



CHAPTER I

INVESTIGATION OF BARIUM SULFATE DEPOSITION BY CAPILLARY FLOW

1.1 Abstract

One of the most troublesome and expensive problems found in the oil production process is scale composed of barium sulfate (BaSO_4), due to its relative low solubility compared with other typical scale minerals. Consequently, there is a need to better understand the mechanism of barium sulfate deposition. This research is focused on developing a technique for investigating barium sulfate deposition - in particular. In this research, capillary technique has been developed as a potential technique for scale deposition experiments. Subsequently, this technique is used to investigate the deposition mechanism by the change in pressure drop. Sample of 100 mg/L of brine solutions, BaCl_2 and Na_2SO_4 , were pumped through the capillary and a scale was deposited at the inner capillary wall. Thus, a change in pressure drop is dependent on the deposition rate. The mass of the deposit formed was determined by dissolution with DTPA (Diethylenetrinitriolpenta acetic acid) which effectively dissolve and form complex with barium ions. The results show that deposit has been formed a rough surface where the surface thickness is same for entire capillary length during 6 hours operation. After 6 hours, barium sulfate was rapidly deposited at the beginning of the capillary due to the effect of barium sulfate deposit which covered the capillary inner wall. It indicates that the deposit is non-uniform and preferentially located near the beginning of the capillary.

1.2 Introduction

Scale formation is one of the most important and serious problems that damages water injection system in oilfield. The injection system used is to inject seawater into oil-bearing reservoirs to maintain reservoir pressure and improve secondary recovery oil. Unfortunately, the seawater injection could be the main

cause of scale formation when it chemically mixes with the formation water that naturally exists in reservoir. The degree of scale formation depends on concentrations of sulfate ions present in the injected sea water as well as barium, strontium and/or calcium-divalent cations present in the formation water (Jordan *et al.*, 2008). Consequently, the resulting precipitation of CaSO_4 , BaSO_4 and SrSO_4 can damage wellbore and production lines by fouling the equipment and blocking the flow lines. Furthermore, even expensive remedial procedures may not be able to restore the original productivity of a well that has been damaged in this manner (Vetter, 1975).

One of the most troublesome and expensive problems found in oil production processes is scale composed of barium sulfate (BaSO_4), due to its relatively low solubility compared with other typical scale minerals (Risthaus *et al.*, 2000). Moreover, BaSO_4 is the least soluble of the common sulfate scales in water. It is hard to dissolve and cannot normally be removed by chemical means (Ezuber, 2009). Thus, the best way to avoid this expensive problem is through the prevention of scale formation. Normally, studies of scale formation have been focused on precipitation in the bulk solution. However, there is a lack of study of scale deposition which is very important in order to understand how deposit has been formed in the flow line. Thus, the mechanism of scale deposition and the conditions which affect its deposition must be known.

Precipitation experiments with BaSO_4 and SrSO_4 in steel tubes have been done by Rollheim *et al.* (1993) in order to obtain knowledge about the scale formation mechanisms of these mineral scales. They collected and measured the barium concentration of effluent at different times and locations along the tube. Consequently, they reported that a scale formation process is mainly determined by a surface controlled reaction. Moreover, there is a greater degree of scale formation at the beginning of the tube due to high saturation. Another study investigating barium sulfate crystal growth on a stainless steel substrate was done by Quddus *et al.* (2000) Scanning Electron Microscopy (SEM) was used to study the morphology of deposited crystals. After 3 hours exposure to scale-formation solution, the micrograph shows the presence of a dense population of uniformly distributed BaSO_4

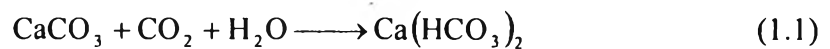
crystals on the entire surface of the substrate. However, the mechanism of BaSO₄ deposition has not been elucidated, so that further investigations are warranted.

The purpose of this research is to develop a capillary flow technique to investigate scale deposition by measuring the pressure drop across a capillary. Moreover, the uniformity and location of BaSO₄ deposition are investigated to obtain better understanding of the process.

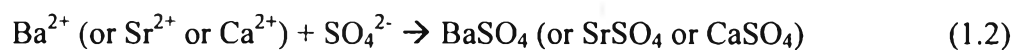
1.3 Literature Review

1.3.1 Scale Formation

Mineral scale formation mainly occurs as the result of fluid pressure reduction or mixing of brines with different compositions. In case of calcium bicarbonate scale, fluid pressure reduction causes a reduction in the solubility of carbon dioxide. Once carbon dioxide is evolved, calcium carbonate can react with carbon dioxide and precipitate in the reservoir or deposit somewhere downstream by the reaction shown below:



Seawater injection for pressure maintenance is another cause of scale formation. Mixing seawater with formation brine can lead to the formation of sulfate scales in the well bores as shown in Figure 1.1. The reaction can be seen below:



However, this reaction depends on having sufficient concentrations of sulfate ions in the injected seawater, and barium, strontium, and/or calcium divalent cations in the formation water. Additionally, the flow paths, pressures, and temperatures at various locations can also be the dependent parameters (Vetter *et al.*, 1982; Mackay, 2003).

Some of the factors that affect scale precipitation, deposition and crystal growth are supersaturation ratio, temperature, pressure, ionic strength, evaporation, contact time and pH.

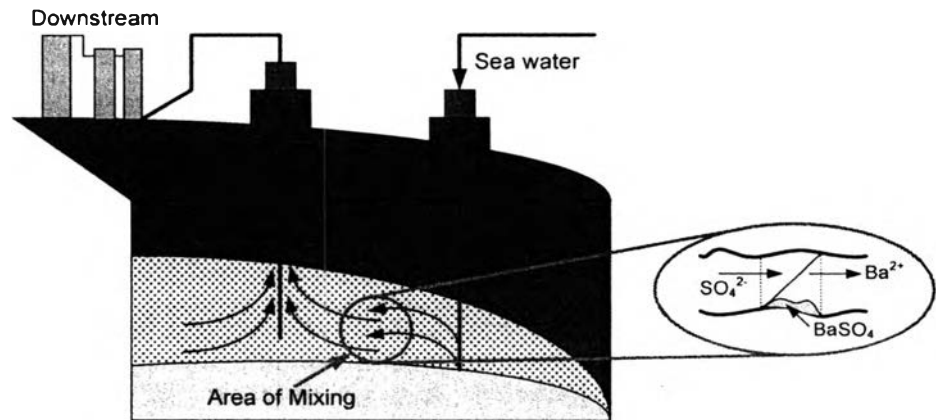


Figure 1.1 Schematic of mixing of injected seawater and formation water in a reservoir which causes precipitation of barium sulfate (Bedrikovetsky *et al.*, 2009).

1.3.2 Barium Sulfate

Barium sulfate is one of the most troublesome and costly sulfate scales that deposit in down-hole pumps, tubing, casing flow lines and other production equipment in oilfield process, as shown in Figure 1.2. According to the extreme insolubility of barium sulfate, a highly undesirable scale solid has been encountered in enhanced oil recovery operation by injection of seawater (Symeopoulos *et al.*, 1992). In order to avoid this problem, BaSO₄ scale treatment must focus mainly on its prevention through the use of scale control chemicals.



Figure 1.2 Barium sulfate scale deposited on the pipe wall and surface facilities (Graham *et al.*, 2002).

1.3.3 Barium Sulfate Scaling Tendency

Scaling tendency is generally considered in term of the solubility of barium sulfate at given condition. A thermodynamic approach has been commonly used for scale prediction. Moreover, one parameter that could tell possibility of barium sulfate formation is the saturation index (SI), which is defined as the logarithm of the saturation ratio (SR), as shown below:

$$SR = a_{Ba^{2+}} + a_{SO_4^{2-}} / K_{SP} \quad (1.3)$$

$$SI = \log(a_{Ba^{2+}} + a_{SO_4^{2-}} / K_{SP}) \quad (1.4)$$

and,
$$a_i = \gamma_i C_i \quad (1.5)$$

Where a_i , γ_i , and C_i are the activity, activity coefficient and concentration of i-th species respectively and K_{SP} is the solubility product. If $SI > 0$, the scale formation is possible, for $SI < 0$, scaling is impossible, and if $SI = 0$, the system is in critical solubility. Moreover, the scaling tendency is also a function of the mixing ratio of two incompatible water (Collins *et al.*, 2005).

1.3.4 Barium Sulfate Deposition/Precipitation

Scale deposition has been studied by several authors throughout the years. However, the deposition mechanism is still not elucidated. Both heterogeneous and homogeneous nucleations have been concerned. On the other hand, $BaSO_4$ may deposit directly on the pipeline surface or grows as particles in the bulk of the solution and then deposit on the pipeline surface (Rollheim *et al.*, 1993).

Rollheim *et al.* (1993) studied $BaSO_4$ precipitation experiments in steel tubing. They conducted experiments at a temperature of 40 °C, a flow rate of 4-6 dm^3/min , inner tube diameters of 8-20 mm, and duration of ≤ 4 hours. Additionally, the concentration of Ba^{2+} and SO_4^{2-} solutions were equal molarities, at 30 times the equilibrium concentration. They found that about 95% of precipitated $BaSO_4$ deposited as scale when prescaled tube was used, while around only 75% were deposited when an initially clean tube was used. These results indicate that scale formation on tubing walls is mainly determined by a surface controlled reaction. Unfortunately, they were not able to distinguish between homogeneous and heterogeneous nucleation. Similarly, another work has studied the deposition of

additional scale on a prescaled specimen (Quddus *et al.*, 2000). They reported that once a thin layer of scale is formed, the subsequent scale growth is much faster. This also indicates that surface controlled reaction is a main reaction for scale deposition.

Moreover, recent work (BinMerdhah *et al.*, 2010) has been done in order to study the permeability reduction which is caused by barium sulfate deposition in sandstone cores from mixing of injected sea water and formation water. The result shows that permeability decline caused by BaSO₄ scale formation in the porous media ranged from 5-19% of the initial permeability. Moreover, they reported that several factors influencing scale formation, increasing temperature, brine concentration, and differential pressure, had an effect on the permeability reduction and reaction rate constant. As temperature increases, the permeability decline is less rapid since the solubility BaSO₄ increases with temperature.

1.3.5 Technique for Investigating Scale Deposition

Scale deposition has been investigated by a variety of techniques throughout the years. Deposition has been conducted with steel tubing (Rollheim *et al.*, 1993; Quddus *et al.*, 2000), an electrochemically active rotating disk electrode (RDE) which focuses on scale deposits formed on the surface of metals (Chen *et al.*, 2004; Morizot *et al.*, 2000), and a core system (Merdhah *et al.*, 2007). However, a technique which has not been studied in scale deposition is capillary technique by measurable pressure drop across the capillary. This technique has recently been used to study asphaltene deposition (Hoepfner, 2009; Maqbool *et al.*, 2006).

In this study, the capillary technique will be applied to investigate the mechanism of scale deposition. In order to investigate, two incompatible brine solutions will be injected through a capillary at a constant flow rate and the pressure drop (ΔP) across a capillary will be measured. An increase in ΔP indicates that the scale has started to deposit. The increased ΔP can be used to calculate how much a uniform deposit has been formed in the capillary by using Equation 1.6, as show below. The pressure drop assumed a uniform deposit for laminar flow is given by the Hagen-Poiseuille equation, as written in Equation 1.6.

$$\Delta P = \frac{8\mu L Q}{\pi r^4} \quad (1.6)$$

Where

μ is the viscosity (Pa*s)

L is the length of capillary (m)

Q is the volumetric flow rate (m^3s^{-1})

r is the radius of capillary (m)

1.3.6 Dissolution of Barium Sulfate Scale Deposit

As mentioned earlier that BaSO_4 is the least soluble of other sulfate scales in water and hard to dissolve and remove. Various studies have been done in the past years for barium sulfate dissolution by using chelating agent (Putnis *et al.*, 1995; Dunn *et al.*, 1999; Putnis *et al.*, 2008). Chemical dissolvers that could be considered as strong chelating agents for barium ions are Diethylenetrinitrilopentaacetic acid (DTPA) and Ethylenedinitrilotetraacetic acid (EDTA). Based on the aminoacetate group, they could efficiently form strong complexes with metal ions in solution (Dunn *et al.*, 1999).

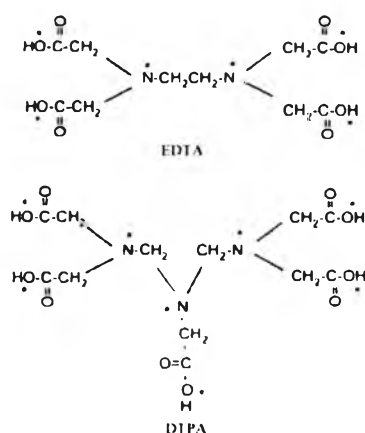


Figure 1.3 Schematic diagrams of the structures of EDTA and DTPA (Putnis *et al.*, 2008).

According to Figure 1.3, the dot shows the positions of the active metal complex sites. EDTA and DTPA have 6 and 8 complex sites, respectively, enabling one molecule to interact with all the reactive centers of a metal ion, forming a stable

complex. Putnis *et al.* (2008) have reported that a given molarity of DTPA is potentially able to dissolve an equal molarity of BaSO₄. Moreover, DTPA, at high pH, becomes progressively deprotonated and the active ionic species in solution become negatively charged. Therefore, the DTPA anions would have a strong tendency to complex with barium ions exposed on the surface (Putnis *et al.*, 1995). In this study, DTPA will be applied to dissolve and collect mass of BaSO₄ which deposited in the capillary.

1.4 Experimental

1.4.1 Materials

Certified A.C.S. grade of barium chloride, BaCl₂, and sodium sulfate, Na₂SO₄, supplied by Fisher Chemical were used to study barium sulfate deposition. Diethylenetrinitriropentaacetic acid, DTPA, 98% total solids, C₁₄H₂₃N₃O₁₀, M.W. 393.35, supplied by Thermo Sci Acros Organics and laboratory grade of barium sulfate, BaSO₄, supplied by Aldrich Chemical Company were used to study barium sulfate dissolution. As well as certified A.C.S. grade of potassium hydroxide, KOH, by Fisher Chemical was used for dissolution study. Deionized water (Ultrapure Milli-QTM (18MΩ) water system) was used as the solvent for preparing all aqueous solutions.

1.4.2 Equipments

- 1.4.2.1 Two of HPLC 510 water pumps
- 1.4.2.2 Syringe pump Model 55-2222 from Harvard Apparatus
- 1.4.2.3 Syringe
- 1.4.2.4 Stainless steel type 316 tubing with OD 0.0625'' and ID 0.020'' and fittings from small parts, Inc.
- 1.4.2.5 Perkin Elmer inductive-coupled plasma spectroscopy/mass spectroscopy (ICP/MS) for elemental analysis
- 1.4.2.6 The differential pressure transducer model Z with a range of 25 psi from Honeywell International Inc.
- 1.4.2.7 USB-6009 14 bit, 48 kS/s Multifunction Data Acquisition system from National Instruments

1.4.3 Software

1.4.3.1 ELAN9000 – installed with Perkin Elmer ICP/MS

1.4.3.2 LabVIEW by National Instruments – used for data acquisition and logging

1.4.4 Experimental Apparatus

A Schematic of the experimental apparatus has been shown in Figure 1.4. The apparatus consists of two HPLC pumps, one for the anion solution (Na_2SO_4) and another for the cation solution (BaCl_2). The given concentration of the two brine solutions will produce a BaSO_4 concentration above the solubility point, and force BaSO_4 to precipitate instantaneously when both solutions are mixed. In order to avoid precipitation in the mixing line which may cause plugging problem, the positive inlet pressure was measured by differential pressure transducer before mixing of two solutions. Then, both solutions are continuously pumped, meet at the second tee and flow through a 3 ft section of 0.02 inches ID capillary, past an additional tee to measure the negative outlet pressure, and then flow into a waste container. Additionally, all experiments are conducted at ambient temperature and a flow rate of 2 ml/min of each solution.

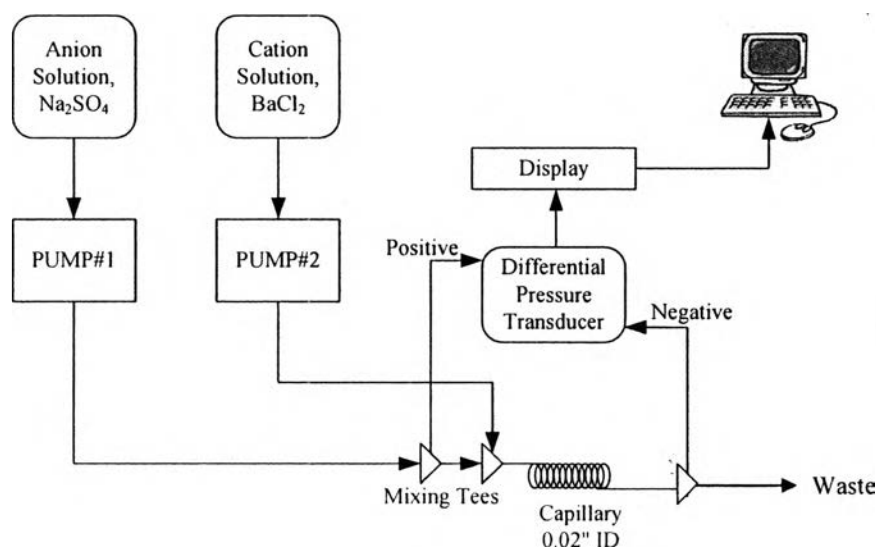


Figure 1.4 Schematic of the experimental apparatus for barium sulfate deposition studies.

1.4.4.1 Testing the Accuracy of Equipments

In order to determine the accuracy of the equipment, test fluids were run through the capillary system at different flow rates and the pressure drop across the capillary was measured using the data acquisition system. The measured pressure drop was compared to theoretical pressure drop which is calculated by using Hagen-Poiseuille Equation 1.6 to verify the accuracy of the designed system.

1.4.4.2 Barium Sulfate Deposition Experiments

The concentration used to investigate the BaSO₄ deposition was 100 mg/L of BaCl₂ and Na₂SO₄. The duration of experiments varied from 6-10 hours. The pressure drop across the capillary was measured to detect BaSO₄ deposition on its inner wall and the pressure drop data was acquired using the LabVIEW software. The change of radius of the capillary was calculated using the pressure drop data, the specified values of flow rate, and capillary length.

1.4.4.3 Barium Sulfate collection

Diethylenetrinitriolpentaacetic acid (DTPA) was used to dissolve the deposit which has been formed in the capillary. In order to prepare DTPA solution, 0.2 g of DTPA was dissolved in a 0.5 M KOH solution to keep the pH in the range of 11-12. Concentration of DTPA solution is 0.48 mmole/L which is able to complex with an equal molarity Ba²⁺ in the deposit.

Prior to dissolution, the capillary was dried at 70 °C overnight. A syringe pump was used to deliver the DTPA solution along the deposited capillary. Because of the limitation of the pump, we could not continuously pump DTPA solution through the scaled capillary. Thus, a syringe was filled with approximately 60 ml of DTPA solution for each load. The effluent was individually collected at the outlet of capillary and diluted by DI water with a dilution ratio of 1 to 25 to reach the appropriate concentration for compositional analysis using ICP/MS technique.

1.5 Result and Discussion

1.5.1 Equipment Design and Testing for Scale deposition

The experimental setup for investigating scale deposition was designed and described in the previous chapter. It is necessary to test the accuracy of the designed experimental setup before deposition experiments will be carried out. In order to test the accuracy, experiments were conducted by flowing water through the system and measuring the pressure drop across the capillary. The goal was to compare the experimentally measured pressure drop values to the theoretical values calculated by the Hagen-Poiseuille equation, Equation 1.6.

Maqbool *et al.* (2006) has investigated factors that could cause error in pressure drop measurement. Three factors were concerned, flow rate, viscosity, and radius of capillary.

1.5.1.1 *Flow Rate*

Experiments were performed by using two HPLC 510 water pumps. The flow rates were measured by continuously flowing water at 2 ml/min for 8 hours and noting the time required to pump a specified volume of fluid. Error was within a margin of +/- 2.0%. Reproducibility was achieved with multiple tests with similar results, which indicated that the flow rate does not significantly contribute to the error in pressure drop measurement.

1.5.1.2 *Viscosity*

Our experiments were carried out using aqueous solutions. The viscosity of water changes with temperature variation. The temperature of water at room temperature is in between 22 – 24 °C which does not significantly affect the viscosity. Moreover, the pressure drop of water tests was measured on different days. It was found that all of these pressure drop values were in agreement within an error margin of +/- 2.0%. The error in viscosity was not a major contributor to the error of pressure drop measurement.

1.5.1.3 *Radius of Capillary*

According to the Hagen-Poiseuille Equation 1.6, the pressure drop is proportional to $\frac{1}{r^4}$. It means that a small difference in the capillary radius

could lead to the great error in pressure drop measurement. Figure 1.5 shows that experimental pressure drops were slightly lower than theoretical pressure drop calculated by using the reported radius from the manufacturer (0.01 inches). Consequently, the measured pressure drop value was applied to the Hagen-Poiseuille equation to calculate the actual radius of the capillary. The actual radius of this particular capillary was found to be 0.01 inches, which is within 5% of the radius claimed by the manufacturer. Figures 1.5 and 1.7 show the comparison between the experimental values of pressure drop across the capillary and theoretical values which were calculated by the reported radius and the actual radius, respectively. Using the measured radius for the calculations, the error was significantly reduced as show in Figures 1.6 and 1.8. This concern has also been reported by Maqbool *et al.* (2006)

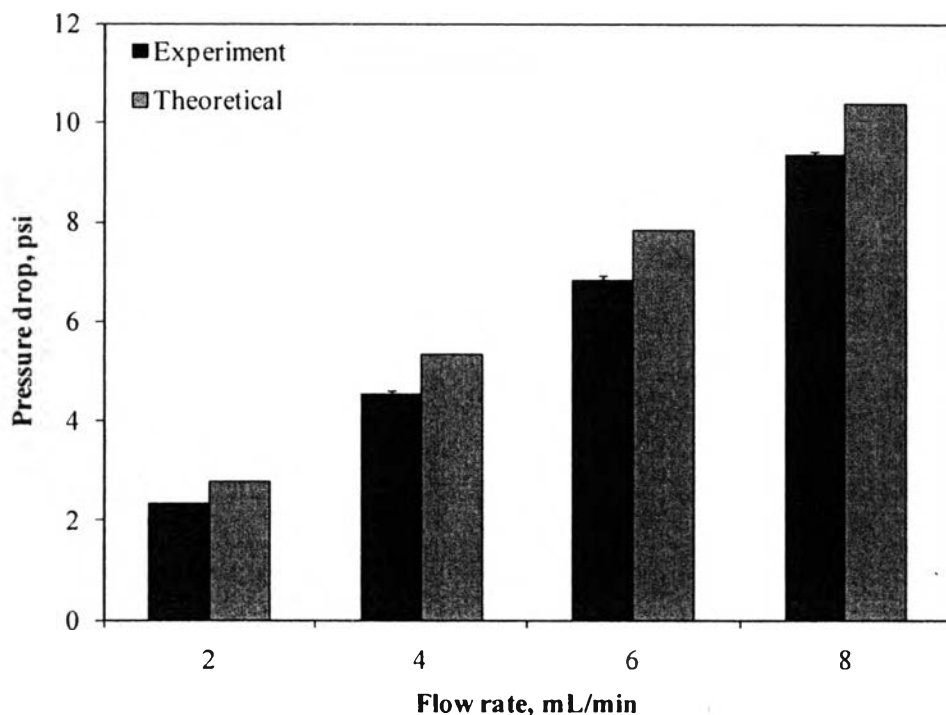


Figure 1.5 Theoretical and experimental values of pressure drop across the capillary for different flow rates.

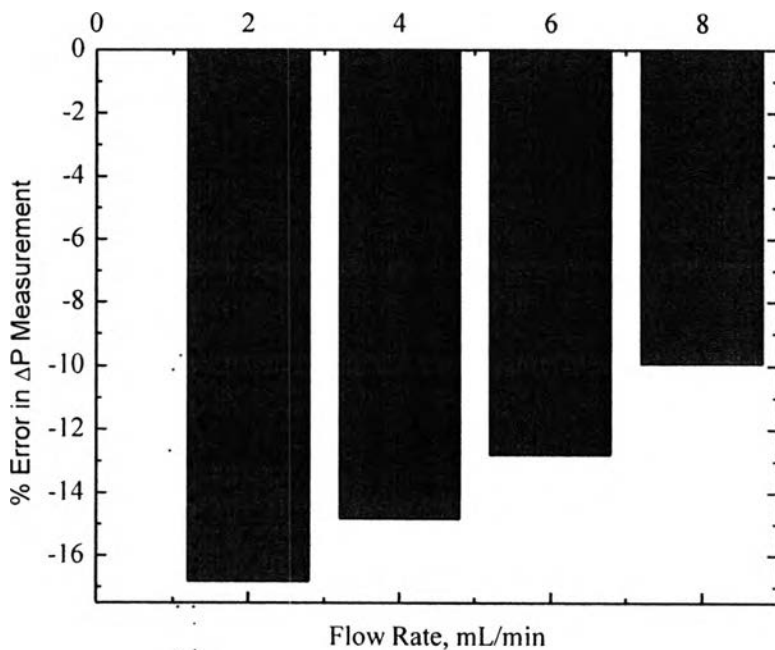


Figure 1.6 Error between theoretical and experimental values of pressure drop for different flow rates.

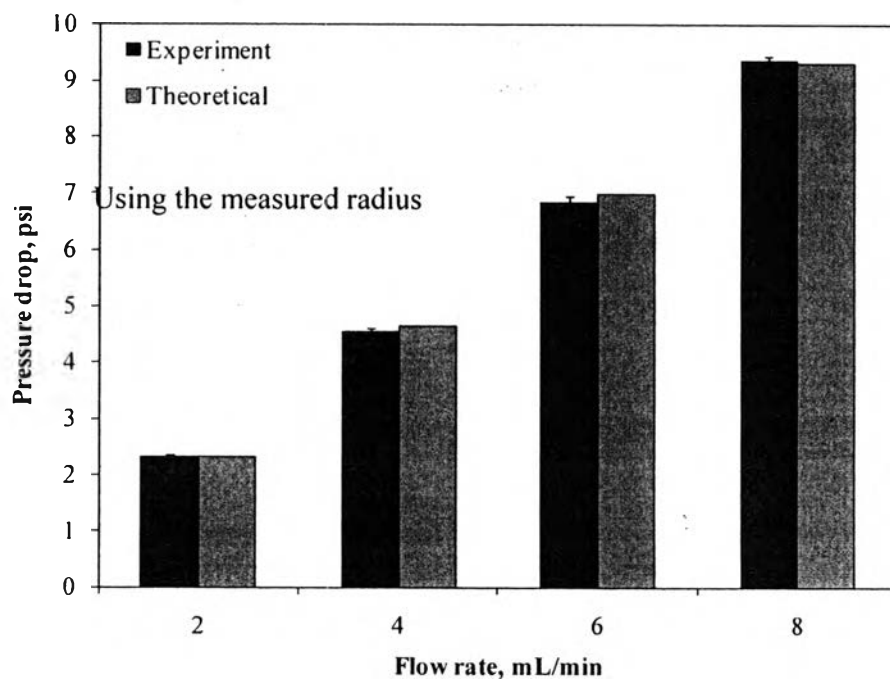


Figure 1.7 Theoretical and experimental values of pressure drop across the capillary for different flow rates, using measured radius for the calculations.

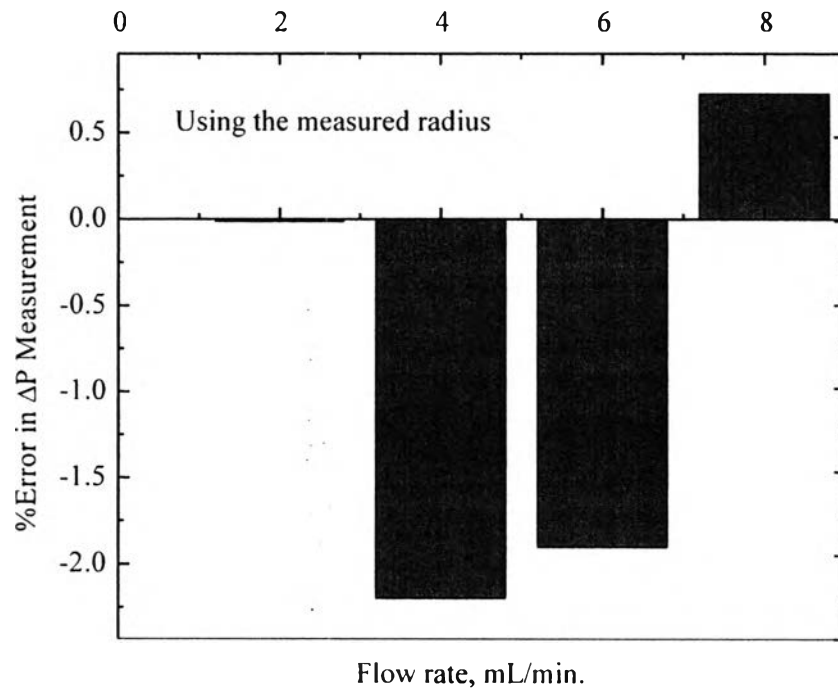


Figure 1.8 Error between theoretical and experimental values of pressure drop for different flow rates, using measured radius for the calculations.

Because of the sensitivity of the capillary radius on the pressure drop measurement, we have investigated radius of different batches of capillary which may cause the error in the pressure drop. In order to investigate this factor, water was run through two different batches of capillaries, A and B, and the pressure drop across capillary was measured. The difference in the pressure drop and radius for two batches of capillary are shown in Table 1.1:

Table 1.1 Comparison of ΔP and radius for a section of 2 batches of capillaries

Batches of capillaries	Length (ft)	Pressure drop (psi)	Capillary radius (inches)
A	3	2.25	0.0105
B	3	1.78	0.0110

As can be seen in Table 1.1, 5% error in capillary radius causes a 26% error in pressure drop at 2 mL/min. Therefore, the actual capillary radius needs to be determined for any particular experiments in order to minimize the error.

1.5.2 Initial Results

1.5.2.1 Barium sulfate deposition

The primary experiment was carried out with 3 ft length capillary at ambient temperature. 100 mg/L of barium chloride and sodium sulfate were used to study barium sulfate deposition. Figure 1.9 shows an increase in the pressure drop, indicating that the barium sulfate had started to deposit. The pressure drop at steady state, prior to deposit detection, is defined as ΔP_0 . The pressure drop due to deposition can be achieved by neglecting the steady state pressure drop, as show in Figure 1.10.

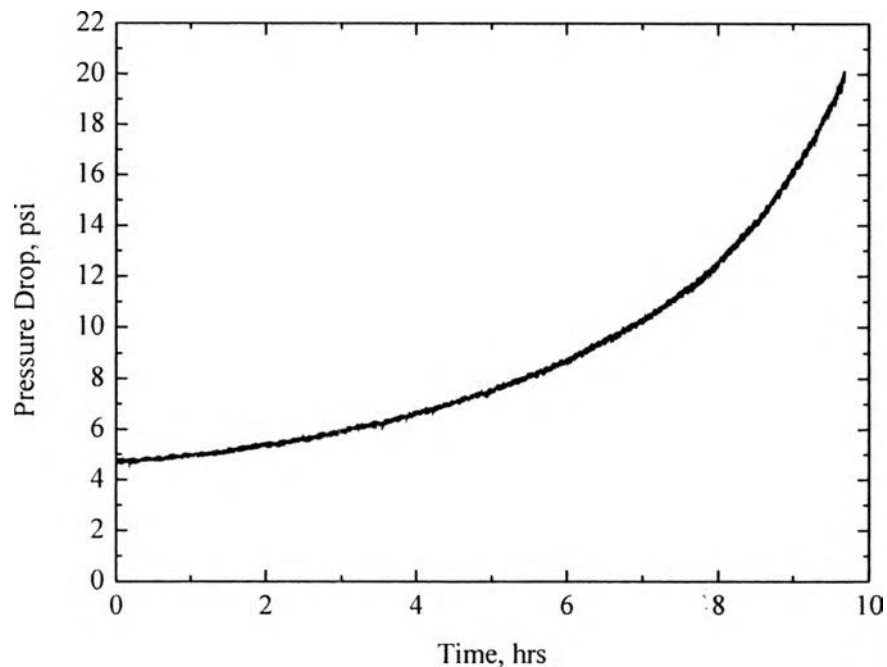


Figure 1.9 An increase in the pressure drop vs. time for 3 ft length capillary.

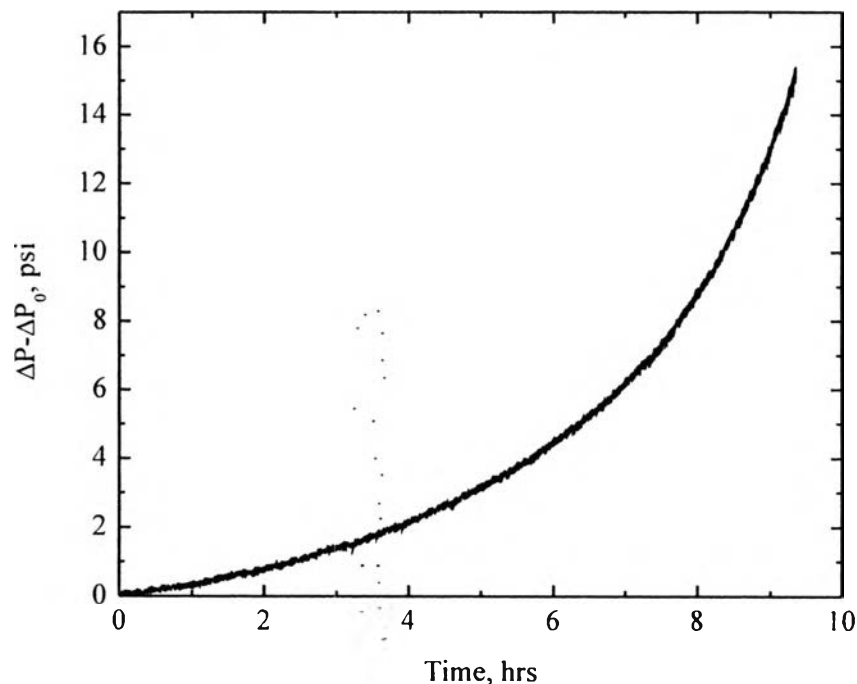


Figure 1.10 Pressure drop due to deposition vs. time for 3 ft length capillary.

1.5.2.2 Mass collection

As mentioned in Chapter 3, DTPA was used to dissolve the barium sulfate deposit in order to obtain amount of deposit. The deposit amount will be determined by ICP/MS composition analysis. Prior to mass collection experiment, an additional experiment was needed in order to confirm DTPA will completely dissolve BaSO_4 . A batch experiment was performed with 0.001M BaSO_4 in the 0.001 M DTPA solution and stirred at 300 RPM. The samples were withdrawn at different times, filtered through a $0.2\mu\text{m}$ PP filter, and measured with ICP/MS to determine the Ba^{2+} concentration. The result shows that DTPA is able to dissolve 100% BaSO_4 within 6 hours, as can be seen in Figure 1.11.

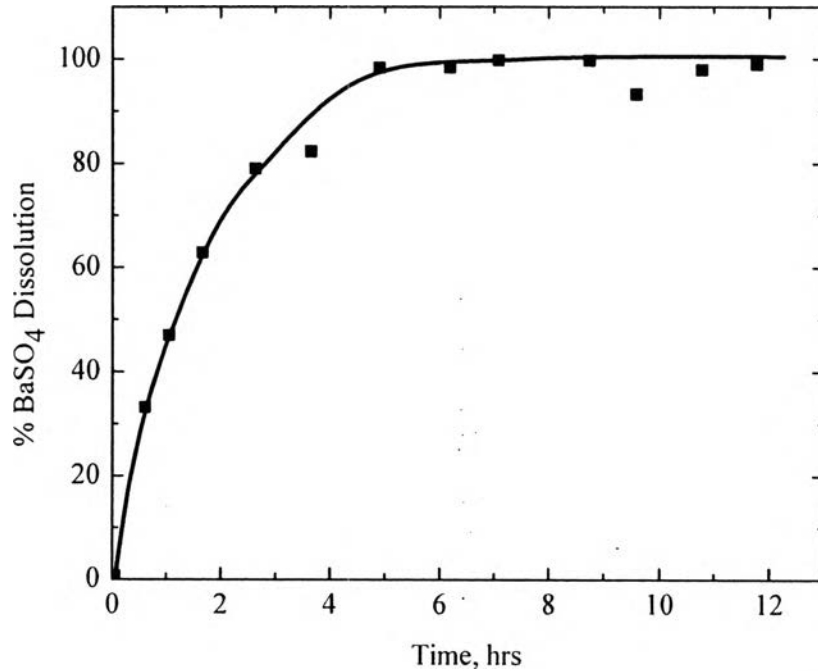


Figure 1.11 Percentage of barium sulfate dissolution as a function of time.

Therefore, we know that DTPA is suitable solution that we can use to dissolve barium sulfate deposits. For the initial experiment, shown in Figure 1.12, the total deposit collected mass was 56 mg. Additionally, capture efficiency of barium sulfate in the capillary inner wall was approximately 20%. In order to verify complete deposit removal, the pressure drop across capillary was measured after dissolution. Using Equation 1.6, we can calculate the capillary radius after dissolution and then compare with the initial capillary, as show in Table 1.2. The capillary radius after dissolution is reduced to a value which is close to the initial capillary radius, indicating most of the deposit has been removed.

Table 1.2 Comparison of capillary radius before deposition, after deposition, and after dissolution.

Length (ft)	Capillary radius (inches)		
	Before deposition	After deposition	After dissolution
3	0.0113	0.0069	0.0110

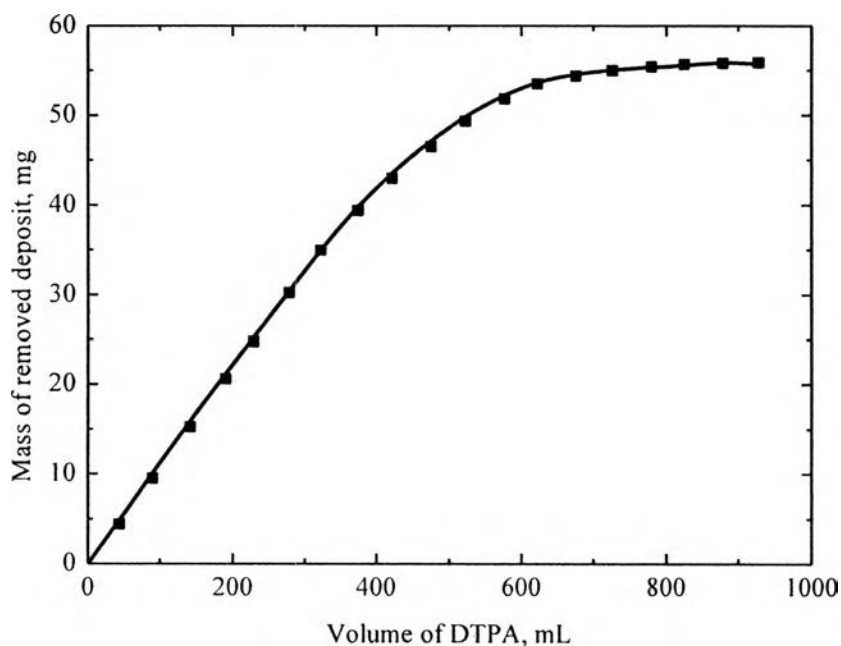


Figure 1.12 shows mass of removed deposit as a function of DTPA volume.

1.5.3 Deposition Analysis

1.5.3.1 Uniform deposition

A simple approach was applied in order to study the deposition mechanism. If we consider that deposition is uniform for entire capillary length, as shown in Figure 1.13, the calculated mass of uniform deposit can be estimated by Equation 1.7 where the final radius after deposition is calculated from the pressure drop after deposition by applying Equation 1.6.

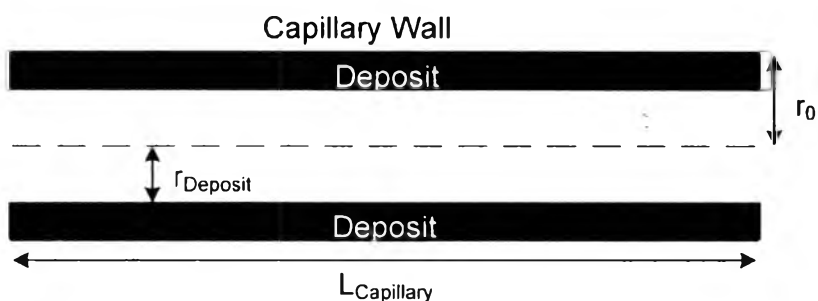


Figure 1.13 Schematic of uniform deposit analysis.

$$M_{Deposit} = L_{Deposit} \cdot \pi \cdot \rho_{Deposit} \cdot (r_0^2 - r_{Deposit}^2) \quad (1.7)$$

Where

$M_{Deposit}$ is deposit mass (mg.)

$L_{Deposit}$ is deposit length (mm.)

ρ is barium sulfate density (4.5 g/mL)

r_0 is initial radius of the capillary (mm.)

$r_{Deposit}$ is the final radius after deposition (mm.)

For the initial experiment, the mass required to form uniform deposit for entire capillary length was 600 mg. Unfortunately, the collected mass was observed only 56 mg. Therefore, the result indicates that the deposition is non-uniform.

1.5.3.2 Non-uniform Analysis

One approach has been developed to interpret the non-uniform deposition result by Hoepfner (2009). It was assumed that the capillary consists of two sections, one with a uniform deposit and another one with no deposit. A schematic of this technique can be found in Figure 1.14.

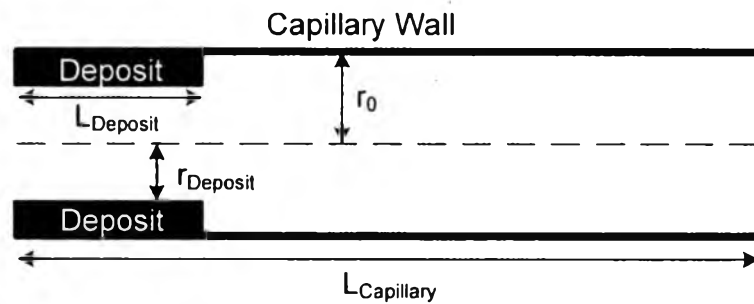


Figure 1.14 Schematic of non-uniform deposit analysis.

For an arbitrary number of segments, the pressure drop can be predicted by modifying Equation 1.6 to obtain Equation 1.8.

$$\Delta P = \sum_{i=1}^{segments} \frac{8\mu L_i Q}{\pi r_i^4} \quad (1.8)$$

If only two sections are considered, Equation 1.8 reduces to Equation 1.9:

$$\Delta P = \frac{8\mu Q}{\pi} \left(\frac{L_{Deposit}}{r_{Deposit}^4} + \frac{L_{Capillary} - L_{Deposit}}{r_0^4} \right) \quad (1.9)$$

Where $L_{Deposit}$ is the length of the deposit section of the capillary.
 $L_{Capillary}$ is the total length of the capillary
 $r_{Deposit}$ is the radius of the section which is constricted by the deposit
 r_0 is the capillary radius in the section with no deposit

If this analysis is combined with a mass balance which is shown in Equation 1.7, the two unknowns, $r_{Deposit}$ and $L_{Deposit}$, can be solved where $M_{Deposit}$ is the collected deposit mass. This approach was applied to the 3 ft length initial result and found that the uniform deposit section was only 0.185 ft long.

To further confirm the presence of a non-uniform deposit, a repeat experiment was conducted with a 3 ft length capillary and same condition with the initial experiment. After deposition, the capillary was cut into 3 sections, 1 ft of each as shown in Figure 1.15. Moreover, each of sections was individually collected the mass by DTPA solution described in section 1.3.

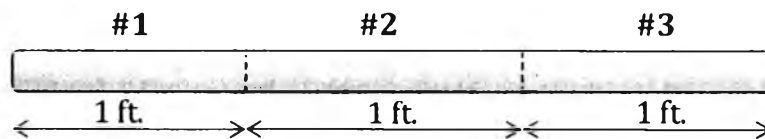


Figure 1.15 Schematic of capillary sections.

The results, shown in Table 1.3, show that more deposit is located at the beginning of capillary. The highest deposit mass was observed in the first 1 ft capillary section. One reason could be that there is a greater driving force, saturation ratio, which provides a higher chance of barium sulfate deposition at the beginning of the capillary. However, there are some deposits which have been collected at the second and third capillary sections, indicating that the non-uniform analysis cannot be applied in order to investigate deposition mechanism.

Additionally, deposition experiments performed on longer capillary used to better understand the deposition mechanism. The preliminary results can be seen in Appendix A.

Table 1.3 The collected mass of 3 capillary sections.

Capillary Sections	Collected Mass (mg)
1	28.4
2	23.9
3	7.2

1.5.4 Different Operation Time

To better understand deposition mechanism, an additional experiment was conducted with 3 ft length capillary for 6 hours operation time. After deposition, the capillary was cut into 3 sections, 1 ft each, as shown in Figure 1.15. The pressure drop of each capillary section was individually measured. For 6 hours experiment, after deposition, the measured pressure drop of each section is slightly different, as shown in Table 1.4. However, the mass required to form uniform deposit with the same pressure drop of each section, calculated by Equation 1.7, is largely less than the collected mass, as shown in Table 1.5. These finding shows that the deposits have formed a rough surface where the surface thickness, which contributes the pressure drop measurement, is same for entire capillary length during 6 hours operation. After 6 hours, barium sulfate was rapidly deposited at the beginning of the capillary due to the effect of barium sulfate deposit which covered the capillary inner wall. As can be seen in Table 1.4, the result of 10 hours experiment, the measured pressure drop of first 1 ft section was significantly higher than later sections.

Table 1.4 Comparison of the measured pressure drop of each section after deposition for different operation time.

Capillary Sections	Pressure drop (psi)	
	6 hours	10 hours
1	2.78	14.35
2	2.63	5.91
3	2.28	2.43

Table 1.5 Comparison of the calculated uniform deposit mass and the collected mass of each section after deposition.

Capillary Sections	6 hours experiment		10 hours experiment	
	Calculated uniform mass (mg.)	Collected mass (mg.)	Calculated uniform mass (mg.)	Collected mass (mg.)
1	96	11.28	202	28.40
2	90	7.97	148	23.86
3	71	4.44	60	7.25

1.6 Conclusions and Recommendations

1.6.1 Conclusions

The capillary flow technique has been developed as a potential technique to investigate barium sulfate deposition. Pressure drop across the capillary was measured to study how the deposit formed. The sensitivity of capillary diameter can give an error of pressure drop measurement with a range of 10-20%. For the mass collection procedure, it has been shown that DTPA is able to effectively dissolve an equal molarity of BaSO₄ within 6 hours. Therefore, DTPA is suitable compared to dissolve BaSO₄ deposits.

Once the technique has been developed, deposition experiments show that BaSO₄ deposits formed in a stainless steel capillary are highly non-uniform and preferentially located near the beginning of capillary. Moreover, the results show that the deposits have formed a rough surface where the surface thickness is same for entire capillary length during 6 hours operation. After 6 hours, barium sulfate was rapidly deposited at the beginning of the capillary due to the effect of barium sulfate deposit which covered the capillary inner wall.

1.6.2 Recommendations

- In this study, the main propose was to develop a capillary technique in order to investigate barium sulfate deposition. However, there is a need to further analysis to minimize the deposit at the mixing tee which could cause an increase in the pressure drop.

- Additionally, a variety of parameters which could affect the deposition needs to be investigated. Basic parameters could be: temperature, pressure, brine concentration, flow rate, and surface type of capillary.

- To further understand the deposition mechanism, one possible experiment is to flow precipitated barium sulfate into capillary. In order to do so, a new experimental technique needs to be developed.

- When the deposition mechanism has been well-understood, another challenging study is to develop a model in order to predict barium sulfate deposition.

1.7 References

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