oil or gas is produced through wire

wrapped screens as shown in Fig. 1.7. These screens are used to prevent sand from entering into the production process.

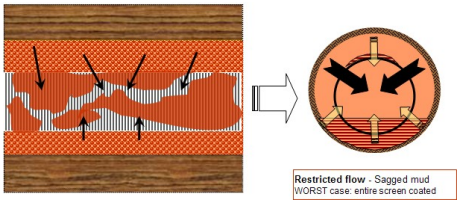


Figure 1.7: *To prevent solids production, screen completions are often run where the inflowing gas or oil is produced through wire wrapped screens. Courtesy: G. Svanes, A. Nottveit.*

This type of wire wrapped screen solution can be run in clear completion brine, but due to challenges with formation stability when using brines, oil based systems are often preferred. The fluid used during the drilling operation can also be used for completion, provided that it is clean enough to flow through the production screens. Plugging of the production screens depend on several parameters, such as the fluid's viscoelastic properties, particle content, particle size and extensional viscosity. If sufficient material is allowed to settle onto the screens, production may be impaired [XIV] as shown in Fig. 1.8.

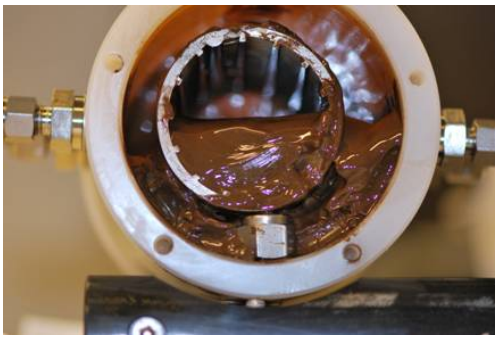


Figure 1.8: *Picture taken from the front of a horizontal placed inner production screen covered with settled barite (brown-colored mass). The settling can cause plugging of the screen and hinder production. With this set-up, production can be simulated through the horizontally placed valves shown on the left and right side of the picture. Courtesy: G. Svanes.*

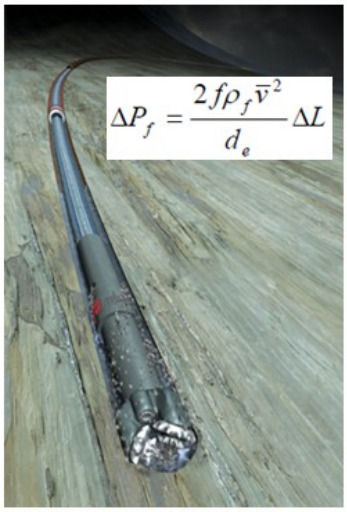
This figure shows a laboratory investigation of flow-back properties of an oil based drilling fluid through a horizontally placed inner screen. Weighting material (brown-colored mass) settling onto the screen will hinder production from certain portions of the well. It is therefore critical to have a fluid of highest possible stability to prevent this effect.

By use of other special fluid systems which contains specially treated micronized weighting material, the particles will pass through the screen openings and promote less production impairment [XV]. Field experience with such systems also indicate that this grade of weight material is produced back from the formation if it contains the correct PSD [33].

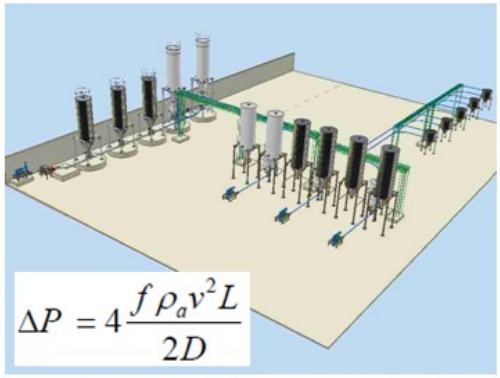
1.3.3 Hole cleaning, wellbore clean-up and settling mechanisms

Whether it be weight material or cuttings settling in the well bore, the underlying fundamental physics is the same. Events with removal of cuttings or debris from the wellbore makes up the majority of NPT during drilling and completion operations [XIII,XVII]. The issue of hole or pipe cleaning is also relevant for several other industries, and hundreds of publications are made each year discussing fundamentals of hole or pipe cleaning. In one publication [XVI] the similarities of this issue between hole cleaning in the drilling industry and pneumatic bulk transport of dry powders are explored.

Hole cleaning and pneumatic conveying of dry powders are both examples of two-phase flow. During bulk transport, particles are kept in suspension by a gas while in cuttings transport (hole cleaning), the suspending medium is a fluid. The models for pressure loss prediction are though strikingly similar as shown in Fig. 1.9, and further work relating bulk transport to hole cleaning is possibly fruitful.



Pressure loss prediction for bore hole cleaning



Pressure loss prediction for pneumatic conveying systems (Darcy-Weisbach)

Figure 1.9: *The models for pressure drop prediction in drilling operations are similar to pressure loss prediction for pneumatic transport.*

In pneumatic conveying (Fig. 1.9-right), the Darcy-Weisbach equation is widely used as a fundamental equation for the pressure drop of single phase flow:

$$\Delta P = \frac{4 f \rho_a {v_a}^2 L}{2D} \tag{1.1}$$

where ρ_a is the air density, v_a is the air velocity, D is the pipe diameter and L the pipe length.

The friction factor f is expressed as $f = 0.316/Re^{0.25}$, Re being the Reynolds number. Several models exist for extending Eq. (1.1) to multiphase flow by suitable modifications of the friction factors [34].

During drilling operations, parameters like the shear stress acting on the cuttings bed, effectively meaning the pressure loss ΔP_f, was studied by Ozbayoglu et al. [35] and by Saasen et al. [36]. Additional effects such as pipe rotation or cuttings size impact on hole cleaning have also been described [37]. From these studies, several models were developed to enhance the understanding of hole cleaning [38, 39, 40]. These models also have the potential of being developed to study weighting material sag as most of the physics involved is similar. Furthermore, the effect of particle morphology, density and PSD has been studied in respect of hole cleaning, elements that will be further described in Ch. 2 as having an impact on sag performance as well [41].

Chapter 2

Sagmodelling

As described in Ch. 1, particles settling in fluids has an impact on many aspects of a drilling operation and a more comprehensive understanding of the settling process is needed to address these challenges. This chapter briefly introduces common settling models and look into the suspension's properties and how they can be altered to minimize the settling rate. As will be noticed, the basic settling models illuminates the parameters influencing the stability of the systems, but do not account for other mechanisms such as particle interactions that complicates the settling process significantly.

2.1 Settling fundamentals

To investigate the fundamental processes during particle sedimentation, we consider a particle of mass m and density ρ_p, as shown in Fig. 2.1, settling in a fluid of density ρ_f. The particle is subjected to a net gravitational force, F_g, where buoyancy from the displaced fluid has been deducted, and the frictional drag force F_d. From Newton's second law we have:

$$F_g - F_d = m\frac{dv}{dt} \tag{2.1}$$

where v is the settling velocity at time t.

Performing dimensional analysis for a falling sphere of radius r, settling in a Newtonian fluid at velocity v, we realize that the drag force is a function of the Reynolds number given by:

$$Re = \frac{v2r\rho_f}{\eta} \tag{2.2}$$

where ρ_f is the density of the fluid in which the particle is suspended in, and η is the apparent viscosity of the same.

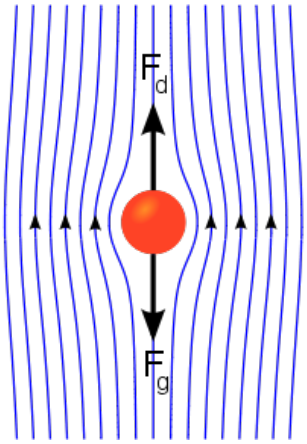


Figure 2.1: *Single particle of density ρ_p and radius r is subjected to gravitational forces F_g and drag forces F_d [43].*

The frictional drag force, F_d in Eq. 2.1, will increase with particle velocity until the particle reaches its terminal velocity, v_t, where the acceleration, $\frac{dv}{dt}$, is zero.

When the terminal velocity is reached, the drag force reaches its equilibrium and is expressed by:

$$F_d = \frac{1}{2} C_D \rho_f v_t^2 A \tag{2.3}$$

where v_t is the terminal settling velocity, ρ_f is the fluid density, A the particle surface area and C_D is a constant called the *drag coefficient*. For given fluids, the drag coefficient depends weakly on particle velocity, but highly on its morphology.

For a spherical particle of radius, r, the drag is given by:

$$F_D = 6\pi\eta r^2 \tag{2.4}$$

where η is the fluids apparent viscosity. From this, Sir Gabriel Stokes [42] determined the terminal settling velocity of a sphere to be:

$$v_t = \frac{2r^2 g(\rho_p - \rho_f)}{9\eta} \tag{2.5}$$

The validity of these equations for drilling fluids is poor as they assume that each particle is settling alone in an infinite volume of fluid, and so applies only for very dilute suspensions (particle concentration $< 1\%$). Likewise, the expressions assume spherical particles and Newtonian fluid. In particular the latter make modeling of the settling velocity of our systems a challenge. The settling velocity, as a function of the Reynolds number, means that Stokes' law is only accurate for

settling at low Reynolds numbers (< 1), so called *creeping flow* [43]. For small particles (< 1 μm), particle-particle interactions can dominate the gravitational force [44] disturbing the flow-field around the settling particle. The resulting inter-particle forces are discussed in Ch. 3.

2.2 The effect from particle interactions and morphology on settling

The expressions derived by Stokes provide information of settling for a single spherical particle settling in an infinite expanse of a Newtonian fluid. As the particle's morphology changes or as the settling particle is influenced by other particles in the suspension, the settling velocity changes significantly. Felice and Pagliai describes interactions of spheres settling in suspensions of other spheres [45, 46]. Their work is based upon and confirms to a large extent the findings from Batchelor [47] for particle settling in dilute suspensions of monodisperse particles. Furthermore they also performed experiments that confirm the settling models given by Richardson and Zaki [48] that derived a linear expression for the settling velocity of a sphere as a function of the volume concentration, ϕ, of other spheres in a suspension. As these expressions are more relevant for weighting material settling, the following section describes these in more detail.

2.2.1 Settling in dilute suspensions of monodisperse particles

The disturbance in the flow field around an isolated particle drops off on the length scale of the order of the particle radius. For low particle volume fractions, ϕ, of monodisperse particle i.e. particles of same size, the number of interacting particles is directly proportional to the volume fraction. Likewise, the probability of finding additional particles acting within two radii of a given particle is proportional to ϕ^2. The relationship between average settling velocity, v, of interacting particles and the sedimentation velocity v_0 of hard spheres at infinite dilution, was developed by Batchelor [47] and is given by:

$$\frac{v}{v_0} = 1 - 6.55\phi + \varphi(\phi^2) \tag{2.6}$$

This expression includes only effects from long-range electrostatic repulsion forces occurring in suspensions of charged particles and how this repulsion results in a reduced average settling velocity, v. This decrease in settling velocity is mainly due to the cumulative backflow of displaced fluid and neglects effects from particle-particle interactions.

For bi- and polydisperse solutions, the picture is more complex. Work has been performed using force balance derived from the Bernoulli equation to develop a flux balance model to determine the settling rate of a polydisperse

solution [49]. Comparison between this model and experimental data showed that the model underestimates the initial settling rates.

2.2.2 The Hindered Settling Mechanism (HSM)

Eq. (2.6) given by Batchelor [47] is not directly relevant for our systems although it has been confirmed both analytically and evaluated numerically [50]. For particles settling in suspensions, the *hindered settling mechanism (HSM)* describe better the behavior as they account for particle collisions that reduces the overall settling velocity. Many expressions have been proposed for mono- and polydisperse suspensions [51, 52]. The empirical models prepared by Richardson and Zaki [48] are the best known models within the drilling fluid industry for describing the hindered settling mechanism. These use a basic description of the settling process [53] which is denominated as the individual cell model. In this model all particles settle independently of neighboring particles inside equally sized cells of equally sized fluid columns. The hindered settling velocity, v_h, is given as:

$$v_h = v_t^m = v_t(1-\phi)^m \tag{2.7}$$

where v_t is the free particle terminal settling velocity, ϕ is the particle volume concentration and m is an exponent that by Richardson and Zaki was empirically determined to be 4.65. A suspension like a drilling fluid is formed by mechanical agitation, which would be expected to form a random distribution of particles and/or emulsion droplets. Often the weighting agents form aggregates due to inter-particle forces with resulting increased settling rate compared to the idealized models.

Some researchers have developed expressions for particles with a continuous PSD [54, 55, 56]. All of these are based on either numerical modeling or experiments that do not represent settling in drilling fluids well as they use idealized model systems, but are still important in order to determine which parameters are essential for settling.

2.2.3 Particle shape and drag coefficients

Except for a few settling models such as those given by Perrin [57] for ellipsoids settling in Newtonian fluids, few include the effect from particle morphology on settling rate. Although the majority of suspensions contain particles of almost random shape, this is often neglected to have an effect on settling rate. The drag force given in Eq. (2.3) is certainly influenced by the particle shape, i.e. the projected area of the particle. Fig. 2.2 visualizes this effect by describing how particles of same mass, density and total surface area will settle at different rates as a consequence of their shape. For asymmetric shapes, i.e. shapes other than spheres, cubes etc., the projected area of the particle is also dependent on the orientation of the shape as is also shown in Fig. 2.2.

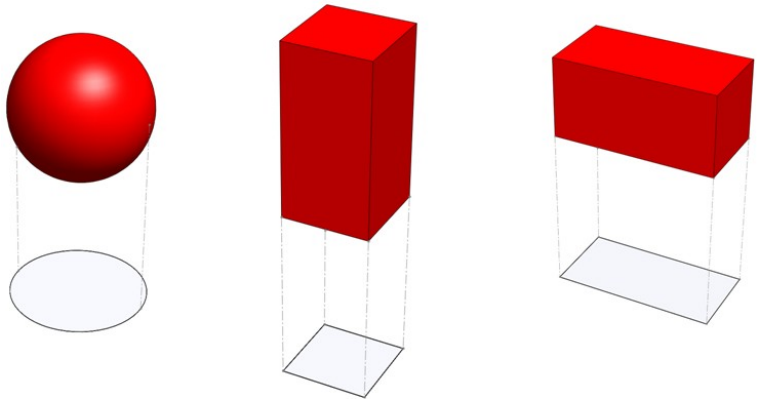


Figure 2.2: *The drag force is a function of the projected area. This is here illustrated by two shapes of equal volume and mass, but with a widely differing projected area . The projected area, i.e. drag force also vary as a consequence particle orientation. Courtesy: Optipro.*

In automotive and aircraft industries, the drag coefficient, C_D, plays a significant role in the design phase. Fig. 2.3 shows drag coefficients for various shapes. The drag coefficient is not an absolute constant for a given body shape. It also varies with the particle's settling speed i.e. the Reynolds number. A smooth sphere falling in air has a C_D that varies from about 0.47 at laminar conditions to 0.1 at turbulent conditions.

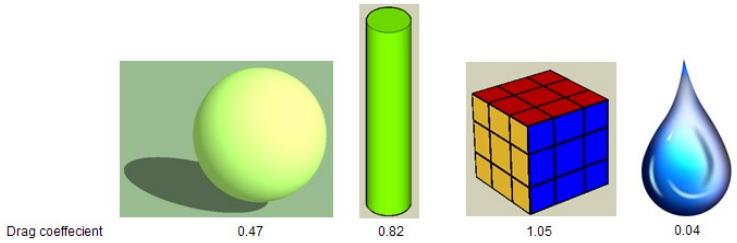


Figure 2.3: *Measured drag coefficients for various shapes falling in air.*

Following the work of Stokes, several models have been introduced that determines the drag coefficients as a function of Reynolds number. Heider and Levenspiel [58] derived, through nonlinear regression from an extensive set of datapoints, an expression for the drag coefficient for settling in Newtonian fluids:

$$C_D = \frac{24}{Re}(1 + 0.186Re^{0.6459}) + \frac{0.4251}{1 + \frac{6880.95}{Re}} \tag{2.8}$$

which gave a good approximation for Re$< 2.6 \times 10^5$.

More recent settling models as given by Pinelli et. al [59] and Kelessidis and Mpandelis [60] provides expressions for the drag force based on settling experiments in non-Newtonian fluids using data fitting. Eq. (2.9) is from experiments using various spheres (glass beads, steel, lead) to determine the drag coefficient:

$$C_D = \frac{24}{Re}(1 + 0.1407Re^{0.6018}) + \frac{0.2118}{1 + \frac{0.4215}{Re}} \tag{2.9}$$

which is applicable for $0.1 < Re < 10^3$.

This is based on empirical approximations and applies for settling of a single spherical particle only. Still it visualizes the parameters dictating the settling well.

2.3 Viscosity and sag

Several studies have been performed to determine the rheological properties of ternary systems (solids, dispersed and continuous phase) as drilling fluids are. Barnes et al. [61] showed that the smaller and more monodisperse the droplet or particle size is, the more viscous the fluid will become. Linking this to drilling fluids, the narrower particle or droplet size distribution is, less materials can be used to increase the viscosity of the continuous phase that aids in reducing the settling velocity. Furthermore Oldroyd [62] showed that for an emulsion, viscoelasticity results from the restoring force caused by the interfacial tension between the continuous and dispersed phase. Numerous studies have been performed that attempts to link drilling fluids' rheological properties to sag [9, 10, 11, 12, 13, 63, 64, 65]. Some of these focus on linking standard viscosity measurements measured according to industry standards [4] to sag. Others have a more detailed approach looking into the viscoelastic properties of the drilling fluid that provides more useful information for predicting the fluid behavior. As described in the previous sections, modeling the fluid dynamics involved during particle settling is not straight forward. It is equally challenging to use the fluids' viscoelastic properties to predict settling only as numerous other parameters influencing on settling are not detectable even using highly sophisticated rheometers.

For drilling fluid applications one is often not able to properky describe the boundary conditions that they operate within. Examples of this is the inability to describe effects such as from heat convection, wave transmission during logging operations, flow set-up during casing/liner running, and how these affect for instance the viscoelastic properties of the drilling fluid. One finding in this work confirms the inability to make good correlation between viscosity measurement at high shear rates, i.e. larger than $5.1\,s^{-1}$, and sag stability. This is described in more detail in Ch. 5. Furthermore the particles themselves put up their own shear which will be dependent of their particle size and properties of the fluids that they are suspended in. This will be described in the following chapter.

Chapter 3

Fluid Composition and Sag Performance

Ch. 2 described settling from a pure mechanistical aspect whereas our fluid systems comprise of components that all interact with each other also on a microscopical level. Of significant interest here, are inter-particle forces acting between various particles as well as the interaction between particles and the emulsion in which they are suspended in the case of oil based drilling fluids. Typically this type of interaction is most relevant for systems with particles or emulsions of colloidal size (sub-micron). Sect. 3.1 describes why drilling fluids fall into the colloidal dispersion category. The section also includes a theoretical description of the inter-particle forces, and how they influence fluid behavior. In Sect. 3.2 it is described why oil based drilling fluids often are more complex to characterize than water based. The nature of emulsions and how they interact with solids is a part of this discussion. During the drilling process, the properties of the drilling fluid are influenced by how the components of the circulating system are operated. Sect. 3.3 describes the resulting effect on the fluids' sag potential.

3.1 Drilling Fluids as colloidal systems

Colloidal systems are made when a substance A is insoluble *(dispersed phase)* in another substance B (*dispersion medium)* and where A is broken down into small entities in the size range of 1 nm - 1 μm. Several types of colloidal dispersions exists, and their designation is dependent on the type of dispersed phase and dispersion medium. The systems dealt with in this work, are called *colloidal dispersions*, where a solid is dispersed in a liquid. Oil based drilling fluids are furthermore based on an *emulsion*, where a liquid is dispersed in another liquid. Freundlich [66] divided these colloidal dispersions into two classes; *lyophilic* (solvent loving) or *lyophobic* (solvent hating), dependent of whether the system

can be re-dispersed after having been dried out or not. For lyophilic colloids, the stability results from the solution itself being thermodynamically stable. For a lyophobic dispersion, the attractive van der Waals force, causes the particles to aggregate if they come close to each other. Nevertheless, additional forces exist that prevents coagulation.

The solid phase in drilling fluids are weighting agents such as barite, ilmenite, hematite or manganese tetraoxide. Solids from the drilled formation or other particles added for e.g. fluid loss control (see Ch. 1) also contributes to the solid phase. Typical size distributions of different weighting agents, are shown in Fig. 3.1. As can be observed, the weighting agents have varying portions of particles that fall into the sub-micron size range. This means that the solids have a high surface to volume ratio that makes the inter-particle forces strong, in some cases stronger than the gravitational force.

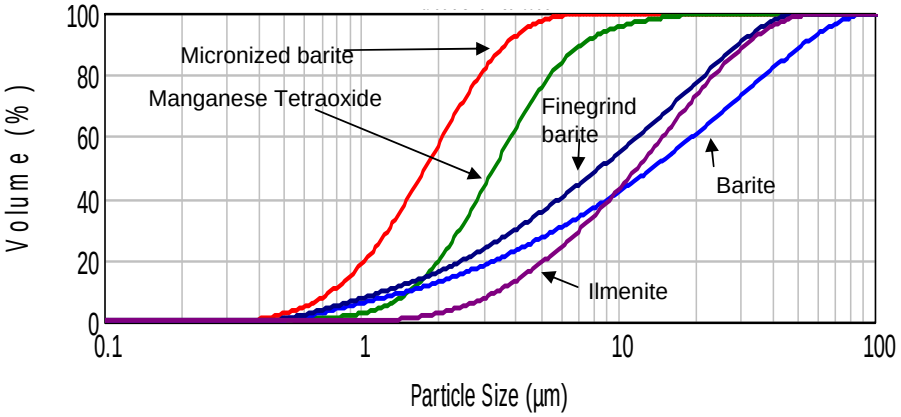


Figure 3.1: *Particle size distribution of various weighting agents. Measurements are made using laser diffraction and is here given as cumulative particle volume % of particles for each size range. Courtesy: Z.Ibragimova.*

To determine the net forces acting between the particles and between particles and internal water droplets, one needs to know the inter-particle distance (surface to surface), H, in the drilling fluid. This can be estimated based on the assumption of a true homogenous suspension and spherical particles of average diameter, D_{50}, of 15 μm. As a model fluid a conventional oil based drilling fluid is used which has a particle content providing a fluid of density of 1580 kg/m^3. The complete composition of this fluid is given in Table 3.1.

Table 3.1: *The fluid composition to make up 350 ml of a model oil based drilling fluid used for settling experiments.*

Component	**Amount in 350 ml fluid**
Base oil	268 ml
$CaCl_2$	78 ml
Primary emulsifier	11.7 ml
Secondary emulsifier	3.9 ml
$CaOH_2$ (Lime)	11.05 g
Organophilic clay	7.15 g
Fluid loss control agent	5.2 g
Barite	266.8 g

To obtain this fluid density, the weighting particle content is 762.4 kg per cubic meter of drilling fluid. Based on an average particle size of 15 μm, 1 m^3 of fluid contains $N = 1.0272 \times 10^{14}$ particles. If one then splits this 1 m^3 into N equal cubes, each containing the a single particle as visualized in Fig. 3.2, one estimates the inter-particle distance, H=6.35 μm.

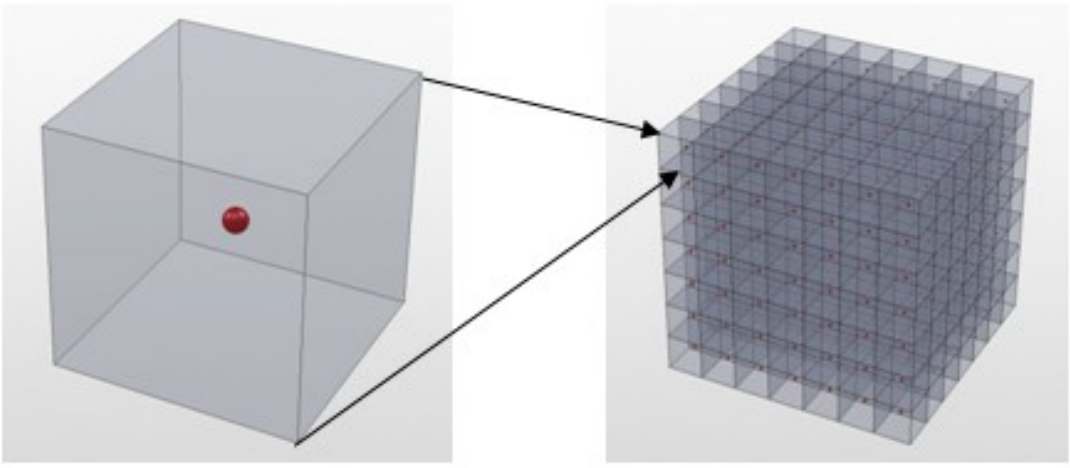


Figure 3.2: *To calculate the inter-particle distance for particles in* $1\,m^3$ *of the model drilling fluid this is split into* 1.0272×10^{14} *cubes which equals the number of particles. (Courtesy: OptiPro and Hodne [67]).*

This distance is linearly dependent on the particle size, as shown in Fig. 3.3. That is, by splitting the particles in two, the number density of particles doubles and the inter-particle distance (center-center) is halved. Using the model fluid described in Table 3.1, this means that by reducing the average weighting agent particle size from 15 μm (API barite) to 7.5 μm, the inter-particle distance is reduced from 6.4 μm to 3.2 μm. This illustrates how grinding of particles results in significantly increased particle-particle interactions due to the increased surface area, which can have operational consequences. Note that this example describes the inter-particle distance for the weighting agent particles only and excludes other particles that typically are incorporated a drilling fluid.

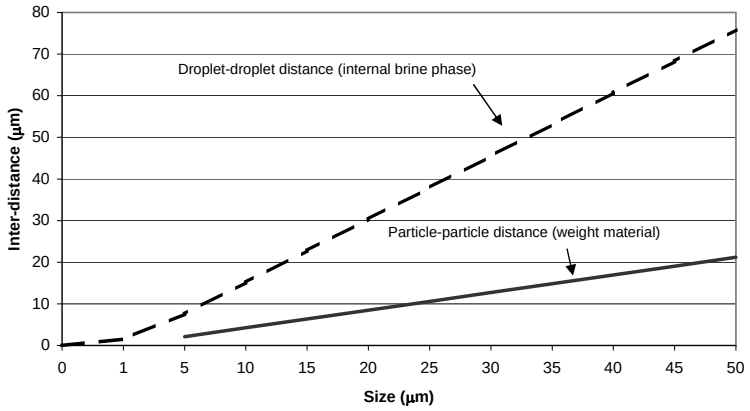


Figure 3.3: *The distance between particles situated in a fixed model fluid volume (here: 1000 ml). Example: If the average particle size of* 40 μm *is cut back to* 20 μm*, the number of particles doubles and the inter-particle distance is half. Similarly the inter-droplet distance for an emulsion based fluid is also given.*

In this figure, the inter-brine droplet distance is also shown for the same fluid composition. The distance between water droplets in the fluid is estimated to 2.3 μm based on a water volume of 150 liter per cubic meter of drilling fluid and an average droplet size of 1 μm.

3.1.1 Attractive forces- Hamaker theory

The effect of attraction between two bodies separated by a distance R was already discussed in 1687 by Sir Isaac Newton in his *Principia* [68] where he stated that the resulting force between two bodies was proportional to R^{-n} where $n > 6$. In 1873 van der Waal [69] developed the important equation for the state of a gas founding the basis for further studies of interactions between molecules and larger embodiments. He found that at large distances the effective force between the molecules is substantial.

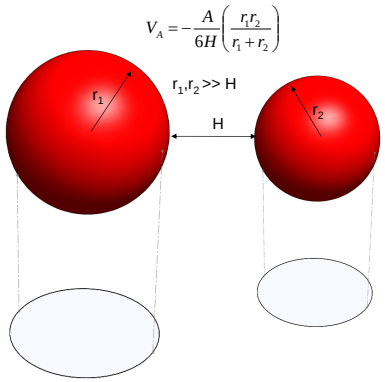


Figure 3.4: *The non-retarded potential energy between pairs of solid surfaces of various geometries based on calculation by Mahanty and Ninham [72].*

For larger particles, there are two approaches to the prediction of the interaction between approaching bodies as a function of their separation distance; the microscopic approach developed by Hamaker [70] in 1937, and the continuum macroscopic approach developed by Lifshitz [71] in 1955 which treats each interacting material as a continuum with certain macroscopic electrodynamic properties of the interacting materials such as dielectric permittivities.
Hamaker developed theories for calculating the attractive interaction free energy between bodies of different geometries based on pairwise summation of intermolecular forces. For two spherical particles of radius r_1 and r_2 with a centre-centre distance R, the attractive interaction potential is, according to Hamaker [70], given as:

$$V_A(R) = -\frac{A_{12}}{6}\left[\frac{2r_1r_2}{R^2-(r_1+r_2)^2} + \frac{2r_1r_2}{R^2-(r_1-r_2)^2} + \ln\frac{R^2-(r_1+r_2)^2}{R^2-(r_1-r_2)^2}\right] \quad (3.1)$$

Here the Hamaker constant, $A_{12} = \pi^2 C\rho_1\rho_2$, is introduced where C is the interaction constant while ρ_1 and ρ_2 are the number densities of particle 1 and 2 respectively. For spherical particles where the distance between the particle surfaces, $H \ll r_1, r_2$, the Derjaguin approximation [73] can be used. The expression for the non-retarded van der Waals interaction free energy then reduces to:

$$V_A = -\frac{A}{6H}\left(\frac{r_1r_2}{r_1+r_2}\right) \quad (3.2)$$

where $H = R - r_1 - r_2$. Fig. 3.4 illustrates the concept of non-retarded free energy of two spheres [74].

The van der Waals interaction energy, V_A, given from Eq. (3.1) assumes that the particles are interacting in vacuum. For typical drilling fluids, the particles

are surrounded by a fluid which changes the Hamaker constant by as much as one or even two orders of magnitude [73].

For barite suspended in water or oil, the Hamaker constant is not found in the literature, and the attractive forces are therefore not estimated here. For visualization of the resulting attractive force V_A/A_{12}, one can consider two particles of 10 μm and 15 μm respectively and plot the resulting attractive force as a function of inter-particle distance, H. This is shown in Fig. 3.5.

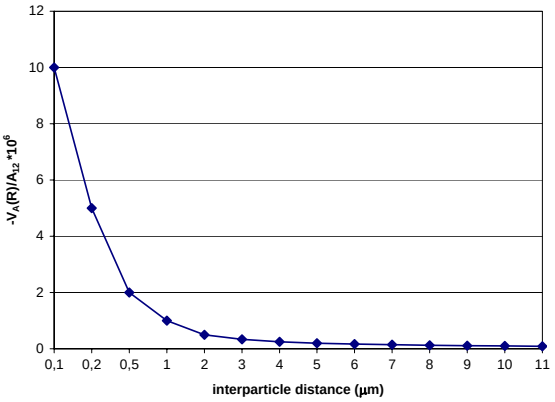


Figure 3.5: *The resulting attractive force between two particle of* 10 μm *and* 15 μm *as a function of inter-particle distance.*

From Eq. (3.2) and looking at particles of radii r_1 and r_2 and taking into account some boundary conditions, it is noted that the interacting energy is dependent on size and size distribution. Assuming equal average particle size, D_{50}, a broader particle size distribution, i.e. large difference between r_1 and r_2, increases the interaction energy. Similarly, keeping the size distribution constant, i.e. shifting the average particle size to coarser material, also increases the interaction energy.

Considering the same model system described in Table 3.1, but changing to an average particle size of 2 μm, the inter-particle distance is 7-800 nm which makes these systems subjected to van-der Waal forces in addition to repulsive forces, as are described further in the following section.

3.1.2 Repulsive forces

The repulsive energy potential origins from the electrostatic double-layer interactions acting when two colloidal particles approach each other. Particles suspended in water carry in most cases an electrical surface charge. The charged surface will change the ion distribution in the surrounding interfacial region, and ions of opposite charge (*counter-ions*) will be attracted to the region closest to the surface. Also, the particles of the same charge as the surface charge

will be repelled so a solution of counter ions will be present around the particle. Fig. 3.6 illustrates the resulting double layer surrounding a particle. The inner region of counter-ions is called the *Stern layer*, while the more loosely bound ion layer outside is called the *diffuse layer*. Outside the diffuse layer, the ion concentration is in equilibrium with the solution.

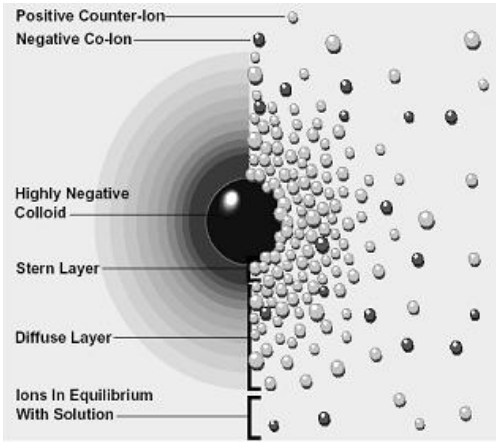


Figure 3.6: *Visualization of the electrical double layer surrounding a charged particle or emulsion droplet. Courtesy: L.A. Ravina, Zeta-Meter, inc. Long Island City, NY.*

The potential energy of the electrical double layer decreases exponentially with distance from the particle surface, with a decay length called the *Debye* length, κ. The strength of the surface potential is related to the surface charge and the thickness of the double layer. As one leaves the particle surface, experiments have shown that the potential drops off roughly linearly in the Stern layer and then exponentially through the diffuse layer, approaching zero at the imaginary boundary of the double layer as shown in Fig. 3.6 and 3.7.

For two identical spherical particles of radius r approach each other, and where $\kappa r \gg 1$, which is the case for the majority of weighting agent particles, the repulsive potential energy is, according to Verwey and Overbeek [75]:

$$V_R = 2\pi\epsilon r\psi_0^2 \ln[1 + \exp[-\tau(s-2)] \tag{3.3}$$

where ϵ is the *relative permittivity* of the fluid expressing the ability of the fluid to reduce the force influence between two charges, and ψ_0 is the electrostatic surface potential. Here $\tau = \kappa r$ and $s = R/r$ where R is the center-to-center distance.

The effective Stern surface potential of particles can only be estimated indirectly. In practice one measures the electric potential at the boundary between the moving particle and the liquid. This boundary is called the slip plane, and is usually defined as the point where the Stern layer and the diffuse layer meet.

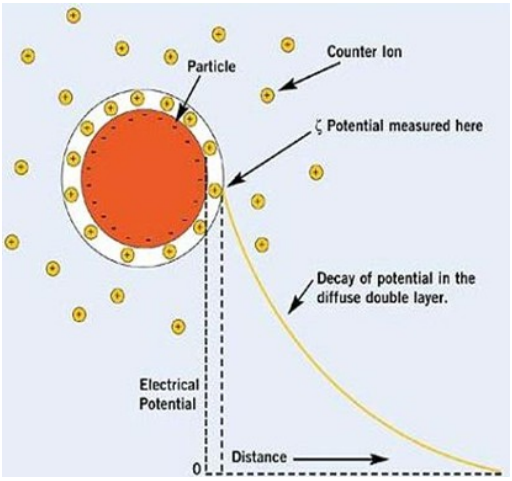


Figure 3.7: *The electrical double layer potential decays as a function of distance from the colloid. The electrical potential at the interface of the Stern and diffuse layer is called the zeta potential, denoted by the symbol* ζ*. Courtesy: L.A. Ravina, Zeta-Meter, inc. Long Island City, NY.*

The Stern layer is considered to be rigidly attached to the colloid particle, while the diffuse layer is not. This electrical potential, at the interface between the Stern and diffuse layer is called the zeta potential and is denoted by the symbol ζ.

Different techniques are available, based on different electrokinetic phenomena, to measure the zeta-potential. One technique uses acoustic response of particles moving in fluids of different densities. This instrument is called an *Acoustosizer*. By applying an alternating voltage to the particle suspension, the particles will start oscillate at rates dependent on particle size, kinematic viscosity of the suspending fluid, and the frequency of the applied field. This effect, called the Electro kinetic sonic amplitude (or ESA), was first used actively by O'Brien [76]. The oscillating electric field causes the particles to move due to their surface charges, and it is this oscillation that generates the sound waves. The sound has the same frequency as the applied field and is usually in the MHz range. The ESA signal is only generated if the particles have a charge and if they differ in density from the surrounding medium. As the forces acting are relatively low, the particles must also be sufficiently small to undergo significant motion ($< 10\,\mu$m).

The first step in determining size and zeta potential from the ESA is determination of the particle motion. Due to the oscillating electric field, the particles move with a sinusoidal velocity. If the frequency of the field is sufficiently high, inertia forces will cause a time delay (phase lage) of the particle motion relative to the applied electric field, and the particle size can be determined as illus-

trated in Fig. 3.8. A complete particle size distribution is determined by using 13 different frequencies of the applied electric field. If the size is already known from the time delay analysis, the velocity amplitude can be used to get the zeta potential.

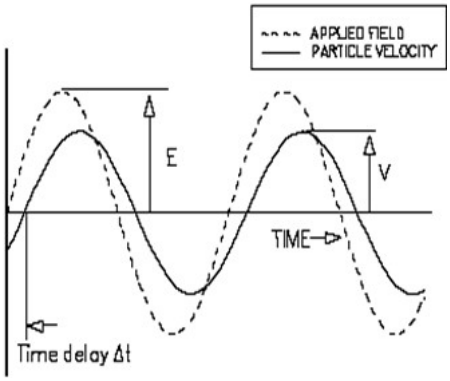


Figure 3.8: *The Acoustosizer sets up an alternating electric field that makes particles in the suspension move. The time delay provides information of the size of the particles as well as of the surface charging strength (zeta-potential. Courtesy: L.A. Ravina, Zeta-Meter, inc. Long Island City, NY.*

Smoluchowski [77] was the first to properly derive an equation to calculate the zeta potential from electrokinetic mobility:

$$\mu_d = \frac{\zeta \epsilon}{\mu} \tag{3.4}$$

where ζ is the Smoluchowski zeta-potential, ϵ is the relative permittivity and μ is the kinematic viscosity ($= \eta/\rho$) of the fluid.

Eq. (3.4) can be used for $\kappa r < 100$, but the values of ζ will then be somewhat high for potentials above 50 mV. For drilling fluids where $\kappa r > 300$ the equation yields accurate potential values.

By experience, zeta-potential below an absolute value of 30 mV indicates particle coagulation or aggregation [44].

Table 3.2 shows the results [XXII] from measurements of the ζ-potential for various weighting materials. For barite and ilmenite, these measurements were performed with the particles suspended in distilled water with a particle concentration corresponding to a typical drilling fluid density of 1500 kg/m^3. The measurements for manganese tetraoxide are from Hodne et al. [78], and were performed with a particle volume concentration of 0.067 %. The measurements for all weighting materials show that these will form aggregates if not specially treated, which is in accordance with both field experience and laboratory observations.

Table 3.2: *Smoluchowski zeta potential of various weighting materials in distilled water [XXII], [78].*

Material	ζ- potential (mV)
Barite	-2.07
Ilmenite	-1.61
Manganese tetraoxide	-1.55

3.1.3 DLVO-theory

By summation of the repulsive and attractive forces, the total interaction potential between the particles is given by:

$$V_T = V_A + V_R \tag{3.5}$$

where V_A is the attractive van der Waal forces, and V_R are the sum of the repulsive forces. The summation of the attractive van der Waals and the repulsive double-layer forces is the essence of the DLVO theory, named after Derjaguin, Landau, Verwey and Overbeek. This estimates the resulting force acting between particles to determine in what state they will appear. Depending on the ionic strength of the bulk solution, the resulting forces can give rise to three different states for the particles in a suspension:

i) Dispersed; at low ionic strength and high surface potentials we get a stable dispersion.

ii) Flocculated; at moderate ionic strength and medium to low surface potentials the suspension will tend to flocculate.

iii) Coagulated; at high ionic concentrations and relatively low surface potentials the particles coagulate.

The net interaction energy between particles as a function of inter-particle distance is plotted in Fig. 3.9, and from this the state of particle in the suspension can be detected. If the net interaction energy is positive, an energy barrier is formed and the particles are kept dispersed. If the net interaction energy falls into the negative attractive energy side, the particles will start to flocculate. In the inner region of strong attractive forces, called the energy trap, the particles are trapped together due to strong van der Waal forces forming coagulates.

The effect of electrolyte is also discussed in conjunction with DLVO-theory [44] and was later investigated by Greenwood [79]. As the ion content in the surrounding fluid increases, the electrical double layer is compressed and the particles starts interacting more strongly with one another. Field experience and laboratory experiments [XXVI] have shown that even drilling fluids with weighting agents specially treated to obtain better stability, are highly influenced by

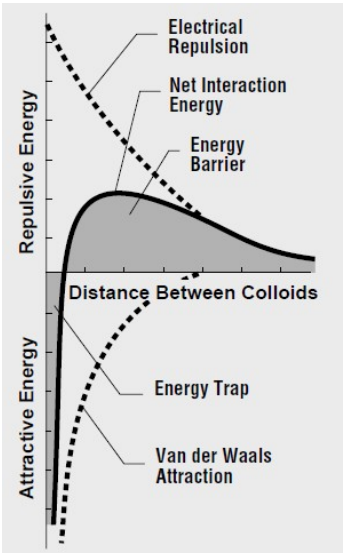


Figure 3.9: *Summarizing the attractive and repulsive forces based on DLVO-theory, a net interaction curve is formed. Courtesy: L.A. Ravina, Zeta-Meter, inc. Long Island City, NY.*

the electrolyte concentration. This can cause particle coagulation resulting in an unstable fluid system.

3.1.4 Stabilization of drilling fluids

The emulsion quality can be monitored by electric stability measurements. Industry standards [4] describe how to measure the "dielectric break-down" voltage of the invert emulsion between two electrodes spaced at a distance apart. The breakdown is defined as the voltage at which the current reaches a critical value and it is an indirect measurement of the emulsion stability of the system. Drilling fluids are often specially treated to provide good emulsion stability. Two mechanisms are exploited for stabilization of these systems:

- the particles or droplets are given an electrical charge that makes them repel each other. This method is described as *electrostatic stabilization*.
- the particles or droplets are coated with an absorbed layer of some materiel that prevents them from coalescence as they approach each other. This method is known as *steric stabilization*.

Of these mechanisms, steric stabilization works best for oil based fluids. By coating the weight material particles with e.g. a polymer, these are prevented from aggregation, providing a more stable suspension. Studies made by Growcock et al. [80] on drilling fluids, show that the breakdown voltage is dependent

of solids type and concentration. This can also be interpreted as steric stabilization of the emulsion.

The brine droplets in the internal phase of oil based drilling fluids are prevented from coalescing by the particles used in the fluid system. This is in agreement with observations made by Sztukowski et al. [81], who showed that *solids* can stabilize emulsions. The stabilization is achieved by either adsorbing solids onto the water/oil interface or by adsorbing onto a film already established by a component such as a surfactant.

3.2 Emulsion properties and sag stability

The emulsion stability depends on element such as type of emulsifying agent, salt type and concentration and on the oil to water ratio. The internal water, or more precisely, the brine phase, contains salts like calcium chloride ($CaCl_2$), calcium bromide ($CaBr_2$), sodium formate (NaCOOH), cesium formate (CsCOOH) or ammonium calcium nitrate ($NH_4Ca(NO_3)$). The selection of salt and concentration is made to match the water phase salinity in the formation and hinder waterflux into or out of the formation to avoid wellbore instability. The brine phase is also used to provide fluid density, avoiding the use of particulate material that can either settle or plug production when running screen completions [82].

The emulsion stability is also dependent on brine droplet size and the viscosity of both the brine phase and oil phase. For a well mixed and sheared emulsion, the droplet size is on average approximately 1 μm. Keeping everything else constant, the shear energy applied when preparing the fluid, determines the internal phase droplet size, and hence the emulsion stability. A poorly sheared emulsion can have a droplet size in the order of several tenths of microns. Fig. 3.10 shows the droplet size in an emulsion used in an oil based drilling fluid having been prepared with low shear energy.

Various techniques for preparation of the emulsion exists, but dispersion by a mechanical grinding process is most commonly used for drilling fluids. A stable emulsion is produced by use of high pressure pumps combined with shear guns. Fig. 3.11 shows such a system where the fluid flow is directed towards a steel plate, where the water droplets are broken up into smaller droplets and thereby increasing the emulsion stability.

These systems have certain disadvantages like being relative expensive, heavy and requiring pump capacity, which is often limited at a rig. Equipment using ultrasound to create stable emulsions are used in e.g. the food industry [83], eliminating the need of heavy equipment. For drilling fluids, this technique has not been widely used when mixing emulsions, but it has been applied for use in the separation of cuttings and fluids.

In Ch. 2 it was described how drag force can be estimated for particles. Similarly the drag force can be estimated for the emulsion droplets. Frumkin and Levich [84] determined the drag force for an emulsion droplet to be:

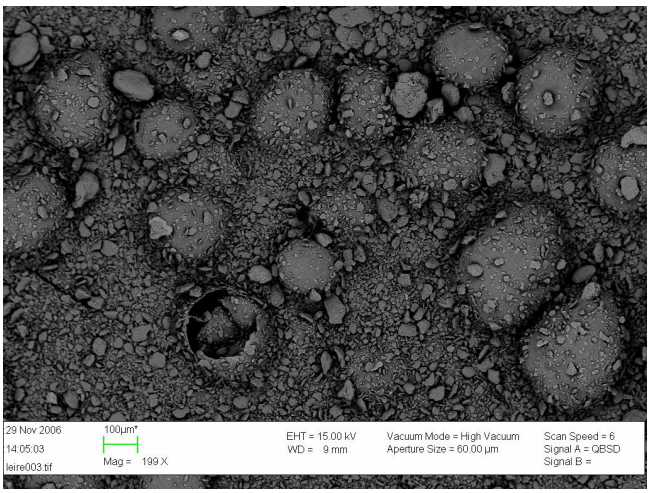


Figure 3.10: *The droplet size of a poorly sheared emulsion shows a droplet size in the range of 100 µm.*

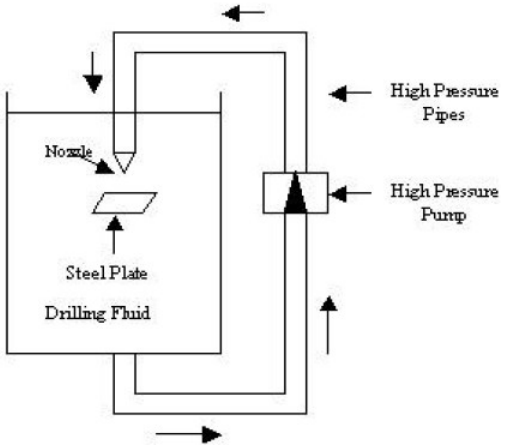


Figure 3.11: *Shearing guns where a high pressure pump injects the fluid flow through a nozzle towards a steel plate breaking the emulsion. The pressure drop over the nozzle should be minimum 50 bar.*

$$F_D = 6\pi r^2 (\frac{3\eta_1 + 2\eta_2}{3\eta_1 + 3\eta_2})\eta_2 \tag{3.6}$$

where r is the droplet radius, η_1 and η_2 are the viscosites of the brine and the continuous phase respectively. Eq. (3.6) assumes that the interface between the droplet and the continuous phase is perfectly fluid, and not affected by any

surface interactions. For drilling fluids this is mostly not the case, as the surface of the brine droplet is coated by a surfactant making the droplet behave almost like a rigid sphere. This implies that Stokes' law given by Eq. (2.5) is applicable also for brine "droplets" settling in the continuous oil phase.

3.3 Process Control and Sag

The complex nature of drilling fluids makes numerical modeling of the sedimentation process inherently difficult. Operational elements influencing the fluid composition, complicates the picture even more. The drilling process itself involves numerous other sub-processes that have an effect on the drilling fluid quality.

The main components of a typical circulation system, as shown in Fig. 3.12, consists of a mixing system, different pumps, drill string, drill bit and solids removal equipment. Different ways of operating each of these components influences the drilling fluid quality, and hence the sag stability. The following two paragraphs describe how operating two of these components influence on sag performance.

Figure 3.12: *The circulation system for a drilling rig consists of pumps, drill string, drill bit, solids removal equipment, various pits and mixing system. Courtesy: V. Peikli, L.Ims, J.Ø.Ulriksen.*

3.3.1 Structural Breakdown of drilling fluids by imposed vibration

Many sag incidents are related to logging operations, pumping at low rates and/or casing/liner running. During these operations, the structure or mechanism that prevent particle settling can deteriorate, that can explain the increased sag tendency. From other industries, it is known that imposed vibrations can enhance the particle sedimentation rate. Studies of soil erosion and emulsion separation demonstrate how vibrations cause structural breakdown [85, 86]. During drilling and completion operations, the fluid is subjected to vibrations. These can be ultrasonic waves generated when e.g. running USIT-logs, which are ultrasonic logs used determine cement quality, or by imposed vibrations when transmitting data to surface using mud telemetry systems [87, 88]. The drill string itself also generates vibrations that potentially causes structural breakdown of the drilling fluid [89]. The magnitude of these types of vibrations are described by Osnes et al. [90]. These are all operational elements which have not been studied in detail by the drilling fluid industry.

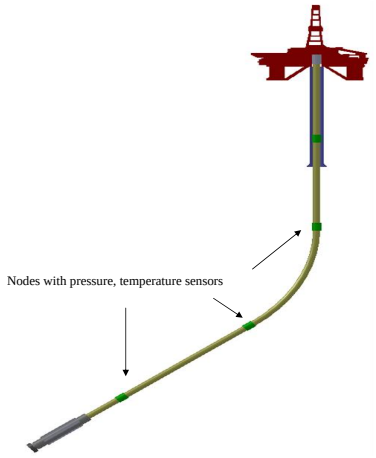


Figure 3.13: *Telemetry pipe opens up new opportunities for logging the status along the wellbore. Courtesy: OptiPro.*

The effect of mud pulse telemetry on sag stability has not been studied either. Results from our investigations, given in Ch. 5, indicate that this can have a significant effect on sedimentation rate. Near future technology using drill string telemetry [91] for data transmission, as illustrated in Fig. 3.13, can eliminate this element as the drilling fluid will not be used actively to transmit data. This technology can also facilitate better detection of the cuttings and weighting material behavior in the well by placing nodes with sensors along the drill string.

3.3.2 Solids Control and Sag

The solids removal equipment serves the function of removing drilled formation from the drilling fluid. The impact from operation of the solids removal equipment on drilling fluid quality and performance, is well known. Several studies have investigated the importance of solid control on hole cleaning, waste management and general drilling efficiency [92, 93, 94]. During the drilling operation, the drilled cuttings and particle components in the drilling fluid, are constantly grinded. Failed operation of the solids control equipment can result in severe build-up of fine material in the drilling fluid. This can cause excessive viscosity which can lead to a lost circulation incident if the formation fracturing pressure is exceeded.

Erratic operation of shakers and centrifuges is in many cases the root cause of numerous failed operations due to this undesired solids build up in the system. In the perspective of better understanding the effect from solids control on sag performance, a dedicated project was set up to address this. The main focus areas in the project was to:

- Increase understanding of how the shaker screen wear arises and the results of screen performance on fluid quality.
- Retrieve control of amount and type of solids recirculated into the borehole by active use of solids control equipment
- Determine the direct effect of solids control performance on sag

The first activity [XX] in this project investigated the true Cutt-point of various shaker screens using a specially developed measuring technique. A polymer based fluid containing a pre-defined sand was circulated over the shaker screen to be tested and the Cutt-point determined from measuring the particles size of the material screened out and the material passing through the screen. Discrepancies of up to 180% (Fig. 3.14) between the Cutt-point claimed by the screen manufacturer and the measured values were discovered. This illustrates the importance of conducting comparison testing of different screens as the resulting Cutt-point influences the amount and type of material being re-circulated to the borehole.

Realizing the importance of process control on fluid quality, the subsequent work [VIII] had the objective of implementing special techniques for optimizing running of shale shakers. This include studies of mechanisms for wear on shaker screens and explains how double deck shakers should be operated to minimize the screen wear. By use of this methodology for a specific field case, 250 times more material was removed from the drilling fluid per shaker screen used than if running using industry recommended practice.

In Ch. 1 it was described how the addition of suitable particles to the drilling fluid could significantly improve the formation strength (Fig. 1.5) [95]. For this approach to work, it is important to establish an optimal particle composition in the drilling fluid. Significant effort has been put by the industry to obtain

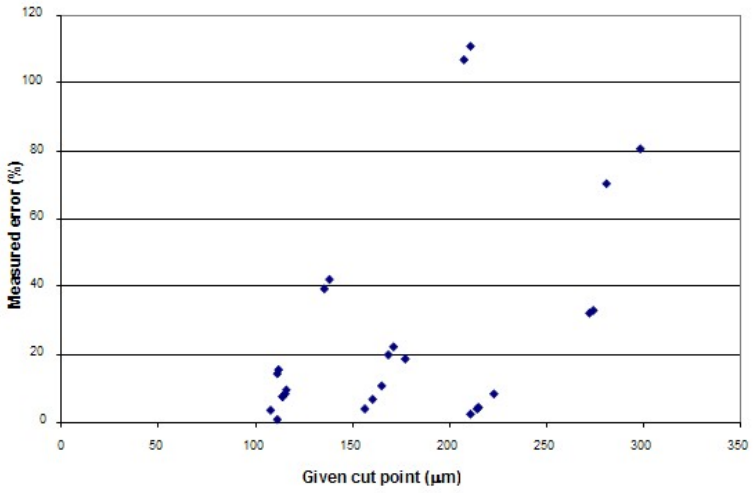


Figure 3.14: *The discrepancy between given Cutt-point by shaker screen manufacturer and measured Cutt-point values [XX].*

the ideal composition of particles to address this effect [24, 96]. Less focus has been put on the practical implementation for how to achieve this in the field. By deploying a unique technique [VII] for running of solids control equipment, one is now able to retrieve control of what particles are being re-circulated to the bore hole. This technique for running of solids control equipment provides

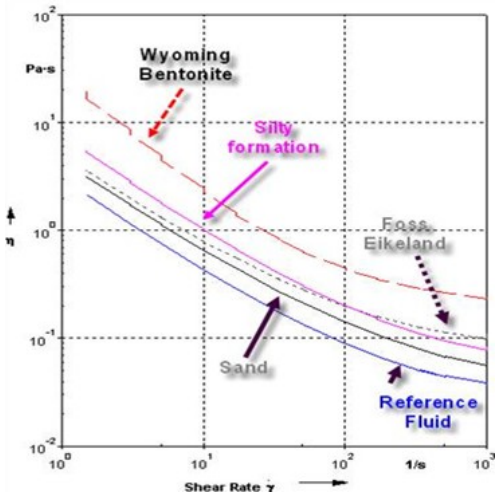


Figure 3.15: *Introduction of different solids contaminants have widely different impact on the fluid viscosity profile [II].*

unique possibilities for future control of the drilling process, but requires specially trained personnel to conduct, or a fully automated control and mixing system [V].

It is well acknowledged that fluid composition plays a significant role on its sag performance. Numerous fluid optimization studies are performed annually addressing issues like formation damage, filtration control, wellbore stability, hole cleaning, etc. [XII], [29], [97]. However, the industry has yet neglected the fact that there is a clear link between solids control performance and sag. The importance of solids control for controlling sag [II] is illustrated in Fig. 3.15. In these experiments equal amounts ($400\,\mathrm{kg/m^3}$) of contaminants were introduced i.e., Wyoming bentonite and sand of equal particle size, resulting in dramatically different viscosity. The different fluid viscosities will equally have different impact on the pump pressure or the equivalent circulating density (ECD).

For sag performance, these results are equally important. A fluid, where the majority of its viscosity is made up from drilled solids, is more likely to show poor sag performance. This will be further discussed in Ch. 5.

Chapter 4

Sag Determination Techniques

For sag detection, several testing methods have been proposed within the industry. These range from simple methods using modified set-up of the standard viscometers used in the field, to large-scale flow-loops with advanced instrumentation for revealing fluid parameters relevant for the sag performance. The following chapter summarizes the methods used in the oil-field industry today with their advantages and disadvantages and describes in detail proposed alternative techniques used in other industries for detecting settling potential. This also includes techniques valid for testing of the basic physics related to sag, not necessary considering the potential for using it as a field test method. Sect. 4.9 describes a technique based on direct weight measurement that we have developed [IX] for continuous sag monitoring. This technique was then used in the majority of the experimental investigations.

4.1 Static sag testing

The most common sag testing method is using steel cells left in a static environment for a specified period of time and at desired temperature. This method is suitable for performing large numbers of tests, but is not simulating conditions such as circulating at low-shear-rates, inclined well bore angle which are also known to provoke sag. The method is crude, giving problems with reproducibility. For this technique, the sag tendency of the drilling fluid is often expressed as the sag factor given by:

$$SF = \left(\frac{MW_{bottom}}{MW_{bottom} + MW_{top}} \right) \tag{4.1}$$

where MW_{bottom} is the density of the fluid at the bottom of the cell and MW_{top} is the density of the fluid at top of the cell as shown in Fig. 4.1.

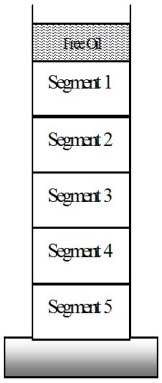


Figure 4.1: *The static sag test is performed by measuring the density of fluid segment 1 and 5 that is placed in a steel cell which is exposed to relevant temperature [I].*

A sag factor of 0.5 means a non-sagging fluid, while fluids with sag factors above 0.52 has been interpreted to have a potential for causing operational problems. As this does not take into account elements like syneresis, i.e. free liquid being displaced to the surface by the settling particles, one realizes that this is not a very good and accurate sag determination technique. Other expressions have been developed to accommodate for such effects [I]. The interpretation to real-life application has shown to be difficult to achieve by using this method and the industry has never recognized this method to become a standard due to its faults.

4.2 Viscometer Sag Tests

The Viscometer Sag Test (VST) was introduced as a low-cost practical on-site test with the intention of reproducing the dynamic settling conditions and linking this towards standard API viscosity measurements such as Funnel Viscosity (FV), yield point (YP) and the 100 rpm reading of a Fann 35 viscometer [98]. The method is used as an indicator of sag to some extent, but the correlation towards field and flow loop-data can at best only be said to be fair [99]. A new modified VST field test using a sag "shoe" [100] has been developed to improve the reproducibility and sensitivity of the standard VST [101]. The idea is that the sloping surface of the thermoplastic "shoe", helps to accelerate settling and to concentrate the weight material into a single collection well at the bottom of the thermocup used when performing standard viscosity measurements. A computational fluid dynamics (CFD)-analysis was used in the design phase to compare the fluid dynamics of the standard VST and the modified version. The results from this method have been compared with results both with the VST and sag flow loop tests with promising results. For expressing the

sag tendency, the "sag register" is used:

$$S_R = exp\left(-k\frac{\Delta MW}{MW}\right) \tag{4.2}$$

where ΔMW is the change in drilling fluid density between two runs relative to the initial density MW. The parameter k is an empirically determined constant that accounts for geometric dissimilarities between the modified VST test and flow loops. This value was estimated to be 10.9 for the modified VST, as would be the case if this test was run in the field, and 50 for the flow-loop tests [101]. A value of S_R of 1.0 will as such mean no sag, while lower values means poorer sag performance.

4.3 Sag Flow Loop

Sag flow loops make the baseline for sag detection and are still considered as providing the most reliable data. The disadvantages with the sag flow loops are their need for sophisticated instrumentation, relatively large fluid volumes and space requirements making them inadequate to use for direct fluid optimization. Even with a flow-loop it is often hard to reproduce downhole conditions such as temperature, hole geometry and effects from drill string rotation. The first real flow loops for the oil industry were developed in the early 1990's in conjunction with hole-cleaning studies where sag was observed in the tests [5]. These tests also confirmed that sag is a dynamic settling problem rather than a static phenomenon and also confirmed the importance of the Boycott effect [6].

Several different flow loops have been developed in order to improve our understanding of the sag phenomenon. Currently all drilling fluid suppliers, several oil field operators and universities are able to provide large-scale testing facilities using flow-loops. Fig. 4.2 shows a schematic of a flow-loop instrumented to determine the dependence of sag from pipe eccentricity and rotation [XXXI].

At the full potential for studying the basic mechanisms of sag may not have been fully exploited using the flow-loops. Applying more sophisticated and accurate monitoring equipment should aid this providing additional information of particle settling under different conditions.

4.4 Dynamic High Angle Sag Test Device

The dynamic high angle test device (DHAST) shown in Fig. 4.3 is a more suitable sized and accurate sag test device compared to flow-loops and viscometers [102, 103].

The instrument is designed to facilitate more downhole-like conditions controlling temperature, pressure and hole angle. In the DHAST a fluid sample is placed in a tube at specified angle and heated to desired temperature. The

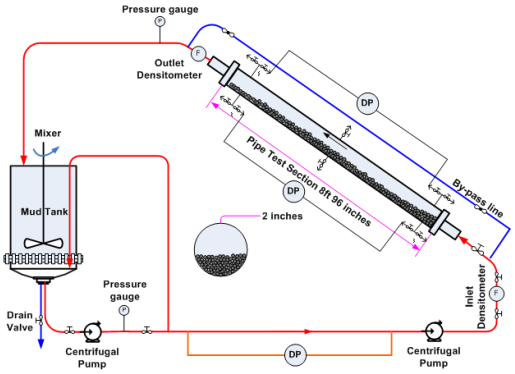


Figure 4.2: *Instrumented flow-loop used to determine sag as an effect of pipe eccentricity and rotation [XXXI]. Courtesy: T. Nguyen.*

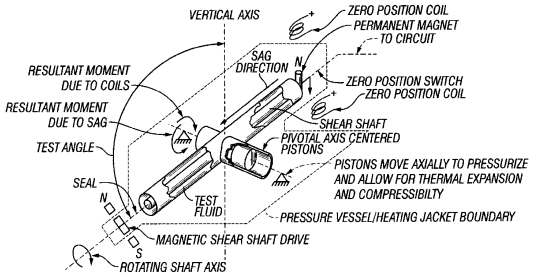


Figure 4.3: *The DHAST measures the change in center of mass providing information of the fluids sag stability [102]. Reproduction from U.S. Patent 6,584,833.*

change in the center of mass is measured indirectly as a change in torque about the pivots holding the tube in place. The torque is measured by energizing external coils so that the upper end of the tube and the shear shaft assembly is pushed back to their initial positions (Fig. 4.3). As the weighting material settles, the change in fluid sample's center of mass moves. This is plotted as a function of time, and fitted to a function of form:

$$X_{cm}(t) = \left(\frac{At}{B+t}\right) \tag{4.3}$$

These fitted parameters both have clear physical interpretation. A is maximum possible shift in center of mass and B is the time taken for the center of mass to reach $A/2$, i.e. the time for half of the material to have settled. It is stated that integrating this function with respect to time, gives the sag coefficient (SC) which indicates the total sag that has occurred within a chosen time interval from $t = 0$ to $t = \tau$:

$$SC = \int_{t=0}^{t=\tau} X_{cm}(t)dt \tag{4.4}$$

The physical interpretation of this expression is not clear. It is stated that if the movement in center of mass is zero, i.e. no sag, the SC will also be zero. Due to the limited volume and geometry of the cell, the SC has an upper and lower limit.

4.5 Ultrasonic measurements for sag detection

Ultrasonic techniques offer potential for fast non-invasive testing, i.e., the equipment is placed outside the flow. This makes possible on-line monitoring of fluid properties, including the particle sedimentation potential. Other industries, especially the food industry, have used ultrasonic measurements for detection of density stratification in fluids or slurries. The technique is based on ultrasound signal reflection being dependent on the sound wave transfer in the base fluid, the longitudinal and transverse speed of sound in the material reflecting the signal as well as particle shape, size and concentration. The principle is shown schematically in Fig. 4.4.

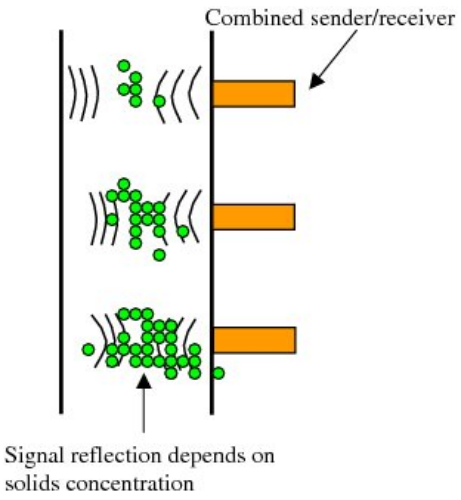


Figure 4.4: *The principle of ultrasonic measurement for sag determination. The amount of reflected energy is dependent on particle concentration. The technique can also be used to determine particle size distribution, flow regimes and displacement efficiency.*

Fort et al. [104] used a single transmitter-receiver pair operating at one frequency to track slurry concentration in a vessel during mixing to determine its homogeneity in the early 1990's. Shen et al. [105] worked with a similar system

employing two opposing transducers to measure the particle concentration profile of a suspension with up to 47 kg/m^3 of glass spheres in water. For higher concentrations, as is needed for drilling fluids (up to 800-1000 kg/m^3), Hipp et al. [106, 107] made a theoretical and experimental study to determine the signal disturbance occurring. They found no linear relationship between concentration and sound attenuation due to multiple scattering and/or particle-particle interactions. This work was based on a core-shell extension of the isolated-particle framework of Epstein, Carhart, Allegra and Haley (ECAH theory), which simulates the sound attenuation in concentrated emulsions and suspensions [108, 109]. The theory emphasizes the challenges using ultrasonic measurement techniques for concentration profiling and addresses these to some extent. Bamberger et al. [1] also discusses the difficulties in signal interpretation using ultrasound for concentration profiling, addressing several issues:

- Viscous losses in the particle boundary layer in the host fluid
- Volumetric expansion and contraction of individual particles
- Scattering of sound by individual particles caused by acoustic impedance mismatch between the host fluid and the particulate material
- Thermal effects associated with contraction or expansion of either constituent
- Particle properties (hardness, shape and size)

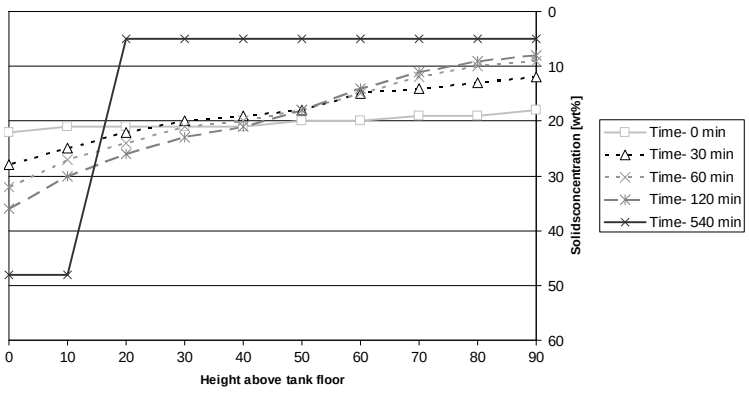


Figure 4.5: *Solids concentrations registered at different levels in a mixing tank as a function of time. As settling occurs, the solid concentration at the lower levels increase and vice versa at the top of the fluid column [110].*

The work resulted in on-line monitoring equipment for determining mixing system efficiency for handling of nuclear waste, measuring density stratification in the mixing tank [79, 110]. Several ultrasonic sensors were placed in the tank

at different heights, and solid concentration profiles were determined. Fig. 4.5 shows the results from one such test, where solid concentrations up to 50 % were successfully detected after 9 hr of mixing.

Several other studies [111, 112, 113] also conclude that ultrasonic instrumentation can be adopted to also measure flow profiles, and from that rheological properties can be determined. An ultrasonic tool has thus a significant potential for characterizing a drilling fluid.

4.6 Nuclear Magnetic Resonance

Nuclear Magnetic Resonance (NMR) is commonly used within the petroleum industry to determine petrophysical properties of the rock. Rismanto et al. [114] showed that this technique also can be used to characterize various drilling fluid properties. One aspect of this work focused on sag detection using a 1D profiling experiment.

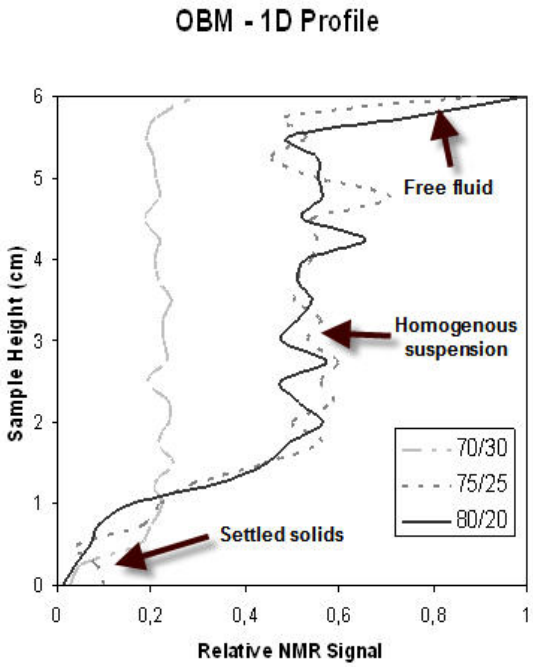


Figure 4.6: *1D profiling experiment for fluid with varying O/W content. Courtesy: Risal Rismanto [114].*

Fig. 4.6 shows the results from a 1D profiling experiment of drilling fluids exhibiting different sag stabilities. Various oil-water-ratios are used ranging from 70/30 and up to 85/15. As shown, the fluid with an O/W-ratio of 70/30

fluid remained stable throughout the 24 hr test period while the fluids with higher O/W-ratios showed substantial sag. Like the ultrasonic measurement, the technique offers the possibility of analyzing the fluid non-invasively. NMR-techniques are not influenced by solids content in contrast to the ultrasonic techniques. It is based on how various atomic nuclei, most often hydrogen, absorb the electromagnetic radio waves. In the work performed, the different the hydrogen content in the different fluids makes it possible to determine the solids concentrations at different heights in the sample.

4.7 Other alternative techniques

In addition to the techniques mentioned in the previous sections, other methods can be used for sag determination. These include:

- Turbiscan; the method uses light scattering measurements to determine the fluid stability. A vertical scan of the fluid sample is performed and a transmission detector monitors the amount of infrared light transmitted through the sample. This provides a solids concentration profile.
- Photooptical detection; as for the Turbiscan, this method measures the amount of light transmitted through the fluid sample. The method has not been tested for sedimentation experiments yet, but has a potential for combining particle sizing and shape with sedimentation measurements.
- Pressure determination; Lewis and Rasmussen [115] used pressure transducers to continuously monitor the fluid density at different levels in a fluid column. The method was also used to determine the particle size distribution of the particles in the suspension.
- Combining rheology and sedimentation; Aas et al., Saasen et al. [12] and Jachnik [13] all used rheometers to detect the particle settling rate in drilling fluids. In addition to determining the settling rate, these techniques provides information of the viscoelastic properties of the suspension and thereby increasing the knowledge of mechanism essential for sag stability.

This list of techniques available for sag determination is far from exhaustive, but shows that the issues of particle settling is relevant for many industries. The significance of particle settling in drilling fluids has lead to initiatives within standardization organizations (here: API) to provide settling determination techniques that could be used in the field. One of the task in this work has been to look for alternative techniques. Of the above mentioned methods, use of NMR and ultrasonics described in Sects. 4.5 and 4.6 respectively, have been proposed. Use of direct weight measurements is another technique developed and used extensively throughout this work and this will be described in detail in Sect. 4.9.

4.8 Process Monitoring for future drilling optimization

To obtain good control of sag stability it is also vital to monitor other relevant drilling fluid properties. Several of the activities included in this work [IV,V,XVIII,XXI] have resulted in equipment and techniques to measure such properties. The information retrieved from these measurements can be used for future sag optimization studies as several of the parameters have an impact on the fluids' stability. Included are continuous on-line measurements of:

- Particle type, content and size distribution; this applies both for particles generated during drilling (cuttings), weight materials and other added particles. In chapter 2 and 3 the importance of each of these elements for sag stability was described.
- Viscosity; in combination with information of solids type and content in the fluid, the continuous on-line viscosity measurements will provide vital information of fluid behavior.
- Emulsion quality; in addition to having a direct coupling to the fluids' sag performance, the measurement of electric stability can provide useful information of water or oil influx that influence the sag stability.

Only through good control of the drilling process will one be able to some extent to predict a fluids' sag performance in the field. Combining the retrieved information with direct sag determination techniques, makes it possible to increase the knowledge of which parameters have the most impact on the fluids' sag stability.

4.9 Direct weight measurement

The equipment developed and used in the majority of the experimental investigation for determining elements critical for sag is shown in Fig. 4.7. This comprises of a laboratory scale coupled with a modified atmospheric consistometer which is described in the well cementing testing standard given by API.

The consistometer is standard equipment used for the preparation of well cement slurries prior to rheological measurements or for the determination of thickening time. Using a consistometer as base for our equipment design, one benefits from having the option of using the outer rotating cylinder for running sag tests at dynamic conditions, i.e. with a simulated drill string rotation. The equipment is furthermore coupled to a cooling bath which makes it possible to run tests both at high and low temperatures. The measurement principle is shown schematically in Fig. 4.8 where the weight of the settling particles is registered when they settle at the bottom of the sampling cup.

The sampling cup has an inner diameter D_i of 50.2 mm and inner height H_{ic} of 49.6 mm giving it a volume of 98.2 ml. This is first inserted into the

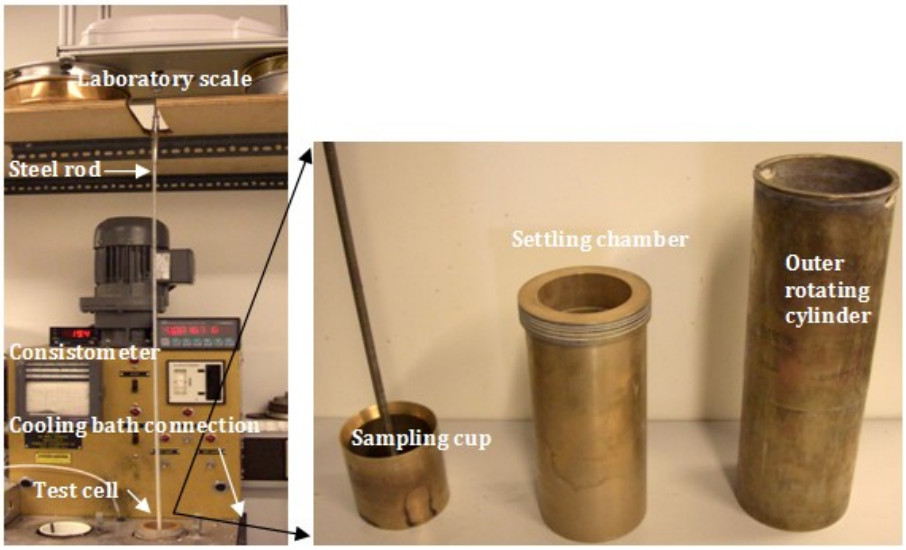


Figure 4.7: *Equipment set-up.*

consistometer before the settling chamber is mounted with a small gap to the sampling cup allowing the sampling cup to hang freely in the suspension to be tested. The sampling cup has an outer height H_{oc} of 56 mm and outer diameter D_o of 60 mm and is attached to the laboratory scale using a 6 mm steel rod with a 4-6 mm gap H between bottom of the sampling cup and the settling chamber.

The inner diameter of the outer rotating cylinder D_{ioc} is 67 mm. This leaves a volume of approximately 34 ml in annulus between the sampling cup and the outer rotating cylinder. Equally, the volume underneath the sampling cup is approximately 19 ml. The bulk density of loosely packed sand and barite used in our experiments are measured to be ~ 1.97 and $\sim 2.37\,\mathrm{g/cm^3}$ respectively. From this it follows that for tests with sand, the maximum capacity of the sampling cup is $\sim 194\,\mathrm{g}$ while the sampling cup can collect 233 g of barite before it is overfilled.

4.9.1 Settling parameters

By use of this technique, several settling parameters can be determined. This includes the **total settling potential**, **settling velocity/rate** and **solid flux**. With a known quantity of dry material, the total settling potential w_{TSP} can be determined taking into account the buoyancy effects. This is given as:

$$w_{TSP} = w_{dry} \times (\frac{\rho_p - \rho_f}{\rho_p}) \tag{4.5}$$

where w_{dry} is the dry weight of the material, ρ_p is the particle density and ρ_f

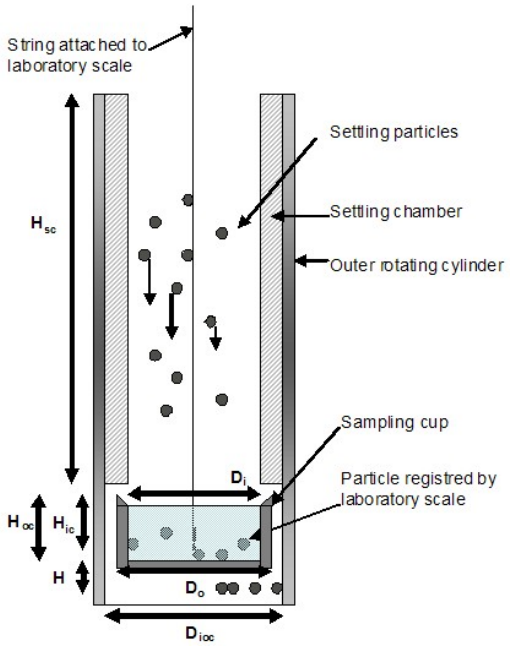


Figure 4.8: *Equipment principle.*

is the density of the fluid in which the solid material is suspended.
The settling potential, R_S, is defined as a ratio:

$$R_S = \frac{w_{SM}}{w_{TSP}} \tag{4.6}$$

where w_{SM} is the mass of settled material in the test and w_{TSP} is the total mass of material in the sample given from the fluid composition. For field applications this parameter can be relevant to measure if the well construction limitations are given and one can determine an acceptable settling potential, based on the available operational window.

The settling mass rate, q_s, is given directly by the time derivative of the settling curve (see also Fig. 4.9):

$$q_s = \frac{dm}{dt} \tag{4.7}$$

The term solid flux expresses the amount of material passing through a selected area over a specified time period ($\mathrm{g\,m^{-2}\ s^{-1}}$). This provides a more universal expression that also includes the area correction.

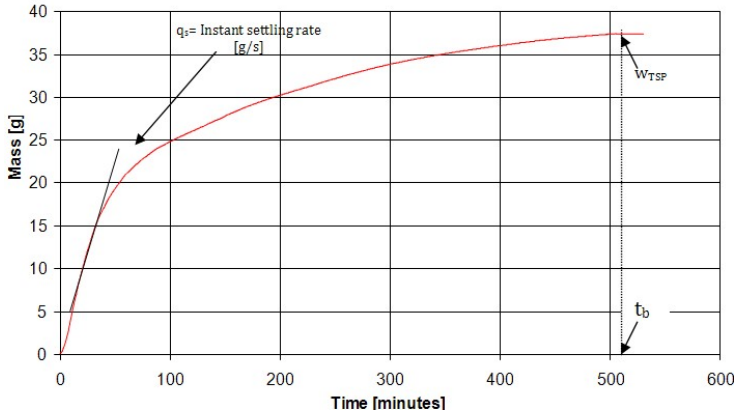


Figure 4.9: *Example of a settling curve. The total settling potential (w_{TSP}) is the registered maximum weight of particles that can settle. The gradient of the settling curve q_s gives the instant settling rate. t_b expresses the time of breakthrough where all particles that can settle have been allowed to settle, i.e., time when w_{TSP} is obtained.*

4.10 Summary of testing techniques

This chapter has described various techniques available to monitor sag. In the initial phase of determining parameters influencing a fluids' sag potential, the static sag test was used (see 4.1. Due to the oil industry lacking a single technique for continuous monitoring of particle settling, possible candidate techniques were investigated. The direct weight measurement technique described above has shown to provide reproducible results. Due to its flexible design, the equipment can easily be modified to test for the influence of various parameters on sag stability. In the majority of the experimental investigations, this technique was used to study effects from vibrations, string rotation, temperature and the impact from poor running of solids control equipment. In Ch. 5 the experimental set-ups and results from these investigations are described.

Chapter 5

Experimental investigation of sag properties

The previous chapters have described parameters influencing sag stability that range from fluid composition to operational elements. This chapter describes the experimental set-ups and results from investigations of these parameters. In the initial investigations the static sag test was used, since a better testing technique was not available. As alternative and significantly improved sag determination equipment was developed, i.e. the direct weight measurement, this new equipment was used in the majority of the subsequent investigations.

In Sect. 5.1 it is shown how different shear devices results in varying sag stability. Oil based drilling fluids often contain various types and concentration of salt in the internal brine phase. Sect. 5.2 describes the impact of this on sag, while Sect. 5.3 discusses how operating solids control equipment is important for sag stability.

The impact of structural breakdown caused by vibrations during operations, has till now been neglected when explaining particle settling. Sect. 5.5 shows the results from an investigation where various drilling fluids are exposed to vibrations. Others have studied the effect from particle size distribution on sag [8], and Sect. 5.7 presents the results from a study that confirms this effect.

5.1 Mixing energy

The making of an oil based drilling fluid starts off with creating a stable water in oil emulsion. To break up the water or brine droplets in the oil, mechanical energy is required. Here the results from large scale tests of various shear devices [I] are presented. One such device, shown schematically in Fig. 5.1, provides shear to the fluid by pumping it into a shear zone. Here it passes slots of well defined size in a stator and a rotor, before either being ejected out of the unit or passed to another shear zone for further shearing.

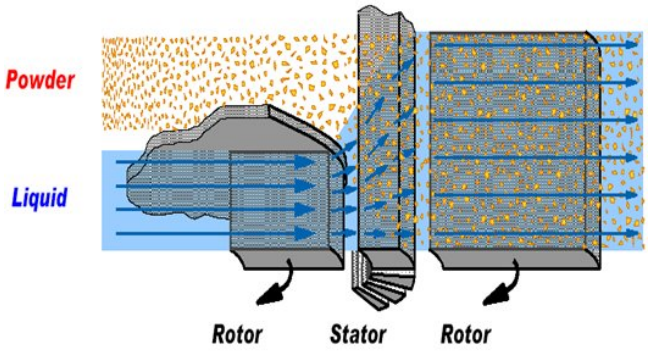


Figure 5.1: *The principle of a shear unit for emulsification of oil based drilling fluids [I].*

The other unit tested, combines mixing and shearing. A mixing hopper is mounted on top of an opening as shown in Fig. 5.2. A lower pressure is created as the fluid passes through the mixing zone. This causes powder or liquid in the hopper to flow into the mixing zone, where it is dispersed thoroughly in the fluid. This technique is well known in the food and pharmaceutical industries, but has so far not been widely used in practice for mixing of drilling fluids.

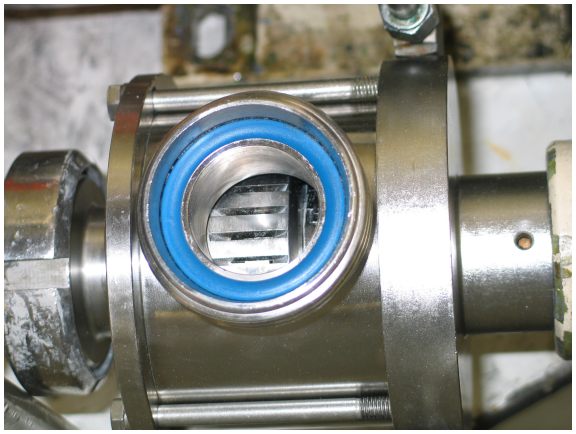


Figure 5.2: *A combined shearing and mixing units where the internal rotor slots are visible. A mixing hopper for dry powder or liquid is placed on top of the opening and the generated underpressure due to the increased fluid velocity in the mixing chamber, makes the powder or liquid flow into the mixing zone.*

To evaluate the efficiency of the different shear units, a freshly made oil based fluid is used. The composition of this is given in Table 5.1.

Several laboratory measurements were furthermore conducted to validate

Table 5.1: *The fluid composition used for validating effects from shear on sag.*

Component	**Concentration**
Mineral oil	580 ml/l
Water	150 ml/l
Emulsifier	20-30 ml/l
CaCl2	30-50 g/l
Organophilic Clay	5-15 g/l
Viscosifer	5.0 g/l
CaCO3	10-100 g/l
Barite	880 g/l

the shearing effect. This includes measurements of electric stability (ES), viscoelastic properties and sag stability. The electric stability was measured on an emulsion consisting of oil and water only, and not on the complete drilling fluid. The measurements were conducted both at ambient temperature and 50 °C according to industry standards [4]. Measurements were made before and after passing the shear unit. In these experiments, two stator/rotor pairs were used. For these two shear zones, the slot widths is given in mm, with numbers given according to configuration stator-rotor-stator-rotor. The results of these experiments, given in Table 5.2, show that by reducing the slot width and/or increasing the rotation rate, more shear energy is applied creating a more stable emulsion.

Table 5.2: *Emulsion quality (E.S.) for different stator/rotor configurations, rotation rates (rpm) and number of circulations through the unit. The width of the slot openings (stator/rotor/stator/rotor) are given in mm.*

No. Circ	**Stator/rotor slot size [mm]**	**Speed [rpm]**	**E.S [V] at Ambient / 50ºC**
0	4 / 4 / 4 / 2	8 000	80 / 160
8	4 / 4 / 4 / 2	8 000	280 / 200
8	4 / 4 / 4 / 2	12 000	440 / 400
1	2 / 2 / 2 / 1	12 000	220 / 230
3	2 / 2 / 2 / 1	12 000	315 / 320
8	2 / 2 / 2 / 1	12 000	460 / 450

Viscosity measurements were conducted on the complete drilling fluid, using a Fann 35 viscometer. Table 5.3 shows measured shear stress as a function of applied shear energy. Increasing the shear energy leads to higher measured

shear stresses as the surface area of the internal water droplets increases. These observations corresponds to the work performed by Ramirez et al. [116] who looked into the effect from internal phase droplet size on viscosity/shear stress.

Table 5.3: *Shear stress, measured according to [4], for different stator/rotor configurations, rotation rates (rpm) and number of circulations through the unit. The width of the slot openings (stator/rotor/stator/rotor) are given in mm.*

No. Circ	Stator/rotor slot size [mm]	Shear rate 1022 s^{-1}	Shear rate 511 s^{-1}	Shear rate 340.7 s^{-1}	Shear rate 170.3 s^{-1}	Shear rate 10.2 s^{-1}	Shear rate 5.1 s^{-1}
0	4 / 4 / 4 / 2	114	68	50	32	12	9
8	4 / 4 / 4 / 2	112	68	52	35	14	12
8	4 / 4 / 4 / 2	135	90	73	54	26	24
1	2 / 2 / 2 / 1	116	73	57	40	16	14
3	2 / 2 / 2 / 1	125	81	64	47	21	19
8	2 / 2 / 2 / 1	145	100	82	61	30	28

The increased shear stress as function of applied shear energy indicates a more stable fluid. To confirm this, sag stability measurements, using the static aging test (see Ch. 4), were also performed. The test temperature was chosen as 100 °C, with a test period of 64 hr. As seen from Table 5.4, the sag factor as given from Eq. (4.1) is significantly reduced when applying more shear energy to the fluid. By changing to narrower slot-openings, smaller emulsion droplets are formed, resulting in even better stability.

Table 5.4: *Sag stability for different stator/rotor configurations, rotation rates (rpm) and number of circulations through the shear unit. The width of the slot openings (stator/rotor/stator/rotor) are given in mm.*

No. Circ	Stator/rotor slot size [mm]	Speed [rpm]	Sag Factor
0	4 / 4 / 4 / 2	8 000	0.538
8	4 / 4 / 4 / 2	8 000	0.527
8	4 / 4 / 4 / 2	12 000	0.518
1	2 / 2 / 2 / 1	12 000	0.530
3	2 / 2 / 2 / 1	12 000	0.519
8	2 / 2 / 2 / 1	12 000	0.516

The effect of increased shear energy on sag stability is now widely known within the drilling industry. Recent developments focus on the practical aspects of making robust and reliable equipment suitable for offshore applications. As the systems are readily available for use at onshore facilities, it is recommended to have shearing devices available at all locations handling larger quantities of oil based drilling fluids.

5.2 Brine type

The effects of salt type and salt concentration in the internal brine phase of oil based fluids, were studied in detail in [III,XX]. The base composition given in Table 5.1 was altered to make fluids of density 1.50 SG, whereafter several combinations of various salts and oil types were tested to obtain a sag stable fluid. The salts were calcium chloride ($CaCl_2$), sodium formate (NaCOOH), potassium formate (KCOOH) and calcium ammonium nitrate ($NH_4Ca(NO_3)$) while the oil types were a mineral oil, linear paraffin, linear alpha olefin (LAO) and an ester. In these experiments, the static sag test was used.

Fig. 5.3 shows the results. The tests indicate that using ammonium calcium nitrate ($NH_4Ca(NO_3)$) salt in the internal phase provides best sag stability. This applies for all base oils tested (mineral oil, linear paraffin, linear alpha olefin and ester).

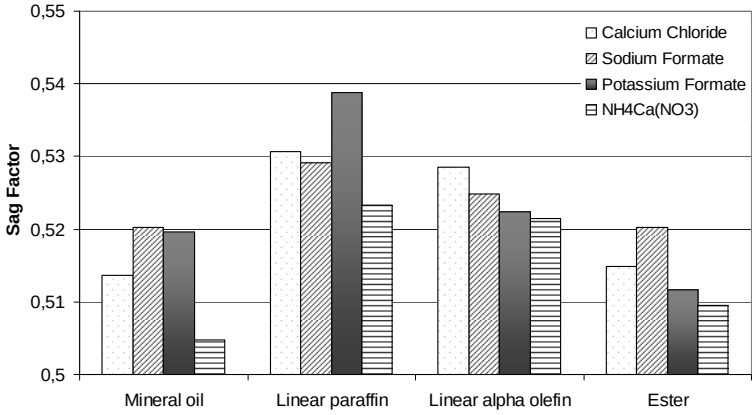


Figure 5.3: *Sag results for various combinations of base oil and salts for the internal brine phase [III,XX].*

The significantly better sag stability using $NH_4Ca(NO_3)$ can be due to less weighting material content in this system as the density of the brine phase is higher for this composition compared to the others. Another aspect of using $NH_4Ca(NO_3)$ is that the salt concentration in the internal phase is higher than for the other systems. **DLVO-theory** includes the effect of salt concentration on the extent of the electrical double layer. Increased electrolyte is predicted to pack the electrical double layer closer which cause the particles to agglomerate more easily. The increased electrolyte concentration also aid in packing the surfactant at the interface, and lower the interfacial tension, resulting in smaller brine droplets and thereby improve emulsion stability. This may explain the better sag stability when using $NH_4Ca(NO_3)$.

When using $NH_4Ca(NO_3)$, the lowest overall viscosity on was observed for all

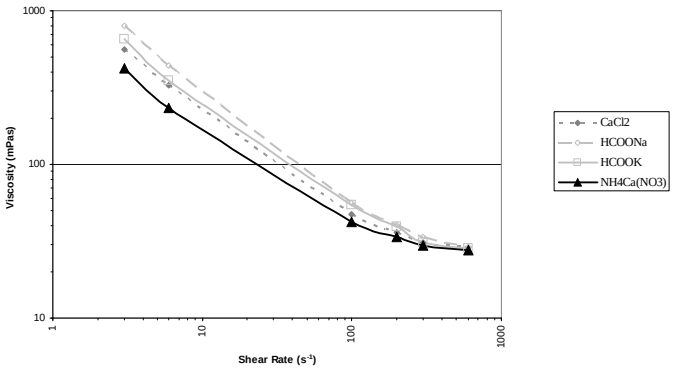


Figure 5.4: *The viscosity as a function of shear rate for different salts in the internal brine phase when using mineral base oil.*

base oil except for the ester based fluid. The results are shown in Fig. 5.4, where the viscosity is given for the different internal brine phases when using mineral oil as the continuous phase. This lower viscosity when using $NH_4Ca(NO_3)$ could again be due to a lower solids content compared to the other systems. These results also indicate that there is poor correspondence between conventional viscosity measurements and a fluid's sag stability.

The findings in this study provided a drilling fluid design that is also beneficial for bioremediation purposes [117], with a potential for lowered costs for oily cuttings treatment. This is an important parameter for drilling fluid design as cuttings treatment is a significant cost driver in drilling operations [XI].

5.3 The effect from solids control on sag

The impact from solids on fluid properties is described in Sect. 3.3.2. To validate the effect from solids control on sag, settling experiments were performed using the direct weight measurement technique on two different samples of oil based fluid [XXVIII]. The first sample was made using the composition given in Table 3.1. In the second sample the organophilic clay used to provide viscosity, was replaced by Wyoming bentonite as to simulate drill solids. The amount was chosen in amounts to provide the same viscosity as for the first sample. By conventional drilling fluid measurements, the fluid properties of the two samples are equal, but the sag stability of the two is dramatically different. The results from the sedimentation tests, given in Fig. 5.5, shows increased sedimentation rates as the organophilic clay is replaced by Wyoming bentonite. The volatility in the readings for the sample with high drill solids content also indicate more particle motion, i.e. settling. At approximately 1000 min the results indicate reversed settling, but this is most likely to be attributed to change in the surrounding environment.

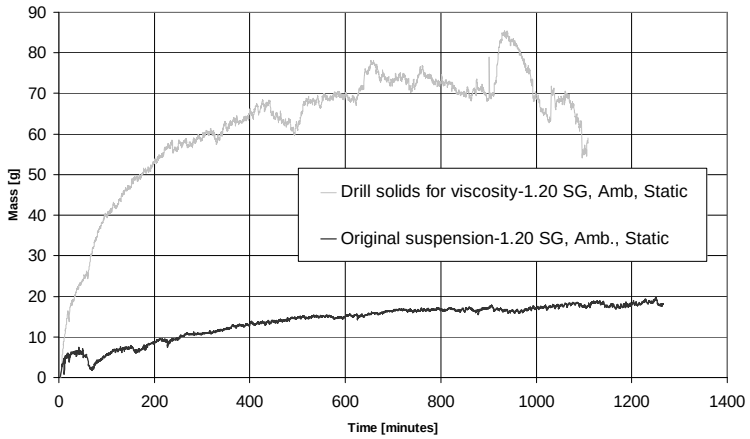


Figure 5.5: *Two oil based drilling fluids of similar viscosity profile, but with different clay type and content provide dramatically different sag performance [XXVIII].*

These experiments show the importance of continuous control of material present in the circulating fluid. To avoid re-circulating formation material to the bore hole, the solids control equipment must be run properly.

5.4 Stabilization of the emulsion by particle additions

Various types of clay are used in oil based drilling fluids. These adsorb on the brine droplet surface and prevents the droplets from coalescing. A short study was performed [XXX] to investigate the stabilizing effect on the emulsion by addition of organophilic clay.

The emulsion consisted of a mineral oil with an internal brine phase based on $CaCl_2$ and an oil to water ratio of 70/30 based on volume. It was found that as 15 g/l of organophilic clay was added to the emulsion, the electric stability doubled.

The effect of emulsion stability on sag performance is evident from this experiment. If the brine droplets are allowed to coalesce, they will settle due to the density difference between the brine phase and the continuous oil phase, unless subjected to some other force than gravity. Fig. 5.6 shows the result. The left hand picture shows the initial state of an emulsion consisting of a mineral oil, emulsifier and water. The right picture shows the same emulsion after being subjected to 24 hr of ultrasonic vibration.

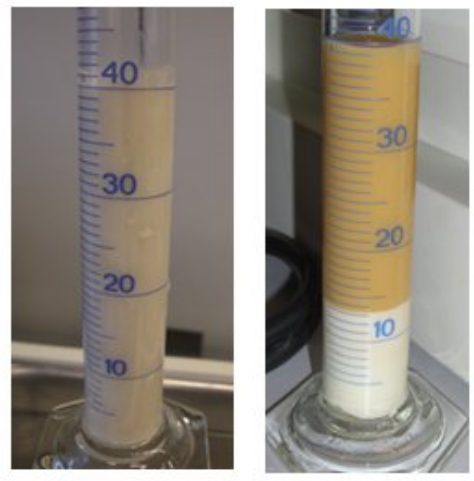


Figure 5.6: *Separation of emulsions when subjected to ultrasonic vibrations. The left picture shows the initial homogenous state of the emulsion. The right picture is taken after 24 hr of vibration [XXX].*

5.5 Structural break-down

Ch. 3 discussed how vibrations can cause structural breakdown of drilling fluids resulting in higher settling rate. In [XIX,XXVII] a modified Fann 35 viscometer, shown in Fig. 5.7, was used to investigate the effects from imposed vibrations on shear stress for different types of drilling fluids. A vibrator was connected

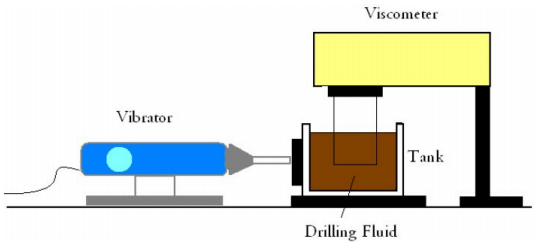


Figure 5.7: *The set-up of a Fann 35 viscometer with possibility of imposing vibrations [XIX,XXVII].*

to the viscometer and the effect on shear stress was measured as a function of vibration frequency. The displacement amplitude was approximately 0.75 mm and the frequency was given from how many strokes per minute the vibrator provided.

For a polymer based fluid no significant effect from vibrations was observed on the shear stress curve. However, for water based fluids based on bentonite and

oil based drilling fluids, vibration induced significant decrease in shear stress, especially at low shear rates. The results from the measurements using a bentonite based fluid, are shown in Fig. 5.8. It is seen that for these types of fluids structural breakdown occurs, resulting in dramatically reduced shear stress. One can also expect that this will cause significant higher sag potential.

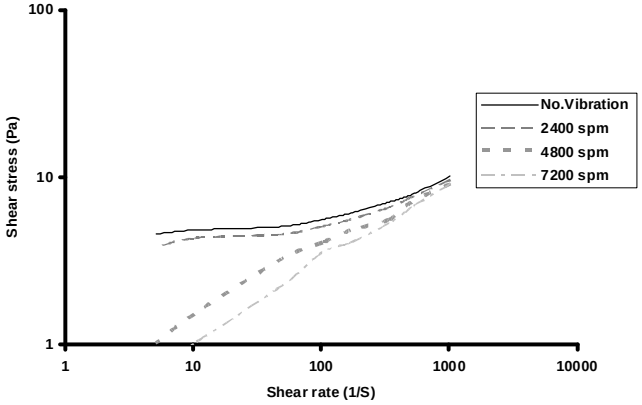


Figure 5.8: *The shear stress as a function of shear rate for a bentonite based fluid when exposed to different vibration frequencies [XIX,XXVII].*

To study the effect from imposed vibrations on sag, several studies [XXV,XXX] were initiated. These clearly show that the settling rate increases significantly due to imposed vibrations. By inserting an oil based drilling fluid sample into an ultrasonic cleaning bath (Cole Parmer 3500), the effects of 40 kHz vibrations are shown in Table 5.5.

Table 5.5: *Sag as a function of vibration for an oil based drilling fluid using static aging test [XXV].*

Time [hr]	Sag factor Reference sample	Sag Factor Ultrasonic bath sample
3	0.50	0.57
5	0.50	0.59
6	0.50	0.60
8	0.50	0.63

The sag factor was determined using the static sag test method described in Sect. 4.1. For the sample exposed to vibrations the sag factor is significantly higher than for an equally composed sample left at static conditions. After 8 hr in the ultrasonic bath, the sag factor of 0.63 versus 0.50 for the reference sample, expresses the impact of vibrations on sag performance. Similar experiments [XXX] were also performed, but using the direct weight measurement technique to determine the settling rate as a function of imposed vibrations. Fig. 5.9

shows that the amount of settled material after 20 hr is more than five times higher when subjecting the fluid to ultrasonic vibrations in comparison to a sample left at static conditions. In the initial phase of the test, less difference between the two samples was observed. After 7 hr testing, the settling rate increases dramatically for the sample exposed to vibrations.

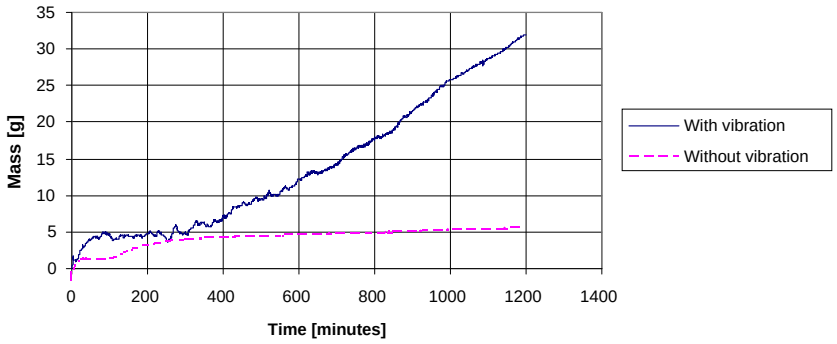


Figure 5.9: *Sag as a function of ultrasonic vibrations using the direct weight measurement technique [XXX].*

5.6 String rotation and particle settling

Nguyen [XXXI] investigates how string rotation influence on settling rate for varying wellbore inclinations. A similar investigation [X] was conducted to determine how settling is influenced by string rotation in a vertical well. These experiments were performed using the direct weight measurement technique. The tests were conducted at ambient temperature using test cell rotation rates of 13 rpm and 9.5 rpm which equals 0.034 m/s and 0.025 m/s circumferential speed of the settling chamber surface respectively. The fluid composition used is given in Table 5.6 with barite content to provide 1.20 SG fluid density. Two static sag reference tests are conducted resulting in registered weight of $\sim 15-20$ grams after 960 minutes. Fig. 5.10 shows the results from this investigation. Starting string rotating at 9.5 rpm, the amount of settled material increases to $\sim 68-70$ grams after 960 min whereas 13 rpm string rotation increases the resulting registered weight further to $\sim 82-85$ grams for the same time period. From these results we conclude that increased rotation leads to significant higher settling rate for the rotation rates used.

The solid flux is equally determined by dividing the settling rate by the surface area of the sampling cup given by the inner diameter. From Fig. 5.10 one observes that the solid flux will be higher at the start of the test period if averaged over a certain period. Averaging over the first hour one also observe higher solid flux with increased rotation rate. The solid flux over the first hour are ~ 7.0, 4.0 and 0.75 g/hr m^2 for 13 rpm, 9.5 rpm and static test respectively.

Table 5.6: *Fluid composition for determining effect from string rotation on sag [X,XXVIII].*

Component	**Content**
Base oil	268 ml
$CaCl_2$ (1.13 g/cm^3)	78 ml
Primary emulsifier	11.7 ml
Secondary emulsifier (wetting agent)	3.9 ml
$CaOH_2$ (Lime)	11.05 g
Organophilic clay	7.15 g
Fluid loss control agent	5.2 g
Barite	As required

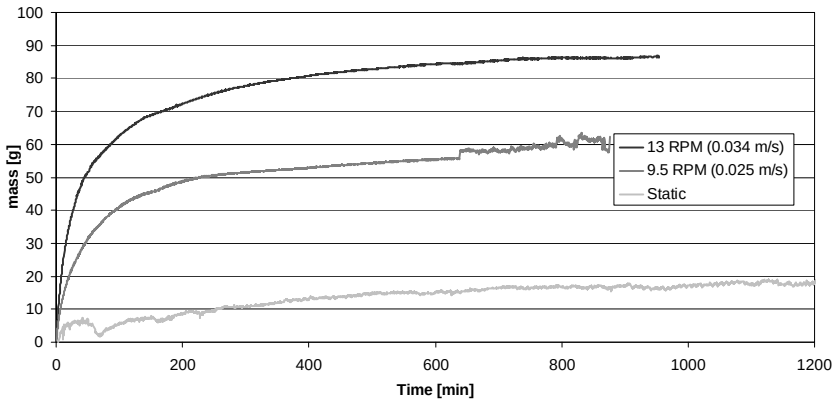


Figure 5.10: *Sag as a function of drill string rotation [X,XXVIII].*

The results show that even slow rotation, which is often the case during casing running, significantly increases sedimentation rate for a vertical well. The total amount settled after 800 minutes is 350% higher when rotating at 9.5 rpm compared to no string rotation.

5.7 Particle size distribution

The effect of particle size distribution (PSD) on the settling rate was discussed in Ch. 2. To examine the relevance of this effect for drilling fluids, settling experiments [IV,XXIV] were performed. Two otherwise identical invert emulsion drilling fluids were produced using two distinct different PSD of the weighting agent (see Table 5.7), one with a narrow and one with a broader size distribution. To make the desired size distribution, samples of barite were sieved and added to the drilling fluid to give equal density of the two samples.

Sedimentation rates of the two samples were determined using the direct

Table 5.7: *Drilling Fluid Formulations for the drilling fluids to study the effect of PSD on Barite sag.*

Component	Sample	
	1	**2**
Mineral oil (ml/l)	603.9	603.9
$CaCl_2$ (g/l)	31.6	31.6
Primary Emulsifer (ml/l)	20.0	20.0
Secondary Emulsifer (ml/l)	10.0	10.0
Lime (g/l)	10.0	10.0
Viscosifer (g/l)	5.0	5.0
Barite (g/l) D_{50}- 34μm	762.0	381.0
Barite (g/l) D_{50}- 23 μm	-	190.5
Barite (g/l) D_{50}- >63 μm	-	190.5
Water (ml/l)	151.0	151.0

weight measurement technique described in Sect. 4.9. The drilling fluid was made with a low clay content to provoke sag within a shorter time frame than would normally be expected, since the intention of the test was to show how the PSD influences sag. The test was performed at ambient temperature and for a test period of 2 hr. The results of these settling experiments are given in Fig. 5.11. The results show that the fluid with the narrower PSD has signifi-

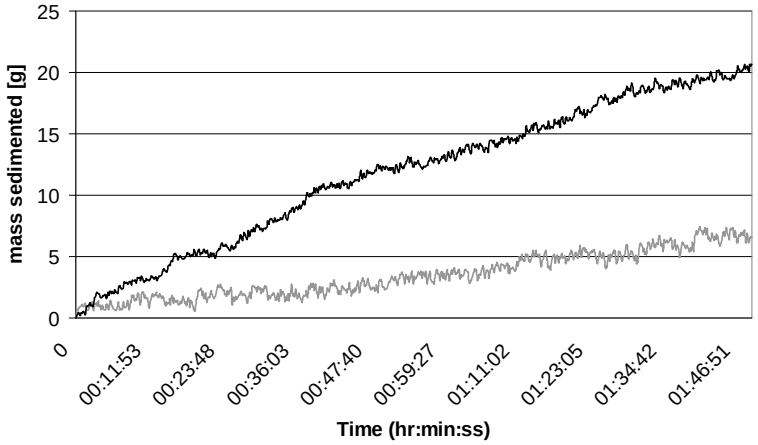


Figure 5.11: *The sedimentation rate for a model drilling fluid with one sample containing barite with a narrow size distribution (grey) and one with a wider size distribution (black)[IV].*

cantly higher sag potential. For repetitive tests, the difference was lower. This shows that controlling the particle size and content of the weighting agent has a significant impact on the sedimentation rate. In practice, utilization of the solids control equipment to its full potential can generate the desired particle size distribution and thereby improve control of sag stability.

5.8 Summary of results

All investigations show the complexity of particle settling in drilling fluids. The parameters identified to influence on sag are all of such character that they are relevant for everyday handling and use of drilling fluids. The investigations showed that fluid composition is of high importance for sag performance. However, the investigations also show the significant impact from operational elements on settling. The investigations also demonstrates the importance of having sag testing equipment available at the rig site to continuously monitor the fluid sag performance.

Chapter 6

Conclusion

The present work has identified several parameters which influence sag stability of drilling fluids. To identify those most critical to particle settling, a novel test technique for sag detection has been developed. The technique has made it possible to identify and quantify effects from parameters earlier not having been investigated by the drilling fluid industry. In parallel with developing the sag detection equipment, alternative settling parameters are proposed for improved understanding and visualization of the state of fluid. This includes determination of instant settling velocity/rate, total settling potential and instant solid flux. Some of these parameters can also be used for techniques currently in use by the industry.

Due to the complexity of drilling fluid systems, settling models such as those developed by Stokes [42], Felice and Pagliai [45], Richardson and Zaki [48], have shown not to be able to predict particle settling in drilling fluids well. Drilling fluids are mostly non-Newtonian, and through measurement it was shown that parameters like particle shape and size, have significant impact on settling. This makes numerical simulation of particle settling inherently difficult, which has not been a part of our investigation.

It has further been shown that different operation of the drilling equipment have an significant impact on a fluids' sag potential. Through settling experiments one has found that erratic operation of solids removal equipment can increase the settling rate due to fluid quality deterioration. Through measurements, one also showed that even conventional drilling fluids fall into the colloidal system category. For such systems, different mechanisms and forces occur, causing them to behave differently from what is estimated from conventional settling models used in the drilling industry.

Others have earlier shown that the breaking of gels [13], low-shear viscosity [65], temperature, wellbore angle [8] etc. all influence the settling rate. In this work, the following additional parameters were identified to have a significant impact on sag potential:

- The internal brine phase of oil based drilling fluids: Alternative salts, such as ammonium calcium nitrate, used in the internal brine phase showed improved sag stability compared to the most commonly used salts. Additional benefits, such as lower viscosity and price, show the alternative salts to be viable products for use in oil based drilling fluids.
- The particle morphology, size distribution and concentration: Particle shape has a significant impact on sag stability. Through experiments it was shown that a fluid with particles of broad size distribution, settles slower than one with particles of a narrow size distribution.
- The shear energy applied during preparation of oil based drilling fluids: Large scale tests run using various shear devices demonstrated significant effect from applied shear energy on sag. The tests showed that the amount of applied shear energy is inversely proportional to settling potential.
- The operation of solids control equipment: Recirculation of drilled formation particles to the borehole by erratic operation of the solids control equipment deteriorates the fluid quality rapidly. An increased portion of particles of sub-micron size in the fluid will have an ensuing negative impact on the sag potential.
- The drill string rotation rates: Slow drill string rotation will for vertical sections of the borehole result in increased settling rates.
- The imposed vibrations from downhole and topside equipment: This work shows that vibrations can increase the settling rate dramatically. For operations where enhanced settling is required, this can be an alternative technique. For drilling and completion operations this can have detrimental effects.

Through the use of a specially developed technique for sag monitoring, several parameters have been revealed to influence on sag performance which had not been investigated by the drilling industry. This list of parameters is far from exhaustive and illuminates the complexity of particle sedimentation in drilling and completion fluids.

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