DETERMINING THE TERMINAL VELOCITY AND THE PARTICLE SIZE OF EPOXY BASED FLUIDS IN THE WELLBORE

A Thesis

by

HASAN TURKMENOGLU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	Jerome J. Schubert
Committee Members,	Frederick Gene Beck
	Yuefeng Sun
Head of Department,	A. Daniel Hill

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ABSTRACT

Determining the Terminal Velocity and the Particle Size of Epoxy Based Fluids in the Wellbore. (August 2012)

Hasan Turkmenoglu, B.S., Middle East Technical University

Chair of Advisory Committee: Dr. Jerome J. Schubert

This thesis was inspired by the project funded by Bureau of Safety and Environment Enforcement (BSEE) to study the use of epoxy (or any cement alternative) to plug offshore wells damaged by hurricanes. The project focuses on non-cement materials to plug wells that are either destroyed or damaged to an extent where vertical intervention from the original wellhead is no longer possible. The proposed solution to this problem was to drill an offset well and intersect the original borehole at the very top and spot epoxy (or any suitable non-cement plugging material) in the original well. The spotted epoxy then would fall by gravitational force all the way down to the packer and then settle on top of the packer to plug the annulus of the damaged well permanently.

This thesis mainly concentrates on the factors affecting the fall rates and how to correlate them in order to derive an applicable test that can be conducted on the field or lab to calculate the terminal velocity of the known epoxy composition. Determining the settling velocity of the epoxy is crucial due to the fact that epoxy should not set prematurely for a better seal and isolation. The terminal velocity and the recovery for epoxy based plugging fluids were tested by using an experimental setup that was

developed for this purpose. The results were also validated by using an alternative experiment setup designed for this purpose. Factors affecting the terminal velocity and recovery of epoxy were studied in this research since the settling velocity of the epoxy is crucial because epoxy should not set prematurely for a better seal and isolation. The study was conducted by using an experiment setup that was specially developed for terminal velocity and recovery calculations for plugging fluids. Results obtained from the experiment setup were successfully correlated to epoxy's composition for estimating the terminal velocity of the mixture.

DEDICATION

Dedicated to…

Mom and Dad

&

Duygum

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Jerome Schubert, and my committee members, Dr. Gene Beck, Dr. Yuefeng Sun for their guidance and support throughout the course of this research and John Maldonado, Clayton Schubert, and Seth Williford for their help on the experimental setup.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the Bureau of Safety and Environment Enforcement (BSEE) for providing all the funding necessary for the research and Turkish Petroleum Corporation (TPAO) for sponsoring my graduate education in Texas A&M.

Finally, thanks to my mother and father for their encouragement and to my beloved one for her patience and love.

NOMENCLATURE

BSEE	Bureau of Safety and Environment Enforcement
TPAO	Turkish Petroleum Corporation
AIME	American Institute of Mining Engineers (former SPE)
SPE	Society of Petroleum Engineers
TETA	Triethylenetetraamine
PFS	Professional Fluid Systems
CIBP	Cast iron bridge plug
F_d	Drag force
μ	Fluid viscosity
R	Radius
V	Particle velocity
g	Acceleration due to gravity
$\boldsymbol{\rho_s}$	Particle density
$\boldsymbol{\rho_f}$	Fluid density
R_e	Reynolds Number
C_D	Drag coefficient
A_p	Projected area of an object
A	Area
Π	Number Pi
R	Radius of a circle

R1	Radius of an inner circle
R2	Radius of an outer circle
ID	Inner diameter
OD	Outer diameter
C_d	Weight percentage of diluent
C_b	Weight percentage of barite

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1. INTRODUCTION

Epoxy polymer based plugging fluids are among the solutions considered for plugging the damaged offshore wells which are not possible to plug by conventional means using cement. These wells are destroyed to a point where re-entering the well is impossible due to casing related (buckled casing) or seafloor related (wellhead buried under seafloor mud) problems. This will prevent reaching a packer to set a cement plug. Since cement is a water based fluid, it is miscible with seawater or brine which is a common packer fluid for offshore wells. Long interaction time with these fluids can cause contamination or dilution of the cement mix which eventually will cause the cement to fail to thicken or fail to reach the required compressive strength. Therefore, wells destroyed or damaged enough to prevent conventional plugging are not suitable for plugging with cement slurry because the cement needs to be delivered to the point of interest with minimum or no interaction with the sea-water or brine. The only way to achieve this by conventional methods is to drill an intersection well which intersects the damaged borehole near the packer, meaning a drilling operation close to the full depth. This is most likely to be a very costly and time consuming operation which will probably offset the competitive price advantage of cement on the alternative plugging materials.

An alternative way to plug these wells is to drill an intersection well that intersects the original wellbore at the very top through perforations between the wells.

This thesis follows the style of *SPE Drilling & Completion.*

Then the epoxy would be injected (spotted) inside the original wellbore. From this point to the packer, epoxy is expected to settle by gravity all the way down to the packer assuming the well is not flowing at the time of settling. Since the epoxy in general does not mix with water or brines, it is the best plugging fluid candidate for the proposed operation.

In the past years many oil platforms have been either completely destroyed or extremely damaged by hurricanes. **Table 1** shows the number of destroyed or extremely damaged platforms according to the BSEE released documents.

Table 1.1 Number of wells damaged or destroyed by hurricanes. (as of 2010)

Hurricane	No. Destroyed	No. Extremely Damaged
Rita & Katrina	113	144
Ike & Gustav	60	31
Ivan, Andrew & Lily	18	

Table 1.1 shows that the total number of destroyed or damaged platforms exceeds 350. All these wells need to be plugged prior to abandoning.

This thesis is part of a project funded by BSEE which investigates the applicability of epoxy based or other non-cement plugging fluid to plug hurricane damaged wells. The applicability of epoxy based plugging materials for abandonment and plugging operations has not been adequately studied in the industry and this research aims to fill this gap.

The work conducted in this thesis is expected to help 2 points,

1) Determining whether epoxy material can effectively drop 7000 feet through a casing annuli and accumulate on top of the packer
2) Determining how long it takes the material to travel to the bottom of a casing annuli and cure.

The experiment setup designed and constructed by El-Mallawany (2010) was used to collect data for the fall rates and the collected data was analyzed to propose an applicable test method and correlation on estimating the fall rates for various epoxy compositions. I also tried estimate and report the amount of epoxy that would adhere to the walls of the pipe.

2. LITERATURE REVIEW

There are many examples of epoxy polymer used in the industry. Stabilizing emulsions (oil based), formation plugging applications, sand consolidation, resin coated proppants, remedial casing applications, plastic plugback applications, substituting emulsifiers, strengthening fractured formations for wellbore stability and many other applications.

In order to confront the more complex offshore drilling challenges, adaptation of the drilling mud composition and properties for the advanced well conditions (high temperature and low pressure) Audibert et al. (2004) suggested using epoxy polymers. They named it EMUL in their work, and compared the results they obtained from the lab work to the other commercially available systems. It is stated that the mud stability can be achieved and formation of hydrates can be prevented by using this new system.

Bosma et al. (1998) studied the possibility of abandoning wells by a cost effective through tubing well abandonment method. The idea was to reduce the cost by proposing an alternative to the traditional abandonment method where the operator needs to remove the tubing and set a mechanical barrier before the plug. The authors argued that significant saving could be made if wells could be abandoned by a coiled tubing operation, during which the production tubing could be left in the well. Epoxy polymer was one of the alternatives to the regular cement along with the silicone rubber and silicone gel. Experiment setup used in their work is show on **Figure 2.1**.

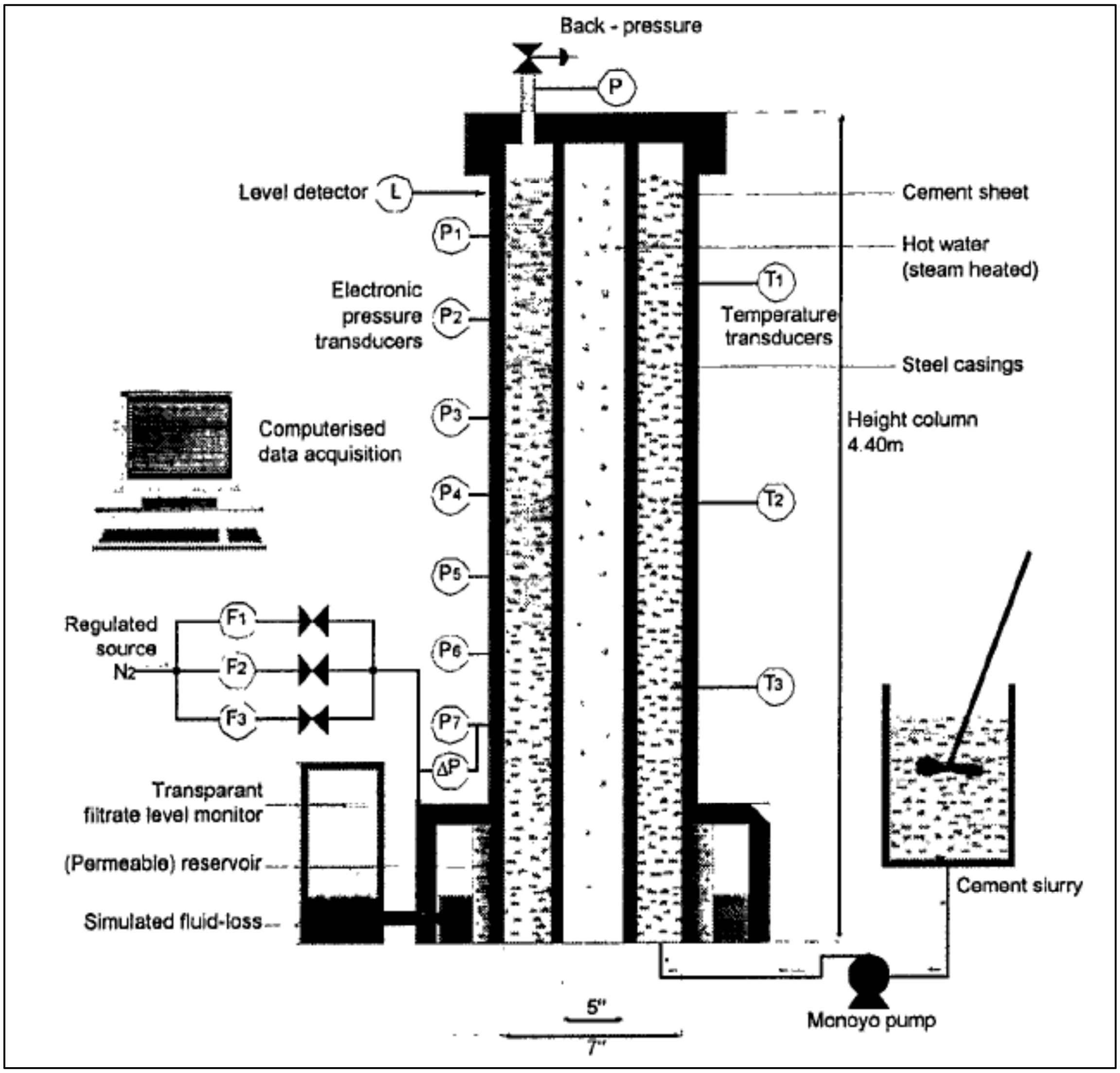

Figure 2.1 Schematic of the experiment setup used in Bosma et al.'s work (Bosma et al. 1998)

Nguyen et al. (2004) studied the possibility of stabilizing wellbores in unconsolidated, clay-laden formations by using epoxy polymers while Knapp et al. (1978) suggested that and acrylic/epoxy emulsion gel system could be used for formation plugging in their laboratory work. **Figure 2.2** shows the images obtained before and after flooding the clay formation in Nguyen et al.’s work. A Case Study of Plastic Plugbacks on Gravel Packed Wells in the Gulf of Mexico was presented at the SPE Production Operations Symposium in Oklahoma City, Oklahoma by Rice (1991). Rice argued that a special chemical mixture can be used instead of cement for wells with a conventional screen such as gravel packs to isolate the water producing zones. He suggested that the cement does not adequately fill the desired section thus a new chemical mixture (containing epoxy polymer) would be more appropriate for plastic plugback technique that was first introduced in 1988 by Carrol and Bullen. The success rate reported in his paper was a high as 67% in isolating the water producing zones in 21 field applications conducted by Chevron USA Inc.

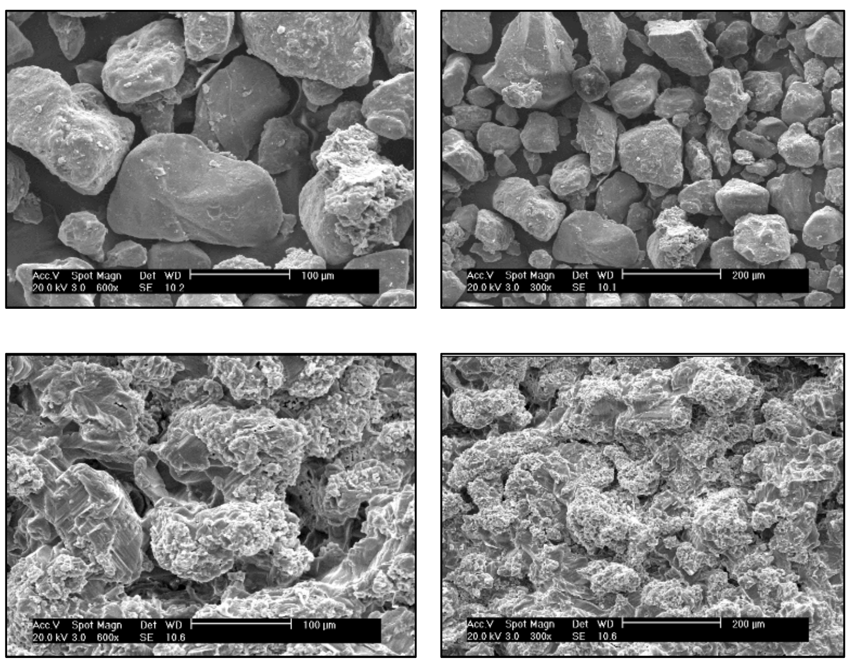

Figure 2.2 Epoxy flooded formations under microscope (Nguyen et al. 2004)

In one of the studies conducted by Soroush et al. (2006) epoxy polymer was suggested as a formation consolidation chemical especially for fractured formations to provide wellbore stability by increasing the formation strength. The term “chemical casing” was used to identify the interval saturated thus strengthened by epoxy polymers. Many advantages and disadvantages of using various chemicals were discussed in their paper Investigation into Strengthening Methods for Stabilizing Wellbores in Fractured Formations.

There is also a US patent Ng et al. (1992) that discusses using epoxy polymers to repair corroded casing in a wellbore. It is suggested in the patent that the corroded casing section is milled out and a retrievable packer is placed under the milled section. The epoxy is placed above the packer to fill the milled section and any thief formation section. The patent suggests that the epoxy is either placed using a dump bailer or using coiled tubing.

Both of these placement methods mentioned in the patent are of course not suitable for the intended application of this thesis. The patents also suggests some epoxy based materials namely Shell’s EPON-828 and Shell’s EPON DPL-862 as the resin and a Sherling Berlin’s diluent 7 as a reactive diluent and fine powdered calcium carbonate or silica flour as a filler and lastly Serling Berlin’s Euredur200 3123 as a curing agent. The diluent’s function is to increase the pot life and gel time of the resin and decrease the epoxy’s viscosity. The filler’s function is to increase the specific gravity of the resin so the resin does not float and start settling on the packer. The curing agent’s job is to make the resin crosslink and therefore harden.

Figure 2.3 from the patent describes the process where epoxy is placed to repair the corroded casing and thief zones and then drilled off.

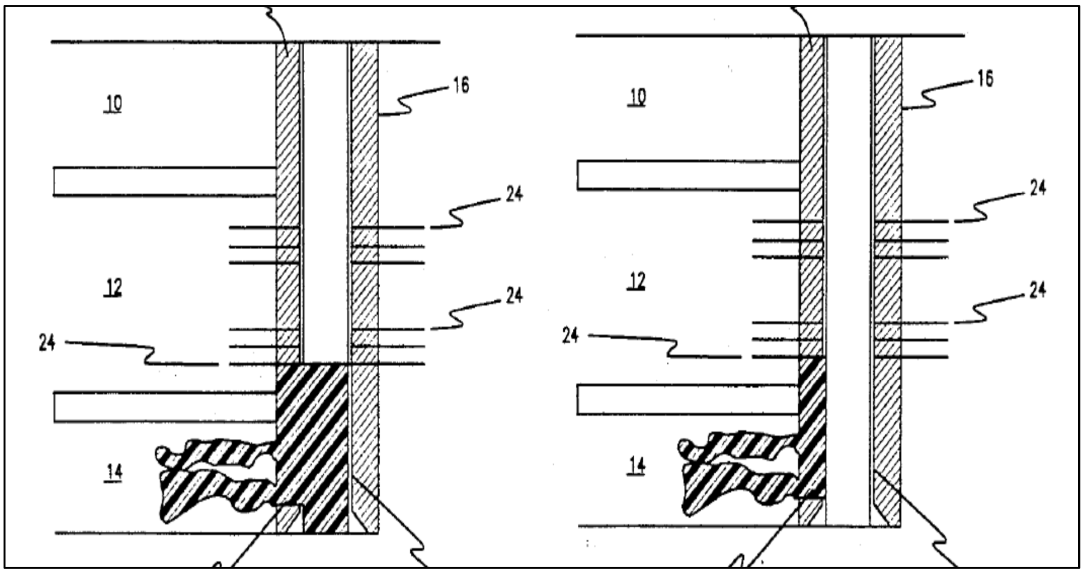

Figure 2.3 Epoxy used for remedial casing procedure (Ng 1994)

Knapp and Welbourn (1978) discussed the possible use of epoxy for formation plugging in their research which was also mentioned in their paper that was presented at the fifth Symposium on Improved Method for Oil Recovery of the Society of Petroleum Engineers of AIME held in Tulsa. It suggests the use of a resin in an emulsion where droplets are less than 1 micron in diameter which are able to seep through the pore spaces of the formation. They suggest pumping the resin in the formation first then pump the curing agent after it. This causes regions of high permeability in the formation to be preferentially sealed. The reason for this application is the cut the water or gas production from a formation. It is also used to control water injection wells to make sure the water is not lost in unwanted zones. The resin's use here is to plug the areas of high permeability and direct the injected water to flow in the desired sections of the reservoir.

The only resin product that has been applied for a similar application to the one we are focusing on is a product called Ultra-Seal from a company named Professional Fluid Systems. The company has applied this resin on similar applications that are limited in number. High Island Block A330 platform that plugged and abandoned, and is an example of these applications. Several years after abandoning, gas seepage from the pressure cap of the well was detected by coincidence when a recreational diver was swimming by. When the company removed the pressure cap by using a diamond saw, they observed that the seepage was coming from the micro-annuli between the cement and the casing walls. The tubing was then sealed with a CIBP and the pressure cap was reinstalled. Liquid Bridge Plug (Ultra-Seal) was pumped inside the micro-annuli and was waited on for 20 hours. The plug was tested to be successful in sealing and the gas seepage was stopped. Another example of the application of Ultra-seal is Chevron's Vermillion 31 platform. When the platform had a leaking packer and the company wanted a way to seal the packer without using the rig equipment, Ultra-seal was used. Annular fluid in this case was 8.6 lb/gal seawater and ultra-seal was weighted up with a filler material to increase its terminal velocity (or settling velocity) during its fall through the seawater thus reducing the total time required to reach the packer. A total of 168 gallons of the resin was loaded into the annulus and was allowed to fall for 14 hours and then set on the packer for an additional 24 hours. After curing, the plug was pressure tested at 1,000 psi and no pressure loss was detected.

CSI technologies has some laboratory work on the Ultra-Seal fall rates but these are very small scale compared to the experiment setup that was used in this work. A 2 inch diameter 5 feet in length clear glass pipe was used. A copper pipe was inserted in the first two feet of the pipe to act as a stringer.

Figure 2.4 Experiment setup that was built by CSI Technologies

The whole system was filled with brine weighted with calcium bromide and had a density of 10.4 lb./gal. Epoxy was then loaded into the copper pipe and time was measured to calculate the speed of epoxy from the copper pipe to the bottom of the clear pipe. **Figure 2.4** shows the experimental setup that was used in this study.

The clear tubing shown on the Figure 2.4 was divided into 3 equal sections (1 foot each) and time was measured at every 1 foot interval as the particle fell. Barite was used as a filler to weight the epoxy to a density of 16 lb./gal. The time it took for the resin to reach the bottom of the cleat tube was measured as 5 seconds. The measurement was made visually. The experiment was repeated 3 times giving the same result of 5 second for 3 feet section. The fall rate was accepted to be 36 ft./min. Although this is a simple and logical way to obtain the fall rate data for epoxy, this experiment has many possible flaws. The first and most important deficiency of this experiment was that the effects of different parameters such as pipe diameter, epoxy density and viscosity, annular fluid density and viscosity were not taken into consideration. 3 foot interval for terminal velocity observation is probably not long enough to claim that the fluid reached its terminal velocity before the pipe ends. Having a small length of tube for the observation will also yield large errors in the velocity calculation.

3. THEORETICAL BACKGROUND ON TERMINAL VELOCITY

Determining the terminal velocity of a particle in a liquid medium has been an issue for petroleum engineers for quite a long time. Slip velocity of particles in a drilling mud, migration velocity of gas bubbles in a kick during well control operations, settling particles in a tank and many other examples in the petroleum industry have the same concept behind the working mechanism.

There are a few fundamental concepts behind the theory of settling objects. The most famous and known theory is the Stokes' law. Stokes' law provides an equation to predict the settling of solids or liquid droplets in a fluid, either gas or liquid. The law assumes that the settling object is a small sphere and that the difference in densities is not large. This is because Stokes' law takes into account only the viscous forces that cause drag and does not account for drag due to impact forces. Therefore, Stokes' law only applies where Reynolds number is very low. Stokes' law is given by the following equation (Batchelor 1967).

$$F_d = 6\,\pi\,\mu\,R\,V \qquad (1)$$

where F_d is the drag force, μ is the fluid's viscosity, R is the sphere's radius and V is the particle's velocity.

When a settling particle reaches the terminal velocity, we can say that the net forces acting on the particle are equal to zero since the particle is not accelerating anymore. This implies that the drag force should be equal to the difference between the gravitational forces and buoyancy forces. Having said that, we can rearrange the formula for drag forces as the following

$$F_d = \frac{4}{3}\,\pi\, R^3\left(\rho_{s-}\,\rho_f\right)g \tag{2}$$

where g is the acceleration due to gravity, ρ_s is the particle's density and ρ_f is the fluid's density.

Now by equating equations (1) and (2) we can solve for the terminal velocity which leads to the following equation

$$V = \frac{2R^2(\rho_{s-}\,\rho_f)g}{9\mu} \tag{3}$$

It was found that (experimentally) the error margin is within 1% when the Reynolds number is less than 0.1 for this equation. When the Reynolds numbers varies between 0.1 and 0.5 then the error increases to 3% and between 0.5 and 1.0 the error reaches to 9% margin. When the Reynolds number is greater than 1, drag due to the impact becomes so significant that the Stoke's law yields larges errors due to the nature of the estimation (it neglects the drag due to impact). Reynolds number can be calculated by using the following equation (Coulson et al. 2002).

$$R_e = \frac{4R^3 g\rho_f(\rho_s - \rho_f)}{9\mu^2} \tag{4}$$

When the Reynolds number is greater than 1, then the impact forces become much more significant and dominant where viscous forces can be ignored. In this case, Newtonian drag is the determining factor for the terminal velocity. Newtonian drag introduces a new parameter called the drag coefficient (C_D) that represents the ratio of the force exerted on the particle by the fluid divided by its impact pressure. The coefficient can be calculated by (Batchelor 1967),

$$C_D = \frac{2F_d}{\rho_f V^2 A_p} \tag{5}$$

where A_p is the projected area of the object that is perpendicular to the direction of flow. For a sphere, the projected area of its shape is a circle and can be calculated by $A_p = \pi r^2$.

For a spherical particle settling in a fluid at a terminal velocity, Newtonian drag could be obtained by integrating equation (5) into (2) to obtain the following (Batchelor 1967),

$$V = \sqrt{\frac{4(\rho_s - \rho_f)gr}{3C_D\rho_f}} \tag{6}$$

Table 2.1 has some examples of drag coefficients for different shapes and materials. It should be noted that the drag coefficient also depends on the Reynolds number.

Table 2.1 Drag coefficients of different objects (Coulson et al. 2002)

C_D	Object
0.48	rough sphere (Re = 10e6)
0.005	turbulent flat plate parallel to the flow (Re = 10e6)
0.24	lowest of production cars (Mercedes-Benz E-Class Coupé)
0.295	bullet
1.0–1.3	man (upright position)
1.28	flat plate perpendicular to flow
1.0–1.1	skier
1.0–1.3	wires and cables
1.1-1.3	ski jumper
0.1	smooth sphere (Re = 10e6)
0.001	laminar flat plate parallel to the flow (Re = 10e6)
1.98–2.05	flat plate perpendicular to flow (2D)

Newtonian drag should be applied to particles with Reynolds number above 1000. For the cases which fall in between 1 and 1000 (intermediate values) for Reynolds number where both viscous and impact forces have significant effects on the terminal velocity, a transitional drag regime can be observed. An empirical equation for such cases was developed by Schiller and Naumann and is given by the following equation (Coulson et al. 2002),

$$C_D = \frac{24}{R_e}\left(1 + 0.15\, R_e^{0.687}\right) \qquad (7)$$

By using equations (4), (6) and (7), terminal velocity of a particle can be calculated. The only problem in applying these equations to epoxy fall tests is that they all require the particle size and shape (sphere). In my research however, shape is unknown and the velocity is measured with the help of the experiment setup. My main objective in this research is to correlate the velocity of the epoxy with at least one of its properties and substitute this property of the epoxy with the unknown size and shape of the particle so that estimating the terminal velocity of epoxy would be possible.

4. CONDUCTED WORK

After gathering enough data from the experimental setup that was developed by Ibrahim El-Mallawany, these results were tabulated and the relationship between the terminal velocity and the rheological properties of the epoxy were discussed. As an alternative to the already constructed experimental setup, a smaller scale experimental setup was built for further investigation and data validation.

The experimental setup at hand (static) consists of a 25 ft long pipe fixed on a pipe rack. The pipe is mounted on the rack which is able to be oriented the pipe from horizontal to vertical or any angle in between. The pipe acts as the wellbore in this experiment setup. The pipe is filled with the completion fluid which is sea water or simply fresh water. The setup allows the user to retrieve epoxy after it falls and clean the pipe after each run. There are pressure transducers for observing the pressure change along the pipe. For simplicity, the experimental setup is used with only one fixed pipe dimension. Different combinations were used when necessary. Terminal velocity obtained from the experiments was used as a constant velocity for the real-life scenario. In reality, the epoxy will accelerate first before reaching the terminal velocity but the distance covered with terminal velocity will be large compared to the acceleration zone in a 7000 ft. well. Thus the acceleration section was ignored and the velocity of the epoxy derived from the experimental setup was considered as constant terminal velocity.

The new experimental setup consists of a closed pipe system where the water is circulated at a constant rate and the annular velocity is kept close to the results obtained in the previous experiment to validate the results obtained from the previous setup. After reaching a stabilized flow in the closed system, small amounts of epoxy were injected into the pipe with a help of syringe or similar device. The expectation was that the epoxy droplet would be suspended in the upward flowing water thus validate the results obtained from the first experimental setup. Specifications of the new experimental setup will be discussed in the next sections of this thesis.

5. EXPERIMENTAL SETUP

There is two experimental setups studied in this research. The first one is the setup that was constructed by Ibrahim El-Mallawany for the epoxy fall tests in 2010. The second experimental setup was constructed to validate the results obtained from the previous setup. The first setup has a static water column in the 7" clear pipe, thus it will be called the "static setup" for convenience while the second experiment will be called the "dynamic setup" due to the fact that it has flowing water system in the 3" clear pipe. Details for the both setups will be discussed under this topic and experimental data will be discussed in the next section of this thesis.

5.1 The Static Experiment Setup Design

There are two main components to the static experiment setup: the pipe support and the base for the pipe support.

5.1.1 Static Design Assembly

The 3D representation for the completed system is shown in F**igure 5.1** and **Figure 5.2.** The pipe support along with the 7" pipe attached to it is mounted on the base and the hoist cable is attached to the pipe support for moving the system to different angles. The base of the experiment setup is anchored to the ground in order to prevent the setup from being tumbled over.

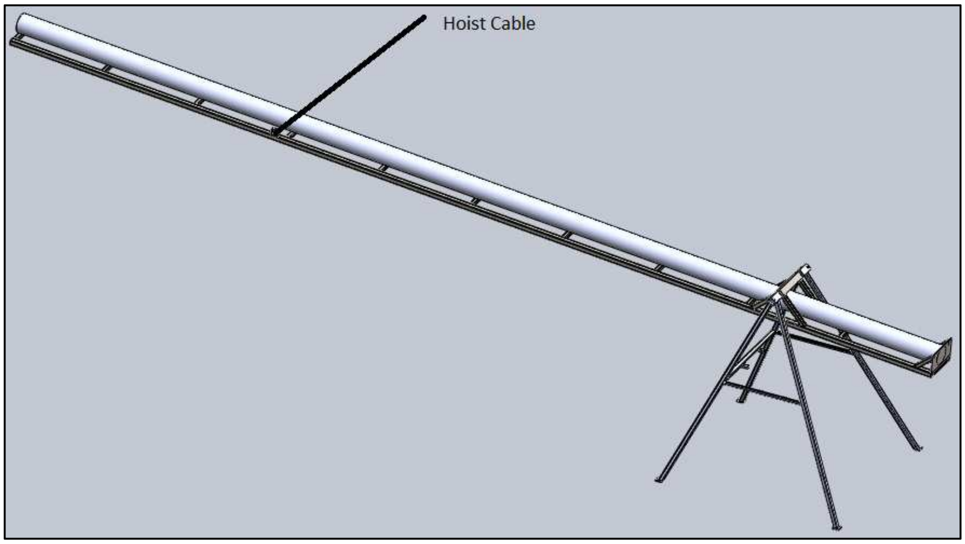

Figure 5.1 3-D model of the assembly (El-Mallawany 2010)

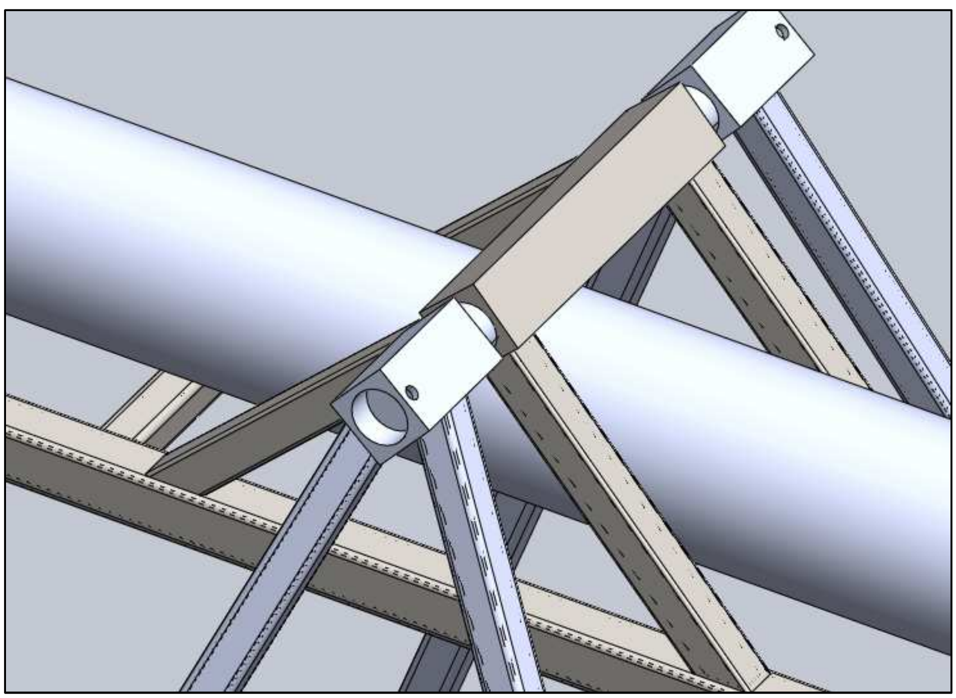

Figure 5.2 Zoomed 3-D view of the connection between the pipe support and the base (El-Mallawany 2010)

Assembly is simply put together by placing the pipe support's 2" hole concentrically with the base's 2" hole and pushing the pin inside. Then finally adding the two restricting bolts to restrict the pin from coming out.

Since the hoist's cable can only pull the pipe support but cannot push it down, it was made sure that the pipe support's weight always provided a torque in a direction opposite to that of the cable so it can lower itself in the right direction when the cable is slack.

The base has two stops to prevent the pipe from tumbling after reaching vertical position. **Figure 5.3** shows the stops in action.

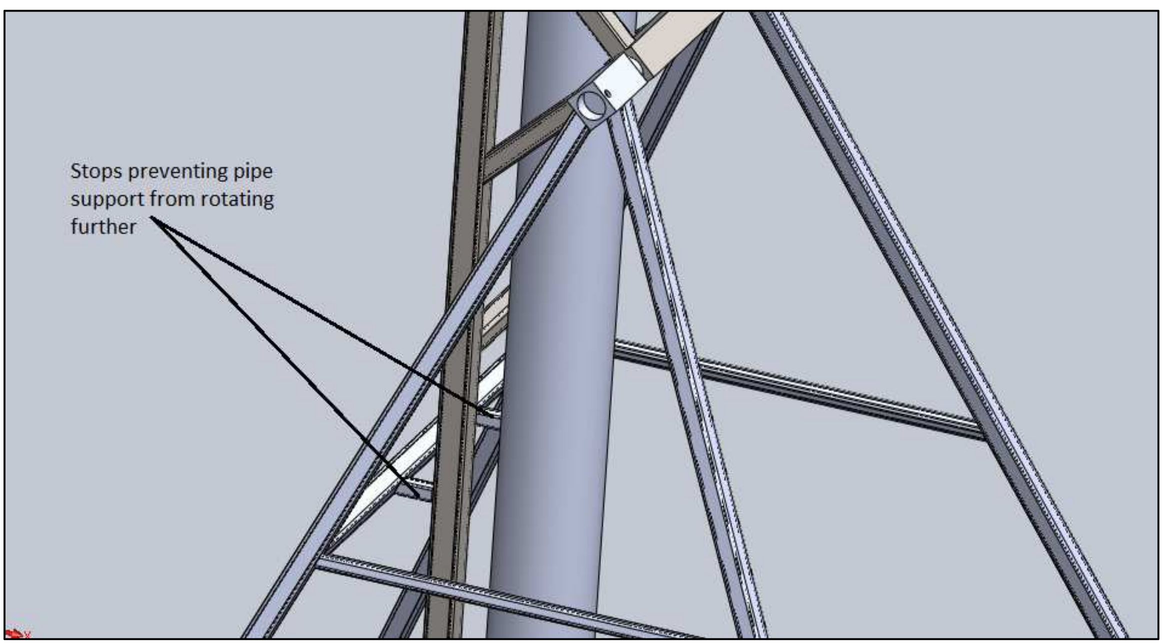

Figure 5.3 The stops of the base in action (El-Mallawany 2010)

5.2 The Dynamic Experimental Setup Design

The purpose for building the dynamic experimental setup was to validate the results obtained from the static setup. If the turbulence in the pipe allows the epoxy particle to be observed in the clear pipe, then the results obtained from the static setup can be put to test in this dynamic setup. The dynamic setup simply consists of a closed system with a 3-inch clear tubing in vertical position. The orientation of the clear tubing can be adjusted if required. The power required for the circulation is derived from a ¾" pump which is capable of pumping 24 gal/min water (@1 ft. head). Specifications for the pump will be discussed in the next sections of this thesis.

5.2.1 The Pump

The pump used in the assembly was a ¾" inlet and ¾" outlet pump with a pressure rating up to 150 psi. It can be found in most home-care stores under the name "hot water circulator pump". This specific pump was manufactured by Bell & Gossett Company. The technical specifications for the pump are shown on **Table 5.1**.

Table 5.1 Technical specifications for the pump used for the research.

Item	Circulator Pump
Type	Closed Loop
Series	NRF
Style	Wet Rotor
Speed	3
HP	1/15
Voltage	115
Phase	1
Amps	1.1
Inlet/Outlet	Flanged
Housing Material	Cast Iron
Face to Face Dimension (In.)	6-3/8

Table 5.1 Continued.

Max. Working Pressure (PSI)	150
Flange/Union Included	No
Shut-Off (Ft.)	18.5
RPM	2950
Impeller Material	Noryl
Shaft Material	Ceramic
Thermal Protection	Auto
GPM of Water @ 1 Ft. of Head	24
GPM of Water @ 5 Ft. of Head	19
GPM of Water @ 6 Ft. of Head	18
GPM of Water @ 7 Ft. of Head	16
GPM of Water @ 8 Ft. of Head	15
GPM of Water @ 9 Ft. of Head	14
GPM of Water @ 10 Ft. of Head	13
GPM of Water @ 11 Ft. of Head	12
GPM of Water @ 12 Ft. of Head	10.5
GPM of Water @ 13 Ft. of Head	10
GPM of Water @ 15 Ft. of Head	6.5
Best Efficiency GPM @ Head (Ft.)	15 @ 8
Min. GPM @ Head (Ft.)	1 @ 18
Drive Type	Direct
Bearing Type	Sleeve
Watts	125
Feet of Head @ 20 GPM	4

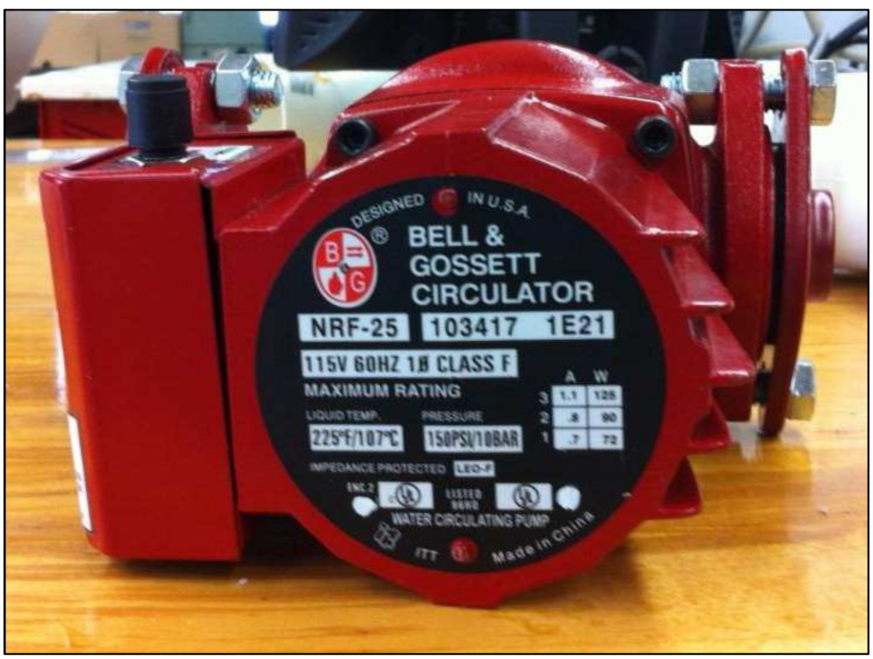

Figure 5.4 ¾" Pump specifications mentioned on the label of the pump

Figure 5.5 ¾" Pump (The pump has 3 different speeds that can be adjusted by the switch)

Figure 5.6 ¾" Pump inlet view

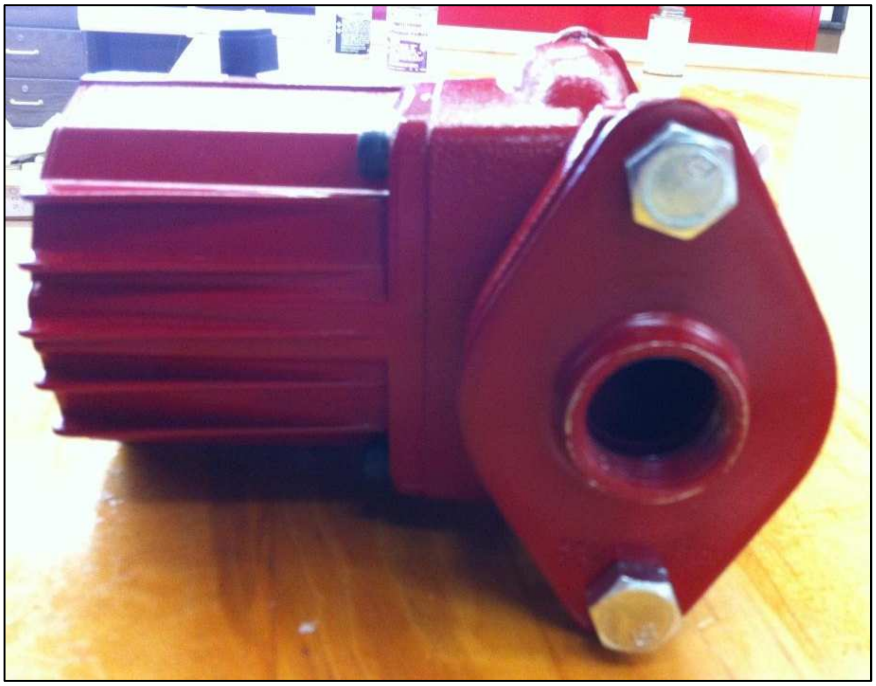

Figure 5.7 ¾" Pump outlet view

5.2.2 The Valves

There are two valves in the assembly. The first valve is placed right after the pump to regulate the flow if necessary. The second valve is simply the drainage valve for draining the 3" tubing when necessary. This valve is placed right before the 3" tubing with a "T" connection. Both of the valves a socket ball type with 1" ID. The valves are connected with hard pipes of 1" in ID.

Figure 5.8 1” PVC valve used in the assembly

Figure 5.9 1” PVC valve with threaded connection used in the assembly

Figure 5.10 1” Hard pipes with threaded connections

5.2.3 The Flow-meter

Flow meter’s function in this assembly is to make sure that the system has a stable and constant water flow before each trial. The display unit for the screen is in gallons. The flow meter has screw type connections which are 1” in diameter. Technical specifications are shown on **Table 5.2.**

5.2.4 The 3-inch Vertical Tubing

3” clear tubing is the main component of the whole assembly. The reason for having clear tubing for this assembly was to be able to observe the water flow in the tubing while injecting the epoxy. The behavior of the epoxy was observed both in static

Table 5.2 Technical specifications for the flow meter

Item	Flowmeter
Type	Turbine, For Water
Housing Material	Nylon
Fitting Size (In.)	1
Flow Material	Water
Fitting Type	FNPT
Accuracy (%)	+/-5
Wetted Materials	304 SS, Nylon, Tungsten Carbide, Ceramic
Pressure Rating (PSI)	150
Fluid Temp. Range (Deg. F)	14 to 130
Max. Viscosity	5cP
Sensor Type	Magnetic
Rotor Type	Nylon
Display Units	Gallon
Display Type	Standard LC Display
Flow Range	3 to 30 gpm
Repeatability	0.50%
Fluid Temp. Range (Deg. C)	0 to 60
Strainer	55 Mesh
Agency Compliance	CE

Figure 5.11 1” Flow meter

water and flowing water conditions. Length of the tubing was initially set to 6 ft. and observed that it was a sufficient length for the purpose of this work. The 3” clear tubing is connected to the 1” pipe system with an adapter. Switching from a narrow clearance to larger tubing would cause instability in the water flow but this was not an issue since the epoxy was injected from the top of the clear tubing.

Figure 5.12 3” OD tubing with 6’ length

5.2.5 The Reservoir

Since it is a closed water circulation system, there is no need for a constant water supply or such kind. Having a closed system also enables us to use a relatively small reservoir to act as an intermediate medium for the pump and the circulated water. In this research, a plastic cylindrical 4 gallon tank was used.

Figure 5.13 Reservoir for the pump's water supply. Once the system is filled with water, the only function of this reservoir was to act as an intermediate medium for the circulated water.

The tank is connected to the pump via ¾” clear hose with ¾” fittings. **Figure 5.13** shows the tank’s shape and the connection method to the pump.

5.2.6 The Supporting Infrastructure

In order to keep the 3” tubing in a vertical position and support it during the experimental runs, a supporting structure was built. The supporting structure was built by joining uni-struts together by simply using bolts on the joints.

Figure 5.14 The support structure

The structure was built on four wheels in order to move the assembly when needed (for water refill or drainage purposes). Height of the assembly is 105 inches, width is 33 inches and the length of the platform is 49 inches.

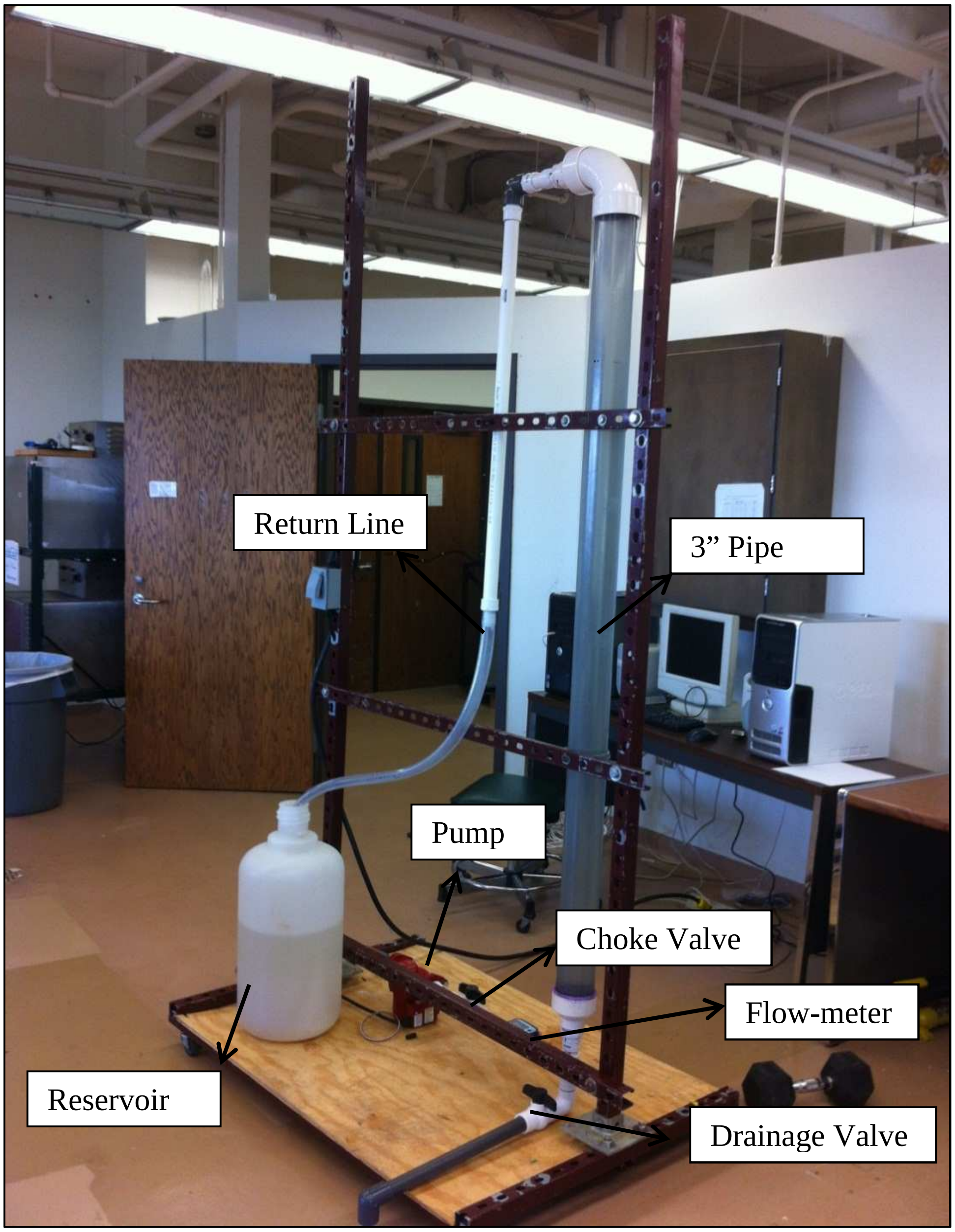

Figure 5.15 The completed experimental setup

6. THE EXPERIMENTS

The objective of this thesis was to test an epoxy sample that is representative to what would be used in a real application. Ultra-Seal, which is produced by one of the well-known manufacturers in the industry Professional Fluid Systems (PFS) was used in the tests. Ultra-Seal has been successfully used in similar applications to the one that we are studying (see the introduction for more information). It's prior use in the industry was the main reason for using Ultra-Seal in this research.

Ultra-Seal as with most other epoxies is a mixture of four main components, an epoxy (resin), a diluent, a hardener and a filler material. *The epoxy or the resin* consists of monomers or short chain polymers that have an epoxide group at their end. The epoxide group is cyclic ether that consists of three atoms that form a shape that resembles an equilateral triangle. This shape makes the epoxide highly strained and therefore reactive. *The hardener* mainly consists of polyamine monomers such as triethylenetetraamine (TETA) that readily form stable covalent bonds with more than 1 epoxide (crosslinking) like for example TETA can form up to four bonds. The product therefore becomes heavily cross-linked and becomes hard and strong. *The diluent* is used to reduce viscosity of the epoxy to make it easier to pump. The diluent is also used to increase pot life and gel time. (Ng 1994) *The filler* is used to increase the density of the mixture. In the oil industry *barite* is the most common filler material even with epoxy.

To be able to try different densities and viscosities of epoxy mixtures each constituent was obtained separately from PFS. The constituents are then mixed at different ratios to obtain the different densities and viscosities desired. The hardener was not used because it was thought that it would damage the equipment by hardening on pipe walls and may cause the valves to get stuck etc. The hardener was not used also to be able to use the mixture more than once. So only the epoxy, the diluent and the filler were used in the mixtures.

Since two different experimental setups were used in this experiment, there will be one section for each experimental setup and the data obtained from them. Each setup and procedure will be discussed in details. In the first section, the static experiment setup will be discussed. This experimental setup has a static fluid column in the plastic tubing and that is why it is called the static experiment setup. The second setup is the dynamic experiment setup and as it can be referred from the name, this experiment setup has a dynamic water column in the tubing that flows from bottom to top.

6.1 Static Experiment

6.1.1 Experiment Variables

Table 6.1 shows the properties and constituents of the epoxy formulations that were used. As it can be seen on the table, most of the readings for the majority of the samples were out of range (300).

Table 6.1 Epoxy formulations

Sample#	Density, ppg	Viscosty						Part A (epoxy), g	Diluent, g	Barite, g
		R3	R6	R100	R200	R300	R600			
1	9.00	3	12	200	>300	>300	>300	1000	178	0
2	9.60	9	16	236	>300	>300	>300	1000	182	100
3	9.15	9	17	255	>300	>300	>300	1002	181	51
4	9.60	8	14	205	>300	>300	>300	1000	250	53
5	9.60	6	11	153	>300	>300	>300	1001	310	25.1
6	9.65	9	16	226	>300	>300	>300	1000	210	52
7	9.90	6.5	12	183	>300	>300	>300	1017	250	53
11	9.40	9	17	235	>300	>300	>300	1002	154	50
12	9.60	4	7	97	195	300	>300	1002	400	50
13	9.80	4	6	91	183	274	>300	1006	402	100
14	10.50	4	6	85	169	251	>300	1003	422	204
16	13.50	16	30	>300	>300	>300	>300	1011	182	1000
17	15.20	26	48	>300	>300	>300	>300	1005	180	1527
18	14.00	22	40	>300	>300	>300	>300	1000	180	1250
20	12.20	17	34	>300	>300	>300	>300	1000	179	730
21	11.30	12	22	>300	>300	>300	>300	1030	179	500
22	17.20	43	80	>300	>300	>300	>300	1050	179	2094
23	8.90	3	10	186	>300	>300	>300	1000	230	0
24	10.60	12	22	>300	>300	>300	>300	1000	184	403
25	11.80	16	30	>300	>300	>300	>300	1004	183	650

A constant annular size was used in this study since the effect of the annular size was already studied by El-Mallawany. His observations for the annular size and epoxy were used as a reference for the interpretations about the annular size. The outer pipe has 6” ID and the inner pipe has 1.9”OD.

The angle is the angle of inclination of the pipe support measured from vertical. All the tests were done in vertical for simplicity. Inclined tests were discussed in the thesis.

6.1.2 Experimental Procedure

1) Get pipe support to horizontal position.
2) Make sure pipe is clean. If not see cleaning procedure.
3) Make sure all hoses are not kinked
4) Close Valve 1 (**Figure 6.1**) and make sure the 6" PVC valve (Valve 4, Figure 6.2) is not stuck by opening and closing a couple of times then close it.
5) Open Valve 2 (**Figure 6.2**). (It is very important to open valve 2 before entering water into the pipe otherwise pressure will build up in the pipe and separate the pipe from the rubber coupling as it is not designed to hold against pressure)
6) Start filling pipe with water by opening Valve 3 (**Figure 6.3**).
7) Close Valve 3 when pipe is full. (Pipe will be full when Hose 2 (Figure 6.2) starts draining water). (If there is a smaller pipe to make an annulus, make sure it is full of water by inspecting if there are any air bubbles escaping the holes drilled at its side.
8) Close Valve 2.
9) Make sure epoxy is well mixed. Record its density, viscosity and weight. (this can be done before or during previous steps.
10) Remove hose 4 (**Figure 6.4**) from the elbow then pour the epoxy into the elbow.
11) Get the pipe to vertical or to desired angle.
12) Start recording data from the pressure transducer.

13) Two persons are needed starting from this step. One should be ready with a video camera to record the experiment and the other to pull the valve handle via the cable attached to it when the video camera starts recording.
14) Stop video recording and pressure data acquisition when all the epoxy falls to the bottom.
15) Start draining the water in the pipe by opening valve 2.
16) Remove hose 1 (Figure 6.1) and start collecting the epoxy at the bottom by opening valve 1.
17) Close valve 1 as soon as water starts to flow through the valve. (you will notice a great change in fluid velocity due to the two orders of magnitude difference in viscosity.)
18) Record the weight of the regained epoxy.
19) Connect hose 1 and start draining the remaining water by opening valve 1.
20) Clean (see cleaning procedure)

Figure 6.1 Pipe fittings 1.

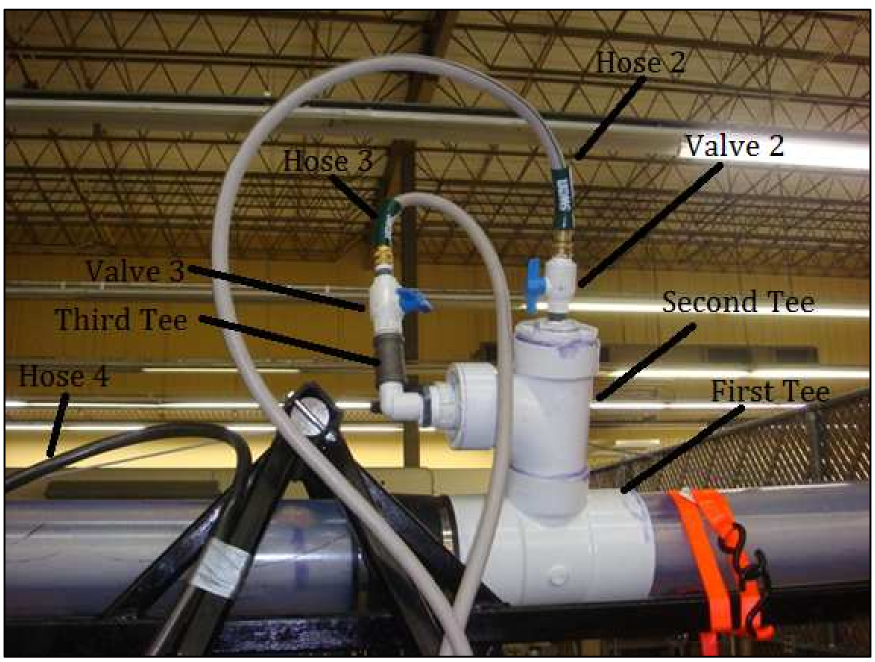

Figure 6.2 Pipe fittings 2.

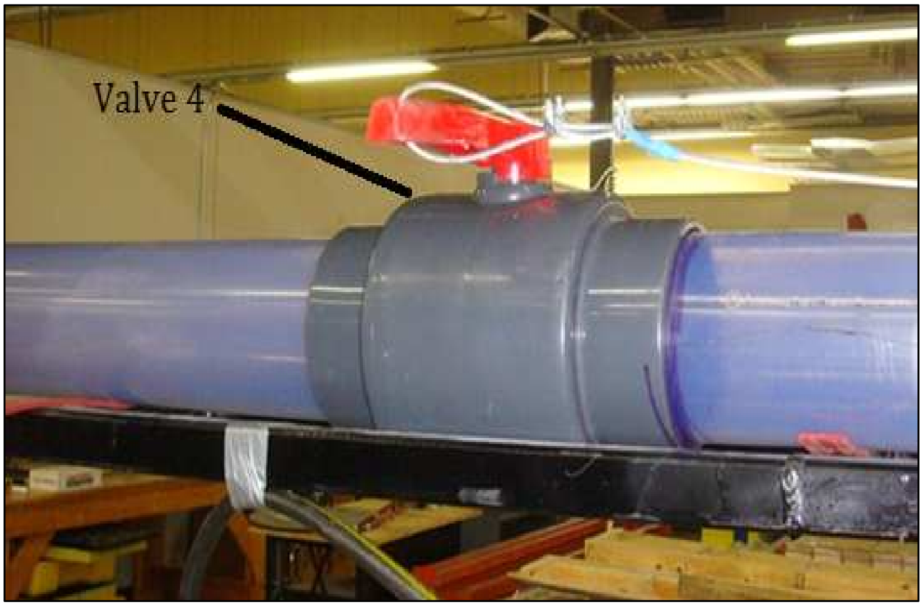

Figure 6.3 Pipe fittings 3.

Figure 6.4 Pipe fittings 4

6.1.3 Cleaning Procedure

1) Get pipe support at a very small angle from horizontal where the elbow is the high point and reachable.
2) Make sure valve 4 and valve 1 are open.
3) Use hose 4 to flush the mud inside the elbow then insert hose 4 into the elbow.
4) Repeatedly close valve 4 for a while to build water behind it then open.
5) Close valve 4 and fill some water behind it with hose 4. Then close hose 4.
6) Get pipe support to vertical position.
7) Open valve 4.
8) Open hose 4 and allow enough time for water to flush entire pipe clean.

6.2 Dynamic Experiment

6.2.1 Experiment Variables

There were two variables in this experiment. The first variable was the flow rate and the second variable was the epoxy composition. Pipe diameter was kept constant at 3” and the flow rates were kept close to the values obtained from the static experiment to see the effects on the epoxy particle. The same epoxy formulations as the static experiment were used to verify the results and validate the data. Since the epoxy specimens from the static experiment were contaminated with water, new samples were prepared by using the same mass ratio from the static experiment.

6.2.2 Experimental Procedure

1) Fill the reservoir with water (keep the valve 1 open during the fill)
2) Start the pump at slow rate (1st speed on the switch)
3) By using the flow-meter, make sure to have the desired flow rate, choke the flow in order to reach the desired rate or increase the pump speed by using the switch on the panel.
4) Make sure the system has a stable flow-rate and there are no leaks.
5) Mix the epoxy to the desired ratio and make sure the final product is homogenous.
6) Record the density, viscosity and weight of the epoxy.
7) By using the provided syringe, inject the epoxy in the 3" tubing slowly until the epoxy breaks free from the needle. Record the amount of epoxy injected.
8) Observe the epoxy and record the time if the particle starts falling down the tubing.
9) Decrease the pump rate if the epoxy starts to move up after breaking free from the needle.

7. RESULTS AND DISCUSSION

7.1 Static Experiment Results

7.1.1 Fall Rates for Vertical and Inclined Pipe

Since most of the epoxy samples had higher readings than 300 for R200, R300 and R600 readings, viscosity of these samples were not considered as a determining factor for the terminal velocity, thus not reported in the results section.

Table 7.1 Terminal velocities for each epoxy

Experiment / Sample Number	Epoxy Formulation				Time, sec	Terminal Velocity, ft/sec
	Epoxy, g	Diluent, g	Barite, g	Density, ppg		
23	1000	230	0	8.9	57	0.427
12	1002	400	50	9.6	55	0.442
13	1006	402	100	9.8	52	0.468
5	1001	310	25.1	9.6	51	0.477
1	1000	178	0	9	48	0.507
11	1002	154	50	9.4	45	0.540
3	1002	181	51	9.15	45	0.541
14	1003	422	204	10.5	45	0.541
6	1000	210	52	9.65	44	0.553
4	1000	250	53	9.6	43	0.566
7	1017	250	53	9.9	43	0.566
2	1000	182	100	9.6	40	0.608
24	1000	184	403	10.6	40	0.608
21	1030	179	500	11.3	38	0.640
25	1004	183	650	11.8	35	0.695
20	1000	179	730	12.2	34	0.715
16	1011	182	1000	13.5	31	0.785
18	1000	180	1250	14	28	0.869
17	1005	180	1527	15.2	27	0.901
22	1050	179	2094	17.2	27	0.901

Weight was one of the properties that was successfully measured and recorded for each epoxy sample that was used in the experiment. **Table 7.1** summarizes the results from the tests.

Table 7.1 has the results obtained from the static experiment setup for different compositions of epoxy mixtures. As it can be observed from the table above, terminal velocity and density tend to have the same trend with some exceptions. It is most likely that this behavior is caused by the diluent amount in the epoxy which is directly proportional with the overall viscosity of epoxy. Viscosity of epoxy is thought to be the main factor behind how much barite can be held within the mixture. Since the viscometer readings are of the maximum scale, an alternative way to relate the viscosity with the terminal velocity will be suggested in the next sections of this research. This alternative method will not require an experiment setup, thus it is hoped that it can be used in the field without the need for an expensive device.

The epoxy does not fall as one part, instead it spreads throughout the water column and then recollects at the bottom. This is shown in **Figure 7.1**. **Figure 7.1** also shows the lead of the epoxy column. The "Time" in **Table 7.1** refers to the time in seconds from releasing the epoxy in the water by opening valve 4 (**Figure 6.3**) to the time the lead reaches the bottom. There are two parts to the falling epoxy; the lead and the tail. What was recorded in the "time" section is the time observed for the lead to reach to the bottom. The time for the tail however, is very difficult to measure and is

Figure 7.1 The epoxy spreads in the water column.

somewhat subjective. This is due to the fact that as the epoxy falls, some of the adhered epoxy on the pipe begins to break out and fall. As a result, it was seen that some epoxy continues to fall even several minutes after the start of the experiment. Moreover, as the epoxy falls in the water, the water becomes blurry from the barite and it is not clear enough to see when the epoxy fall process actually stops or substantially decreases. The pressure transducers were able to pick up the time where the epoxy was first released in the tube but could not detect the pressure change while the epoxy passed the transducer. As it can be seen from the **Figure 7.2** the spike in the pressure is the indication of the epoxy falling in the tube but after that, the expected pressure drop is not observed. This is most likely that the sensitivity of the pressure transducers were not high enough to pick up the pressure drop caused by the epoxy falling down the tube. Thus, the recordings obtained from the pressure transducers were neglected. Visual observation was the only source for the data collection. The word "visual" indicates that the time was measured visually from the experimental videos by actually seeing the epoxy through the clear pipe reaching its target.

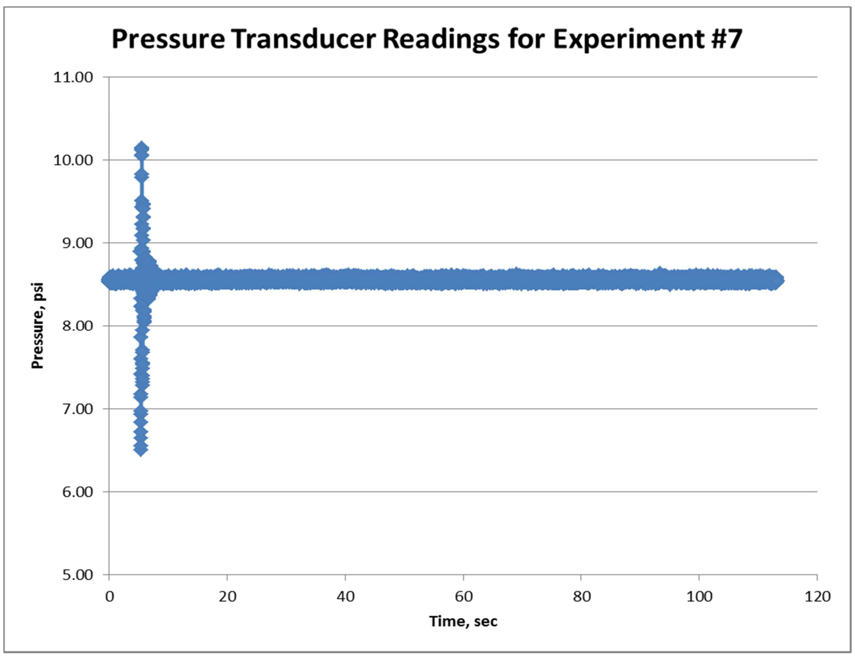

Figure 7.2 Pressure transducer readings

The information that can be derived from **Table 7.1** is as follows. First, it is clear that increasing the density of the epoxy (adding more filler to the mixture) increases its settling or terminal velocity which is expected. Although the denser epoxy compositions have higher viscosities, which decrease the terminal velocity by resisting the water to flow through the epoxy section in the initial stage of the flow/fall, it is safe to say that the main contributor to the terminal velocity is the density of the epoxy. It should also be noted that viscosity of the mixture increases the ability to hold the barite within the mixture and increase the terminal velocity. If we compare the sample#11 which has 154g diluent and 50g barite with a density of 9.4 ppg is actually faster than the sample#13 which has 100g the barite in the mixture but 248g more diluent than the sample#11. Although the sample#13 has higher density than sample#11 in normal conditions, sample#11 can hold on to barite better than sample#13, which gives the advantage of having higher density during the fall in the water column. Before jumping to any conclusions, the relation between the viscosity and density of the epoxy should be studied further in details. Since measuring the viscosity of the epoxy compositions were not possible with conventional fann viscometer, a simpler but effective way of relating the viscosity to the weight of the mixture needed to be derived.

After investigating the terminal velocities in vertical orientation, the effect of the deviation from the vertical was studied by using 30, 45 and 60 degrees deviation from the vertical. The same experiment setup and procedure was used only changing the deviation to desired angle. **Table 7.2** shows the data collected from the tests.

Table 7.2 Formulation and terminal velocities of epoxy mixtures in inclined tubing

Experiment / Sample Number	Epoxy Formulation				Time, sec	Terminal Velocity, ft./sec	Angle
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
10	1000	243	51	9.6	29.0	0.839	30
34	1500	270	1000	12.4	20.0	1.217	30
36	1500	270	800	12.2	20.0	1.217	30
35	1500	270	1200	12.8	18.5	1.315	30
37	1570	270	2003	13.8	17.0	1.431	30
38	1500	270	2500	15.9	16.0	1.521	30
39	1500	270	3000	17.3	14.0	1.738	30
27	888	157	187	10.5	26.0	0.936	45
8	1000	260	50	9.5	25.0	0.973	45
28	1500	270	320	10.5	23.0	1.058	45
30	1500	270	800	11.4	21.7	1.121	45
29	1500	265	660	11.5	18.8	1.294	45
19	1006	183.8	519	11.3	18.0	1.352	45
31	1530	270	1000	12.4	17.8	1.367	45
32	1500	270	1200	12.8	17.0	1.431	45
33	1500	270	1400	13.4	15.0	1.622	45
9	1000	254	51	9.6	30.0	0.811	60
40	1500	270	700	11	16.0	1.521	60

An important observation that can be inferred from **Table 7.1** and **Table 7.2** is that even though the epoxy has similar properties, it flows faster in an inclined section that it does in vertical. Deviating 30 degrees from the vertical increases the fall rate roughly by 100% - 110%, deviating 45 degree from the vertical increases the fall rate roughly by 110% - 130% and increasing the deviation further usually causes the epoxy to flow very slow or even make it stop before reaching the target. Two of the tests however, yielded similar results to 45 degrees inclination results. 60 degrees inclination however, should be treated with care and the viscosity of the epoxy should be kept at minimum to make sure that the epoxy does not stop before reaching the target.

The most important conclusion that can be derived from these results is although the epoxy is expected to fall faster in a vertical it is possible for epoxy to flow faster in a deviated well. This can be explained by the epoxy's rheological properties and the physics behind the flowing mechanism of epoxy in inclined section. The reason for not flowing in 60 degrees inclination in these tests it that thought to be the thixotropic like behavior of epoxy which makes it harder for the mixture to flow once it becomes slow enough or even come to a full stop. The phenomenon of having a greater velocity in the inclined section compared to vertical is also explained by I. El-Mallawany in his research. He simply compares the behavior of a particle and a fluid body in the wellbore to explain the logic behind this phenomenon.

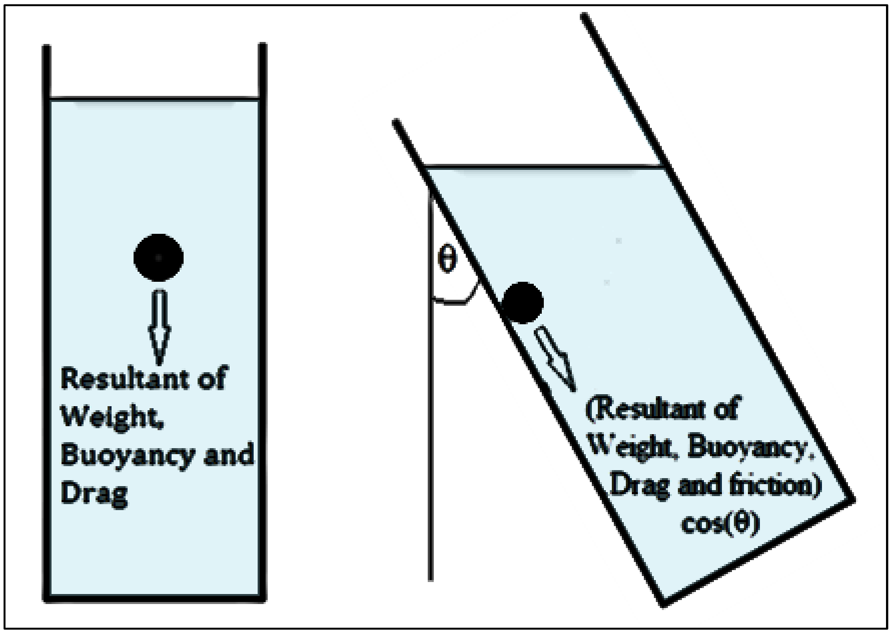

Figure 7.3 Forces on a settling particle in vertical and slant pipe (El-Mallawany 2010)

The main reason for expecting a lower fall rate in the inclined pipe compared to the vertical is that the gravitational force on the particle is less than the vertical. There is also more frictional force acting on the particle in the inclined pipe compared to the vertical where the only friction force is the resistance to particle flow by water. **Figure 7.3** clearly shows why at an angle the downward force is less. Not only is there friction from the pipe wall decreasing the resultant force but the resultant force is also multiplied by cosine the angle of inclination. However, there is another factor that comes into play causing this big difference in speed which is illustrated by **Figure 7.4**.

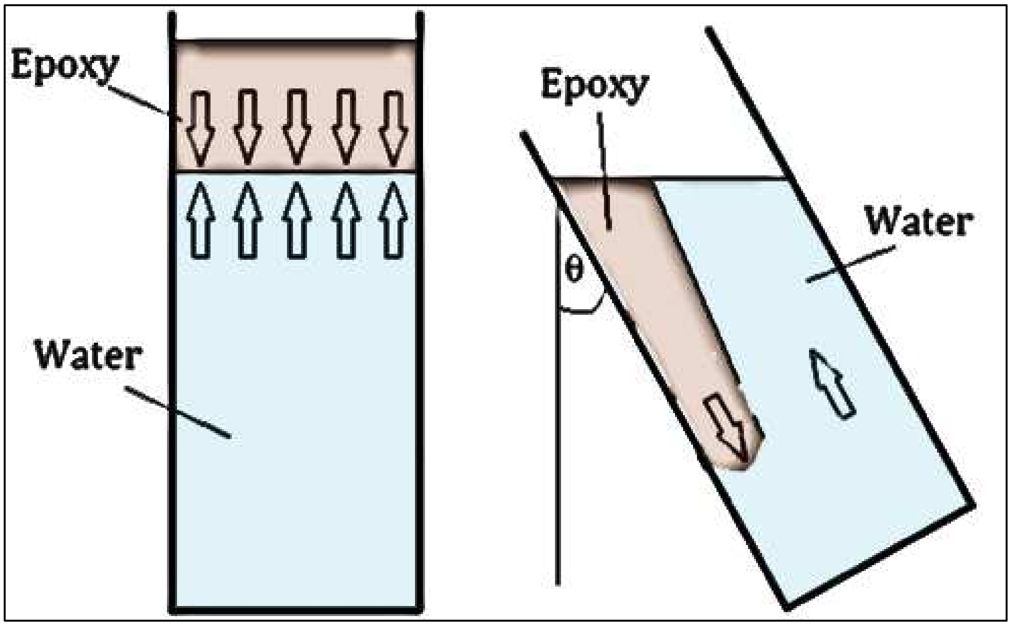

Figure 7.4 Settling of epoxy in vertical and slant pipe. (El-Mallawany 2010)

For pipe on the left in **Figure 7.4**, the water needs to rise and the epoxy needs to fall at the initial stage of the flow. The two motions oppose each other and therefore resist the settling greatly. For the pipe on the right, the epoxy falls to the bottom side of the pipe first then starts to flow downwards. What makes the epoxy, for the pipe on the right, faster is that now the water has a channel to flow above the epoxy layer and therefore the epoxy can easily flow downwards at the bottom side and the water can easily flow above the epoxy layer. "*Another reason is as the epoxy starts to flow downwards its column gets longer and its hydrostatic pressure is increasing only on itself and not in the water which boosts the epoxy forward*" (El-Mallawany 2010).

The next reason is the placement method for the vertical pipe. What is meant here is that this is caused by dumping the entire volume of epoxy all at once in the water.

This increases the concentration of epoxy in vertical pipes and inhibits the upward flow of water and the downward flow of epoxy. As a result, the initial stage of the epoxy fall is slowed down by this phenomenon. It is recommended to inject the epoxy in small volume rates to prevent this phenomenon to occur in vertical pipes.

"The annulus does not seem to cause any significant change in the settling velocity sometimes it makes the settling faster and sometimes slower and in both cases the change is not significant. A possible reason why the annulus did not affect the settling velocity could also be the placement method. Injecting epoxy in small volume rates might show otherwise" (El-Mallawany 2010).

7.1.2 Adhesion on the Pipe

The adhesion of the epoxy on the pipe is also an important factor to take into consideration when designing a remedial job offshore. If the amount of epoxy is not calculated correctly then the chances of failure are high. Overestimating the epoxy amount is probably the best option to make sure of the success of the job but this will increase the cost. For the fall rate tests conducted in the static experimental setup, the amount of epoxy mixture placed in the pipe and the amount of epoxy taken out were recorded and tabulated in order to figure out how much epoxy was lost due to adhesion. Since the pipe is 24.33 ft. long, epoxy adhered to the walls of the pipe per foot can also be calculated. This number however, will also depend on the surface area inside the pipe (annular size). Thus, the annular size also plays a great role in calculating the exact (or estimate) amount of epoxy adhered to the walls of the well. **Table 7.3** shows the data obtained from the tests conducted in the static experiment setup.

Table 7.3 Epoxy recovery percentages

Experiment Number	Epoxy Formulation				Time, sec	Recovery, %	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
22	1050	179	2094	17.2	27	17.76	0
3	1002	181	51	9.15	45	54.38	0
11	1002	154	50	9.4	45	59.29	0
5	1001	310	25.1	9.6	51	59.88	0
4	1000	250	53	9.6	43	60.78	0
7	1017	250	53	9.9	43	61.45	0
23	1000	230	0	8.9	57	63.41	0
2	1000	182	100	9.6	40	63.81	0
17	1005	180	1527	15.2	27	64.01	0
20	1000	179	730	12.2	34	67.37	0
14	1003	422	204	10.5	45	67.96	0
1	1000	178	0	9	48	69.78	0
6	1000	210	52	9.65	44	70.92	0
12	1002	400	50	9.6	55	71.76	0
13	1006	402	100	9.8	52	72.94	0
24	1000	184	403	10.6	40	75.61	0
21	1030	179	500	"11.3	38	77.24	0
16	1011	182	1000	13.5	31	82.95	0
18	1000	180	1250	14	28	83.13	0
25	1004	183	650	11.8	35	91.34	0
39	1500	270	3000	17.3	14.0	48.05	30
10	1000	243	51	9.6	29.0	48.69	30
38	1500	270	2500	15.9	16.0	63.07	30
37	1570	270	2003	13.8	17.0	75.05	30
34	1500	270	1000	12.4	20.0	80.18	30

Table 7.3 Continued

Experiment Number	Epoxy Formulation				Time, sec	Recovery, %	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
36	1500	270	800	12.2	20.0	86.77	30
35	1500	270	1200	12.8	18.5	88.48	30
19	1006	183.8	519	11.3	18.0	0.00	45
26	988	206	1012	13.5	90.0	0.00	45
27	888	157	187	10.5	26.0	46.43	45
8	1000	260	50	9.5	25.0	55.88	45
28	1500	270	320	10.5	23.0	58.37	45
33	1500	270	1400	13.4	15.0	72.43	45
29	1500	265	660	11.5	18.8	78.35	45
30	1500	270	800	11.4	21.7	78.60	45
32	1500	270	1200	12.8	17.0	83.33	45
31	1530	270	1000	12.4	17.8	83.57	45
9	1000	254	51	9.6	30.0	0.00	60
40	1500	270	700	11	16.0	48.05	60

While epoxy recovery by percentage is a useful data to have a rough estimation about how much epoxy to lose during the fall, it does not necessarily give us an accurate result. This is because the recovery percentage heavily depends on the length of the pipe, the inner surface area of the pipe (diameter) and the amount of epoxy used in the test. On a drilling rig, the crew would be more interested on how much epoxy would be lost due to adhesion during the remedial work. Thus, data obtained from each test was re-tabulated into a new table (**Table 7.4**). The amount of epoxy lost in each test was reported in terms of epoxy lost per foot to show how much epoxy would be lost for a field trial. It should be kept in mind that this is for a 6” ID tubing with 1.9” OD pipe inside. The data on Table 333 can further be tabulated and reported as epoxy loss per ft^2 of inner surface area.

Table 7.4 Epoxy adhesion concentration on the tubing (g/ft)

Experiment Number	Epoxy Formulation				Time ,sec	Adhesion per ft., g/ft.	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
25	1004	183	650	11.8	35	6.54	0
1	1000	178	0	9	48	14.63	0
6	1000	210	52	9.65	44	15.08	0
16	1011	182	1000	13.5	31	15.37	0
24	1000	184	403	10.6	40	15.91	0
21	1030	179	500	"11.3	38	15.99	0
13	1006	402	100	9.8	52	16.77	0
18	1000	180	1250	14	28	16.85	0
12	1002	400	50	9.6	55	16.85	0
23	1000	230	0	8.9	57	18.50	0
2	1000	182	100	9.6	40	19.07	0
11	1002	154	50	9.4	45	20.18	0
7	1017	250	53	9.9	43	20.91	0
4	1000	250	53	9.6	43	21.00	0
14	1003	422	204	10.5	45	21.45	0
5	1001	310	25.1	9.6	51	22.03	0
3	1002	181	51	9.15	45	23.14	0
20	1000	179	730	12.2	34	25.60	0
17	1005	180	1527	15.2	27	40.12	0
22	1050	179	2094	17.2	27	112.32	0
36	1500	270	800	12.2	20.0	13.97	30
35	1500	270	1200	12.8	18.5	14.06	30
34	1500	270	1000	12.4	20.0	22.57	30
10	1000	243	51	9.6	29.0	27.29	30
37	1570	270	2003	13.8	17.0	39.41	30

Table 7.4 Continued

Experiment Number	Epoxy Formulation				Time ,sec	Adhesion per ft., g/ft.	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
38	1500	270	2500	15.9	16.0	64.81	30
39	1500	270	3000	17.3	14.0	101.85	30
31	1530	270	1000	12.4	17.8	18.91	45
32	1500	270	1200	12.8	17.0	20.35	45
29	1500	265	660	11.5	18.8	21.58	45
30	1500	270	800	11.4	21.7	22.61	45
8	1000	260	50	9.5	25.0	23.76	45
27	888	157	187	10.5	26.0	27.13	45
28	1500	270	320	10.5	23.0	35.76	45
33	1500	270	1400	13.4	15.0	35.92	45
19	1006	183.8	519	11.3	18.0	70.23	45
26	988	206	1012	13.5	90.0	90.67	45
40	1500	270	700	11	16.0	52.74	60
9	1000	254	51	9.6	30.0	53.64	60

Data obtained from **Table 7.4** would be useful for studies which have the same dimension as the static experiment setup. There is however, a better way to report the amount of epoxy adhered to the walls of the tubing, so that it can be correlated to any experiment or well for volume calculations and similar operations. Instead of quantifying the amount of epoxy lost per foot for this setup, it is wiser to report the concentration of epoxy adhered to the walls of the experimental setup by simply converting the previous data (g/ft.) to a universal and easy to correlate data (g/ft^2). Since the total amount of the epoxy adhered to the walls of the pipe is a function of the inner surface area of the annulus and rheological properties of the epoxy, surface area of the equation can be taken out of the equation by reporting the epoxy concentration by unit area. This is possible by calculating the inner surface area which is simply done by using modified version of the equation below.

$$A = 2\pi R * 1ft \tag{8}$$

where A is the inner surface area and R is the radius of the pipe.

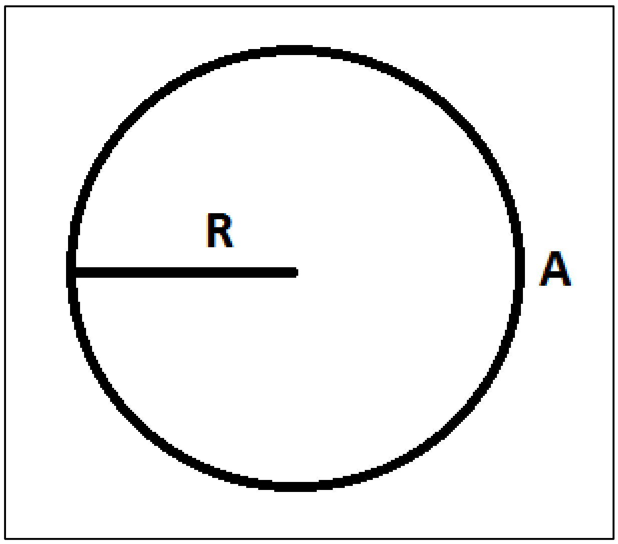

Figure 7.5 Area of a circle

The first section of the equation is simply the circumference of a circle and the second section converts it to area of a cylinder. Since there were two pipes inside each other for the dynamic setup, we will modify the equation to the below.

$$A = 2\pi(R_1 + R_2) * 1ft \tag{9}$$

where R_1 is the inner radius of the outer pipe and the R_2 is the outer radius of the inner pipe.

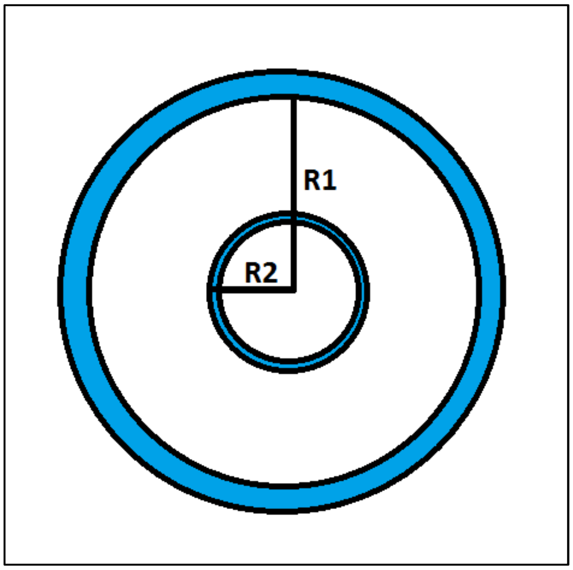

Figure 7.6 Total inner surface area of the dynamic experiment setup

This gives us the total inner surface area that the epoxy will be interacting during the fall. Multiplying the result with 1 ft assures the unit area that will be used for correlations.

Table 7.5 Adhesion concentration of epoxy (g/ft^2)

Experiment Number	Epoxy Formulation				Time, sec	Adhesion per ft^2, g/ft^2	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
25	1004	183	650	11.8	35	3.161	0
1	1000	178	0	9	48	7.075	0
6	1000	210	52	9.65	44	7.293	0
16	1011	182	1000	13.5	31	7.431	0
24	1000	184	403	10.6	40	7.692	0
21	1030	179	500	"11.3	38	7.730	0

Table 7.5 Continued

Experiment Number	Epoxy Formulation				Time, sec	Adhesion per ft^2, g/ft^2	Angle, degrees
	Epoxy, g	Diluent, g	Barite, g	Density, ppg			
13	1006	402	100	9.8	52	8.109	0
18	1000	180	1250	14	28	8.147	0
12	1002	400	50	9.6	55	8.149	0
23	1000	230	0	8.9	57	8.944	0
2	1000	182	100	9.6	40	9.220	0
11	1002	154	50	9.4	45	9.757	0
7	1017	250	53	9.9	43	10.113	0
4	1000	250	53	9.6	43	10.156	0
14	1003	422	204	10.5	45	10.372	0
5	1001	310	25.1	9.6	51	10.653	0
3	1002	181	51	9.15	45	11.187	0
20	1000	179	730	12.2	34	12.379	0
17	1005	180	1527	15.2	27	19.397	0
22	1050	179	2094	17.2	27	54.309	0
36	1500	270	800	12.2	20.0	6.757	30
35	1500	270	1200	12.8	18.5	6.799	30
34	1500	270	1000	12.4	20.0	10.911	30
10	1000	243	51	9.6	29.0	13.195	30
37	1570	270	2003	13.8	17.0	19.055	30
38	1500	270	2500	15.9	16.0	31.338	30
39	1500	270	3000	17.3	14.0	49.245	30
31	1530	270	1000	12.4	17.8	9.142	45
32	1500	270	1200	12.8	17.0	9.839	45
29	1500	265	660	11.5	18.8	10.434	45
30	1500	270	800	11.4	21.7	10.930	45
8	1000	260	50	9.5	25.0	11.486	45
27	888	157	187	10.5	26.0	13.116	45
28	1500	270	320	10.5	23.0	17.291	45
33	1500	270	1400	13.4	15.0	17.368	45
19	1006	183.8	519	11.3	18.0	33.959	45
26	988	206	1012	13.5	90.0	43.840	45
40	1500	270	700	11	16.0	25.500	60
9	1000	254	51	9.6	30.0	25.934	60

As it can be seen from **Table 7.5**, the general trend for the amount of epoxy adhered to the walls of the tubing is expected to be directly proportional to the amount of barite used and inversely proportional with the diluent used in the experiment. Since there are more than one parameters affecting the amount of epoxy adhered and the flow of epoxy in the system is more chaotic than expected, the amount of epoxy adhered to the walls of the tube cannot be related to any of the variables directly. However, it is safe to give an interval for the expected amount of epoxy that will adhere to the walls of the well by using the **Table 7.5**. The maximum amount of epoxy loss for a vertical well will be between 3.161 g/ft^2 and 12.379 g/ft^2. For an inclined well which has a 30 degree inclination is expected to have 6.757 g/ft^2 to 19.055 g/ft^2 epoxy loss. For 45 degree inclination this number varies between 9.142 g/ft^2 and 17.368 g/ft^2. For a 60 degree inclination however, most of the tests failed to give any recovery thus it is not recommended to use high viscosity epoxy mixtures in order to increase the success rate of the remedial job. Another important conclusion that can be inferred from **Table 7.5** is that the amount of barite that can successfully be used in the epoxy mixture should be considered carefully. As far as the tests conducted in the static experiment setup suggest, the density of the mixture should be kept around 14 ppg or less to increase the recovery of the epoxy. This means more epoxy can be delivered to the target if the density of the epoxy is 14 ppg or less and less mixture will be required to accomplish the same operation. A clear example of this case is the Experiment #22 from the vertical case. As it can be observed, the recovery of the expoy is 17%. This is mainly due to the amount of barite that was added to the mixture. Since the amount of barite that the mixture can hold during the fall is limited, excess barite particles break free from the mixture, adhering to the walls and losing barite on the way causes a much lower recovery of the epoxy at the end of the test. The barite particles that cannot be recovered after the test are simply flushed away with the water. The highest recovery rates are observed for epoxy mixtures with 11.8 ppg to 14 ppg. One should also take into consideration that the viscosity of the epoxy is an important factor affecting the maximum amount of barite it can hold. Thus, the diluent ratio should also be kept at minimum in order to prevent barite from breaking free from the mixture.

As it can be observed from the **Figure 7.7,** the adhesion of epoxy is not a thin layered film or similar but has more like a spotted pattern. This makes the estimation of "epoxy volume lost due to adhesion" harder by using small scale experiment setup. Although the pattern in a well would most likely look similar to the pattern on **Figure 7.7,** the size of the well size and the tubing inside the well (annular space) would affect the final outcome. This phenomenon should further be investigated by a larger scale experimental setup or even by a field experiment. The data at hand suggests that the adhesion pattern will look like the **Figure 7.7** and the concentration of the epoxy lost will be within the intervals mentioned in the previous paragraph.

The effect of inclination on the adhesion of epoxy is already discussed in the previous paragraphs but it is worth stating once more that the inclination tends to increase the amount epoxy adhered to the walls of the tube in the static experiment setup.

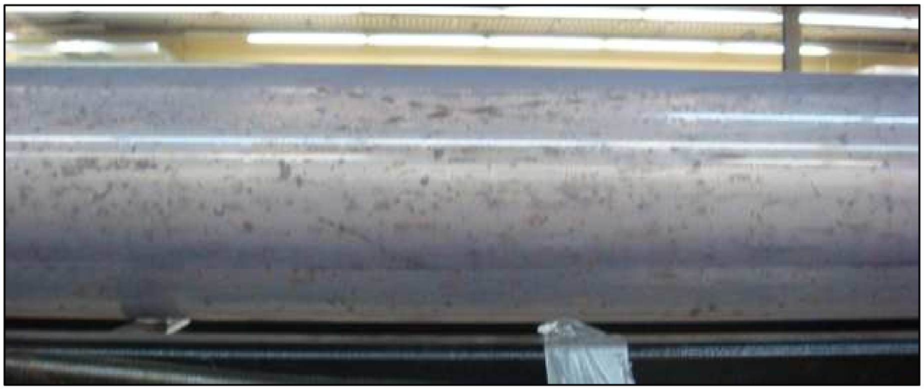

Figure 7.7 Adhesion of epoxy for a vertical pipe at middle section (El-Mallawany 2010)

Figure 7.8 shows an example of adhered epoxy on the experimental setup. As it can be observed, the epoxy tends to move towards the lower wall of the inclined pipe and accumulate there. On the upper wall however, there are less spots due to the fact that the interaction with the epoxy is less compared to the vertical tests. It is most likely that the increase in the interaction on the lower walls of the tubing makes it possible for epoxy to adhere more than the vertical case.

Figure 7.8 Adhesion of epoxy for a slant pipe at middle section

Also, the flow of epoxy for the inclined pipe is very different from the vertical case. Instead of spreading and flowing in a chaotic manner, the epoxy slides on the lower wall of the tubing. This naturally increases the interaction (more contact with the tubing) and the amount of epoxy lost due to adhesion.

7.1.3 Summary of Results for Static Experiment Setup and Conclusions

1) Denser formulations tend to have faster terminal velocity with some exceptions. The exceptions are thought to have a connection with the amount of diluent used. Further study needs to be done to increase the accuracy of terminal velocity estimations.
2) Tests conducted on the inclined tubing yielded higher terminal velocities compared to the vertical tests.
3) Viscosity of the epoxy is directly proportional to the amount of epoxy that will adhere to the walls of the system but the recovery of epoxy is a function of both viscosity and density. Increasing the density of epoxy above 14 ppg causes the barite to break free during the fall and decrease the recovery.
4) Higher inclinations will cause higher adhesion thus decrease the amount of epoxy delivered to the target.
5) Smaller annular size will usually lead to less epoxy loss due to smaller inner surface area.
6) As the epoxy flow stabilizes towards the bottom of the well, interaction with the walls will decrease and the adhesion concentration will also decrease.

7) Barite is a good candidate for epoxy weighting for up to 14 ppg mixture density.

7.2 Dynamic Experiment Results

After analyzing the results from the static experiment setup, terminal velocity values were used to estimate the required flow-rate values for the dynamic experiment setup. The objective was to validate the results obtained from the static experiment setup by using the dynamic setup developed as a part of this study. The same epoxy compositions as the previous tests were prepared by using the same ratio for each sample. Since the required amount of mixture for this part is a fraction of the amount used in the static setup, values were simplified by a factor of 5 to reduce the cost and labor. **Table 7.6** shows the simplified compositions and the required flow rate for each sample that is used in the dynamic experiment setup. Note that only vertical tests were used to validate the results since the inclined tests indicate a different flow behavior that is difficult to observe in the dynamic setup.

Terminal velocity calculation for the dynamic experiment setup results required a step by step procedure. Since the particles in the water were stabilized and not suspended in the flowing water, it was assumed that the velocity of water around the particle was equal to the terminal velocity of the particle in static water column. The flow rate for the water was recorded by the flow meter. Calculations for the water velocity required the inner diameter of the clear tubing which is 3 inches. Flow rates required for each sample to suspend in water are given on **Table 7.7.**

Table 7.6 Comparison of the dynamic and the static experiment results

Experiment / Sample Number	Epoxy Formulation				Velocity from Static Experiment, ft/min	Velocity from Dynamic Experiment, ft/min
	Epoxy, g	Diluent, g	Barite, g	Density, ppg		
23	200	46	0	8.9	25.6	17.7
12	200	80	10	9.6	26.5	19.3
13	202	80	20	9.8	28.1	20.1
5	200	62	5	9.6	28.6	19.3
1	200	36	0	9.0	30.4	19.6
11	200	30	10	9.4	32.4	20.7
3	200	36	10	9.15	32.4	20.4
14	200	84	21	10.5	32.4	20.9
6	200	42	10	9.7	33.2	20.4
4	200	50	11	9.6	33.9	20.4
7	202	50	11	9.9	33.9	21.2
2	200	36	20	9.6	36.5	20.7
24	200	36	81	10.6	36.5	27.0
21	206	36	100	11.3	38.4	27.0
25	200	36	130	11.8	41.7	27.5
20	200	36	146	12.2	42.9	27.5
16	202	36	200	13.5	47.1	29.7
18	200	36	250	14.0	52.1	31.8
17	202	36	305	15.2	54.1	32.3
22	210	36	419	17.2	54.1	34.4

After recording the flow rate values for each sample, these results were converted to velocity values in order to make it suitable for comparison. Since the water in the tubing is flowing in a laminar regime, it should be noted that the velocity distribution for the flowing water is much like a streamline flow where the fluid is faster at the center and relatively slower close to the pipe. If the epoxy sample followed a certain flow-path, this phenomenon would affect the results but since the particles moved around the pipe in a random manner during the flow, so this effect was neglected. It was assumed that the calculated velocity is the average velocity for each epoxy sample.

Table 7.7 Required flow rates for each epoxy samples to suspend in water

Experiment / Sample Number	Epoxy Formulation				Required Flow Rate, gal/min
	Epoxy, g	Diluent, g	Barite, g	Density, ppg	
23	200	46	0	8.9	6.7
12	200	80	10	9.6	7.3
13	202	80	20	9.8	7.6
5	200	62	5	9.6	7.3
1	200	36	0	9.0	7.4
11	200	30	10	9.4	7.8
3	200	36	10	9.15	7.7
14	200	84	21	10.5	7.9
6	200	42	10	9.7	7.7
4	200	50	11	9.6	7.7
7	202	50	11	9.9	8.0
2	200	36	20	9.6	7.8
24	200	36	81	10.6	10.2
21	206	36	100	11.3	10.2
25	200	36	130	11.8	10.4
20	200	36	146	12.2	10.4
16	202	36	200	13.5	11.2
18	200	36	250	14.0	12
17	202	36	305	15.2	12.2
22	210	36	419	17.2	13

The equation that was used to convert the flow-rate values to the velocity is given below.

$$Velocity = \frac{FlowRate/7.4805}{ID^2 * \frac{\pi}{4}/144} \tag{10}$$

where *Velocity* is in feet per minute, *Flow Rate* is in gallons per minute and the *ID* (inner diameter of clear tubing) is in inches.

As it can be observed from Table 7.6, the results from the dynamic experiment setup and the static experiment setup support each other from slowest to fastest epoxy mixtures. The numeric results however, are not in complete agreement. This is due to the nature of these two experiments which are a lot different from each other. As it was mentioned earlier in the thesis, barite that is in suspension in epoxy settles down in a static epoxy mixture. Since the epoxy specimen in the static experiment setup rests in the top chamber before the experiment can be conducted, this allows the barite to settle down in the epoxy mixture. Since the settled part is the first to flow in the pipe, the velocity obtained for the lead is actually greater than the average velocity of the epoxy mixture. Notice that the difference between the two experiment setup results increase as the concentration of barite increases in the mixture. This is due to the fact that the amount of barite settled in epoxy increases as the barite concentration increases.

7.2.2 Predicting the Terminal Velocity

As it was mentioned in the theory section of the thesis, there are several approaches to estimate the terminal velocity for settling substances in liquids. Stokes approach is the most commonly used and accepted approach for spherical solids falling in liquids. In this research, the objective was to correlate the particle size with two variables which are density and the viscosity to use in Stokes correlation. Since the viscosity is not possible to measure with conventional equipment, the diluent mass percentage was used as variable. Since one variable was used as a percentage, density was also correlated to the weighting material namely barite percentage in the mixture. Compositions for each sample and the corresponding weight percentage are given on **Table 7.8.**

The visual representation of the **Table 7.8** is given on **Figure 7.9.** As it can be seen from this chart, it is difficult to determine which parameter is dominant on the particle size. There is however, a cross over between the barite and diluent concentrations around 12.5% barite concentrations. In order to observe the effect, the data were split from 12.5% barite concentration. **Figure 7.10** and **Figure 7.11** show the same set of data as the **Figure 7.9** where **Figure 7.10** is up to 12.5% barite concentration and **Figure 7.10** is the visual representation for the 12.5% barite concentration and higher.

Table 7.8 Weight percentage and particle size for epoxy mixtures

Sample #	Particle Volume, ml	Flow Rate, gal/min	Speed, ft/min	Barite, %	Diluent, %
23	0.2500	6.7	17.7	0.0%	18.7%
12	0.1563	7.3	19.3	3.4%	27.5%
13	0.1667	7.6	20.1	6.6%	26.7%
5	0.1786	7.3	19.3	1.9%	23.2%
1	0.2778	7.4	19.6	0.0%	15.1%
11	0.2941	7.8	20.7	4.1%	12.8%
3	0.2778	7.7	20.4	4.1%	14.7%
14	0.1351	7.9	20.9	12.5%	25.9%
6	0.2439	7.7	20.4	4.1%	16.6%
4	0.2174	7.7	20.4	4.1%	19.2%
7	0.2273	8.0	21.2	4.0%	18.9%
2	0.1852	7.8	20.7	7.8%	14.2%
24	0.1351	10.2	27.0	25.4%	11.6%
21	0.1163	10.2	27.0	29.3%	10.5%
25	0.1111	10.4	27.5	35.4%	10.0%
20	0.1163	10.4	27.5	38.2%	9.4%
16	0.0877	11.2	29.7	45.6%	8.3%
18	0.0641	12.0	31.8	51.4%	7.4%
17	0.0375	12.2	32.3	56.3%	6.6%
22	0.0353	13.0	34.4	63.0%	5.4%

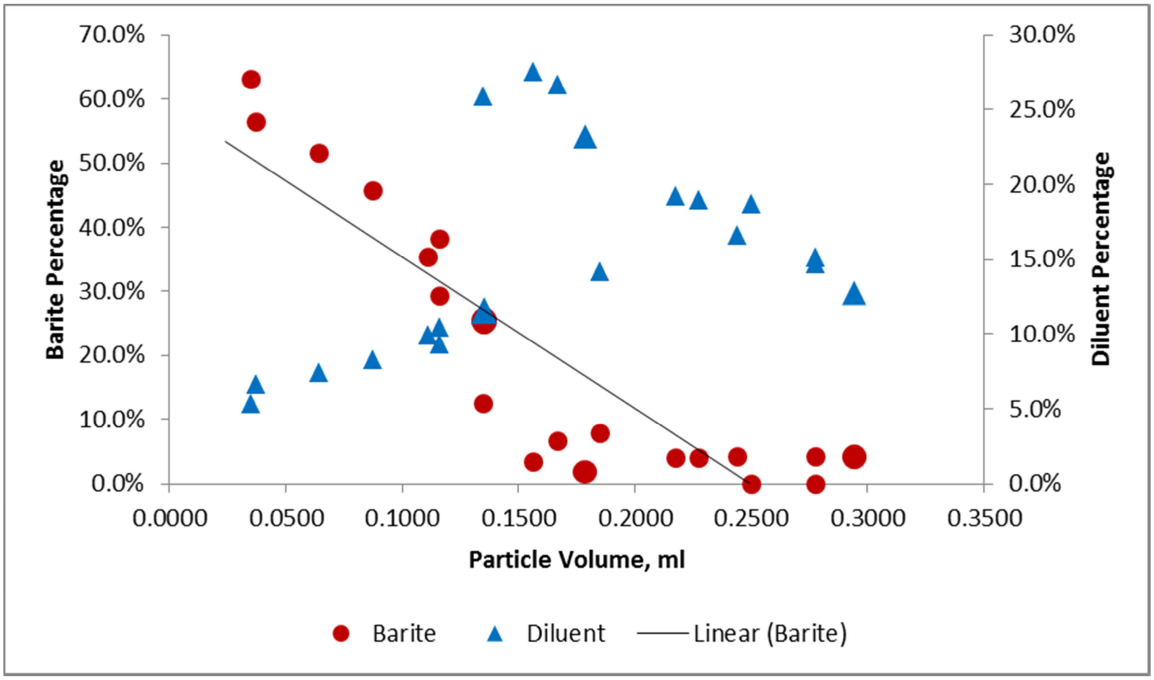

Figure 7.9 Total data from dynamic dxperiment

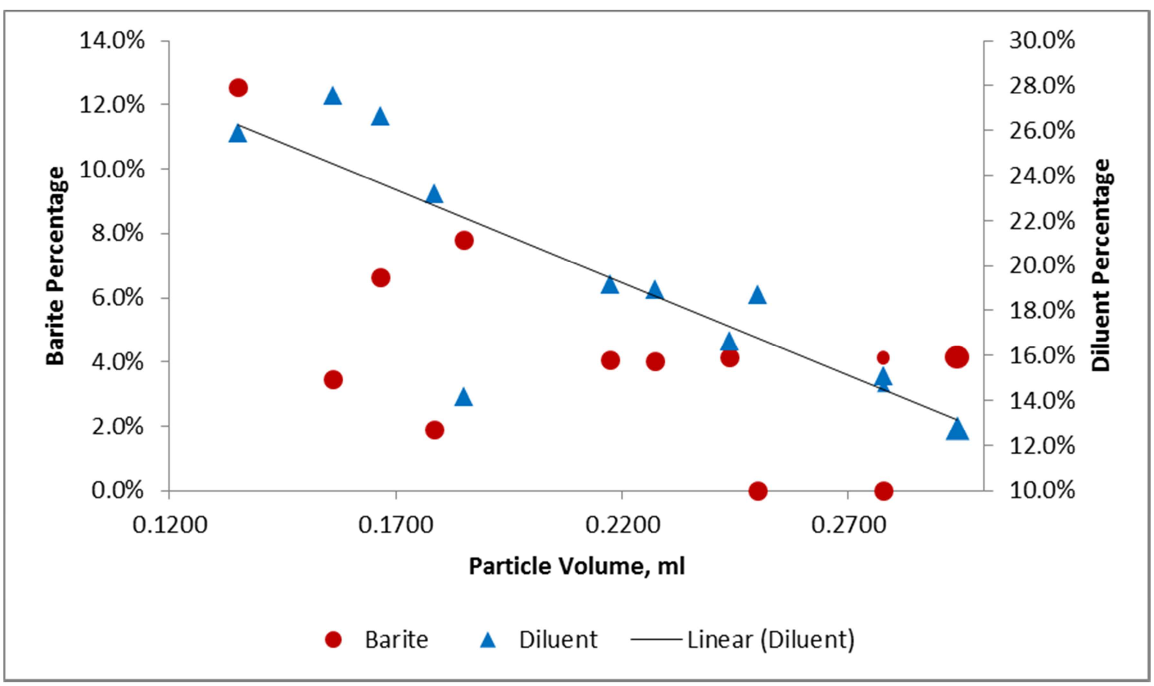

Figure 7.10 Results up to 12.5% barite from dynamic experiment

Figure 7.10 shows that the particle size depends heavily on the diluent percentage used in the mixture. This is valid up to 12.5% barite concentrations. After 12.5%, barite concentration seems to be the dominant factor on the particle size. This is also shown on **Figure 7.10**.

As you can see from the chart, the diluent percentage and the particle size are inversely proportional, which is not the general trend for the rest of the tests. This can be explained by the high concentrations of barite in the mixture. Barite increases the weight, thus the particle size decreases due to higher velocity in the water column.

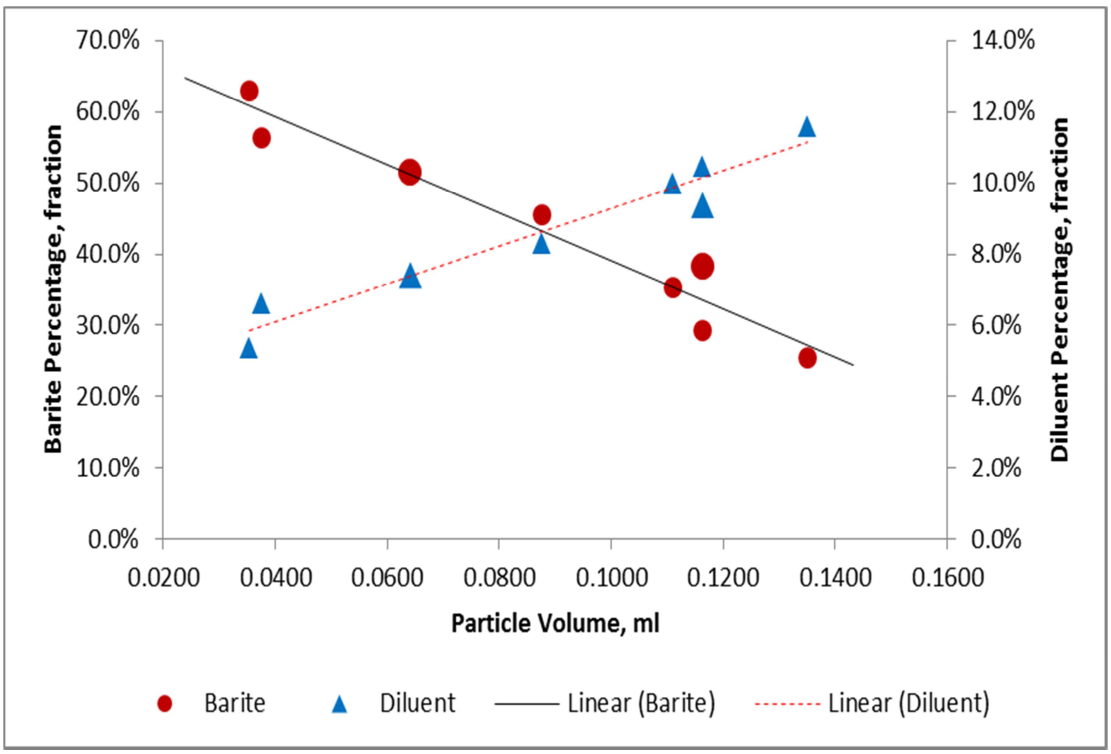

Figure 7.11 Results for 12.5% barite and higher concentration

It is possible to correlate the particle size with two variables such as diluent and barite percentage in the mixture. The results obtained from the correlation however, will yield a certain amount of error. Since the epoxy particles are not perfect spheres but rather look like hamburger buns, the Stokes correlation will also yield further error in the results. To overcome this problem, the percentages for barite and diluent were correlated with the terminal velocity values obtained from the dynamic experiment setup. The procedure is explained below.

It is easy to predict the result for a given data set if there are only one variable effecing the results. In this case, there were two variables affecting the outcome of the experiment; barite and diluent concentration. In order to correlate these two variables, a program called GRACE was used. The GRACE program generates an optimal correlation between a dependent variable (say, y) and multiple independent variables (say, x1, x2, x3 .....up to x30). This is accomplished through non-parametric transformations of the dependent and independent variables. Non-parametric implies that no functional form is assumed between the dependent and independent variables and the transformations are derived solely based on the data set.

The final correlation is given by plotting the transformed dependent variable against the sum of the transformed independent variables. The correlation thus obtained can be shown to be optimal (Breiman and Friedman, 1985; Xue et al, 1996).

Before coming up with the optimum correlation, the program transforms the independent variables (curve fitting). The alternating conditional expectation (ACE) algorithm of Breiman and Friedman (1985) is used by the GRACE program. **Figure 7.12** and **Figure 7.13** shows the optimal transform results for barite and diluent respectively. After obtaining the optimal transform equation, the program then calculates the optimum regression for velocity, the dependent variable. Using the transformed velocity values from **Figure 7.14** and velocity values from the test results optimal inverse transform relation is obtained. Finally, by using the transformed independent variables and dependent variable (velocity), the effect of barite and diluent concentration on the velocity is shown on **Figure 7.15.** The program evaluated both optimal transform and optimal inverse transform and chooses the most accurate correlation. The calculations for terminal velocity values are done according to the chosen transformation.

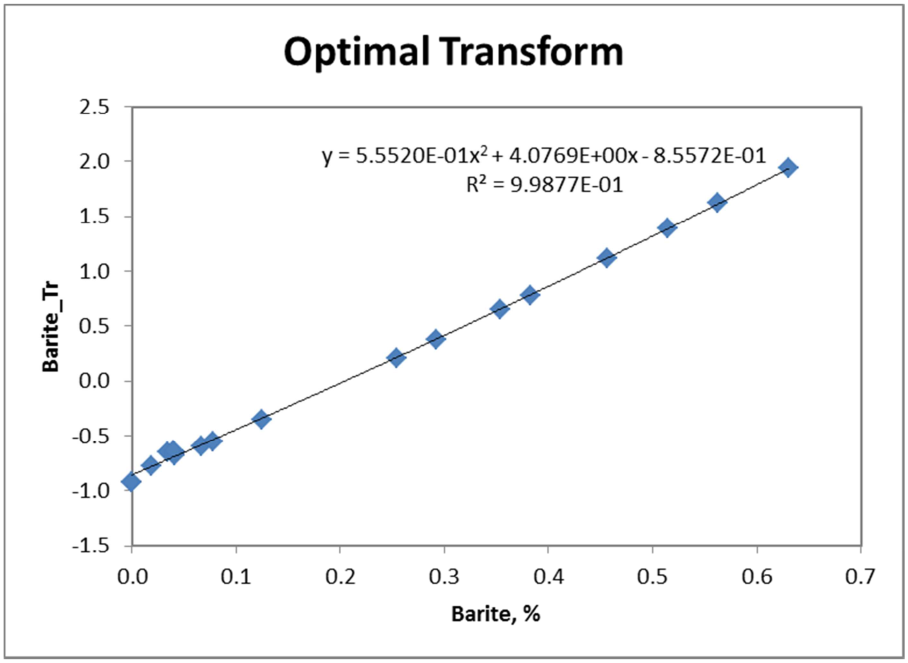

Figure 7.12 Optimal transform for barite

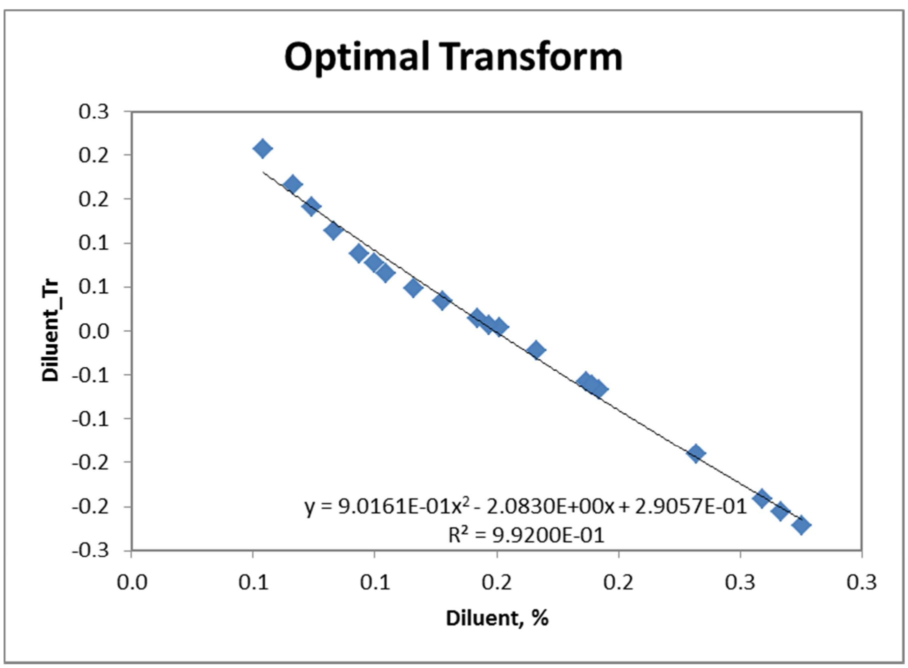

Figure 7.13 Optimal transform for diluent

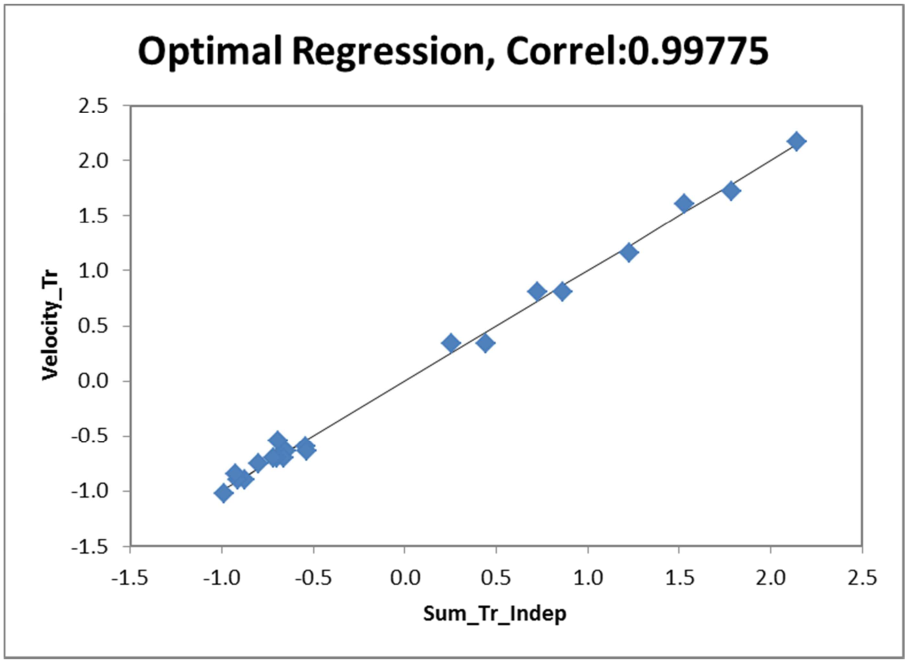

Figure 7.14 Optimal regression for velocity

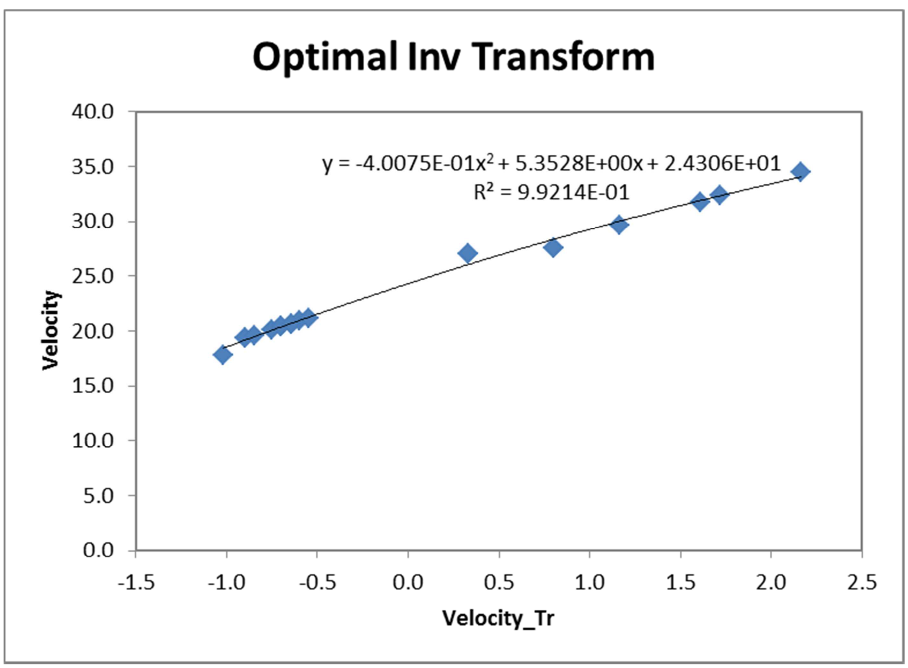

Figure 7.15 Optimal inverse transform for velocity

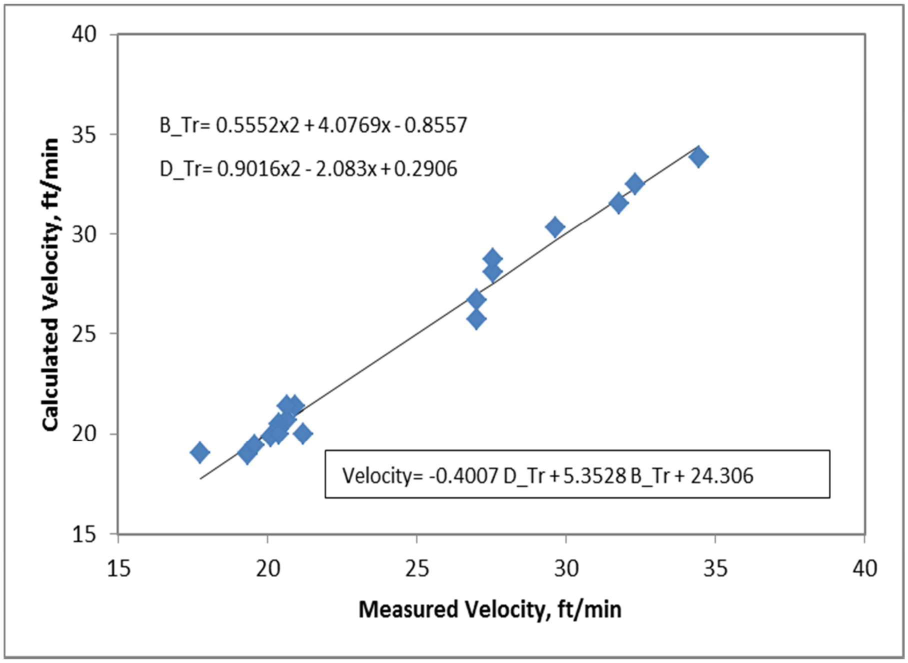

Figure 7.16 Comparison of the measured and calculated results for vertical

Figure 7.16 compares the test results to the results obtained from the correlation. As it can be seen on the chart, the correlation can predict the results quite accurately. The equation given on the chart can predict the test results within %3 error range. This is an acceptable error margin for field use. Results obtained from the static setup were used to plot the charts on **Figure 7.17** and **Figure 7.18.** Corresponding equations are also given in the following figures.

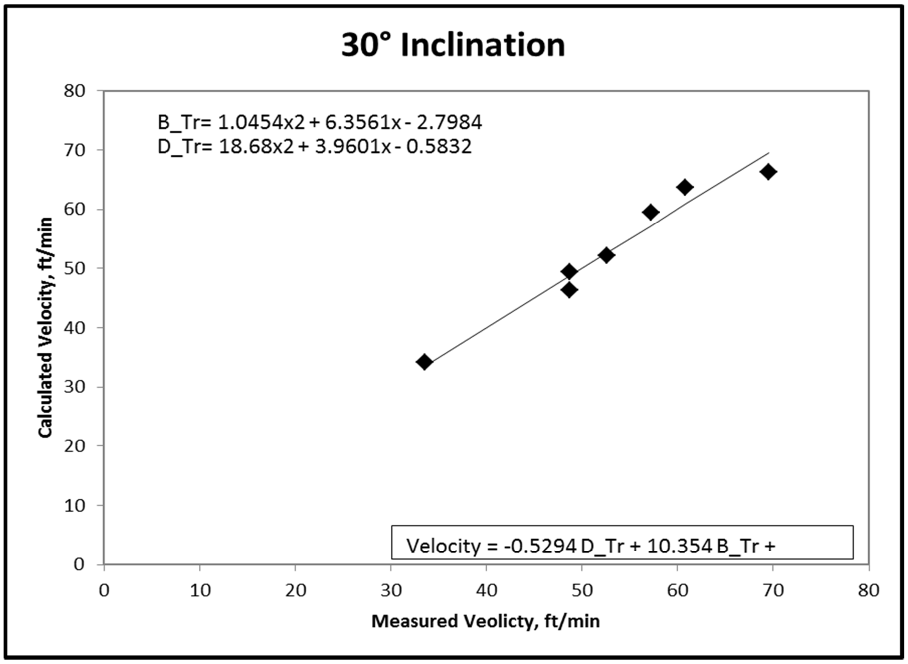

Figure 7.17 Comparison of the measured and calculated results for 30°

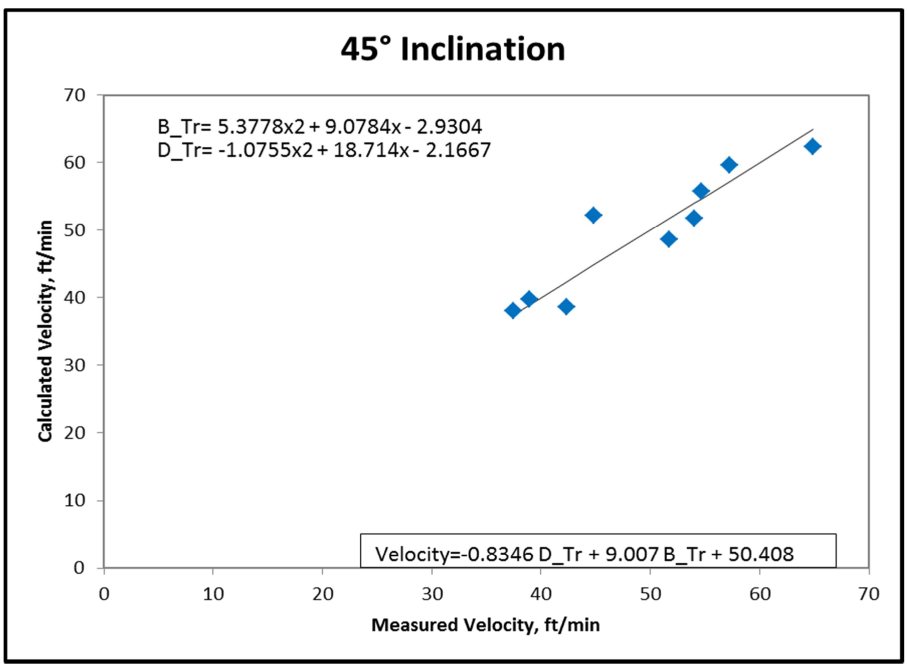

Figure 7.18 Comparison of the measured and calculated results for 45°

7.2.3 Summary of Results for Dynamic Experiment Setup and Conclusions

The dynamic experiment setup results were consistent with the static experiment setup results in terms of the velocity trend for each epoxy formulation. The numeric results however, were always lower for the terminal velocity values. This can be explained by the settling behavior of the barite in the epoxy mixture. Since the samples in the static experiments were put in the top compartment of the setup and had time for barite to settle on the bottom, the lead of the epoxy was always denser than the whole mixture. Heavier lead had higher terminal velocity and thus the results were always higher than the dynamic experiment results. It is safer to conclude that the results obtained from the dynamic experiment setup are more reliable than the static experiment due to the fact that sample has more barite in suspension (more homogenous). It is also better to use the slower terminal velocity values for settling calculations to be on the safe side.

The two variables, –barite concentration and the diluent concentration– were successfully (%3 error) correlated to the terminal velocity of the epoxy mixture. The terminal velocity for any epoxy formulation can be calculated by using the equation provided.

$$TerminalVelocity = -0.4007\left(0.9016 * {C_d}^2 - 2.083 * C_d + 0.2906\right) + 5.3528\left(0.5552 * {C_b}^2 + 4.0769 * C_b - 0.8557\right) + 24.306 \quad (11)$$

where *TerminalVelocity* is in ft/min, C_d is weight percentage of diluent, C_b is weight percentage of barite.

For the inclined section, there should be enough accumulation at the kick-off point of the well for the epoxy to flow like it was shown on **Figure 7.4** and since the flow is proved to be faster on the inclined section, it is recommended to use the velocity on the vertical as the average velocity of the epoxy.

Under the guidance of the results obtained from the tests, for a well that is 7,000-ft deep, and average epoxy (let's say 12 lbm/gal density) would need;

$$\frac{7000ft}{32ft/min} = \mathbf{218\ minutes}$$

This is around **3 hours and 38 minutes**, which is fast enough to keep the epoxy from curing before reaching the bottom.

For the same well (vertical), with 7 inch production casing and 1.9 inch tubing it would be required to have additional epoxy mixture between:

$$7000ft * \left(\frac{7}{12} + \frac{1.9}{12}\right) * \pi * \frac{3.161g}{ft^2} * 453.59\frac{lb}{g} * \frac{1gal}{12lbm} = \mathbf{9.47gallons}$$

to

$$7000ft * \left(\frac{7}{12} + \frac{1.9}{12}\right) * \pi * \frac{12.379g}{ft^2} * 453.59\frac{lb}{g} * \frac{1gal}{12lbm} = \mathbf{37.09gallons}$$

in order to compensate the epoxy loss in the wellbore.

8. CONCLUSIONS

1) Denser epoxy formulations tend to have higher terminal velocity with some exceptions. The exceptions are thought to have a connection with the amount of diluent used. Further study needed to be done to increase the accuracy of terminal velocity estimations and "The Static Experiment Setup" was developed for this purpose.
2) The terminal velocity for any epoxy formulation can be calculated by using the equation provided.

$$TerminalVelocity = -0.4007\left(0.9016 * {C_d}^2 - 2.083 * C_d + 0.2906\right) + 5.3528\left(0.5552 * {C_b}^2 + 4.0769 * C_b - 0.8557\right) + 24.306 \quad (11)$$

3) For well inclinations from 30 degrees to 45 degrees, the fall rate of epoxy will increase by 100% to 130% compared to the vertical cases. It is recommended that the velocity calculated from the equation should be used as the average velocity to be on the safe side.
4) Maximum amount of epoxy loss for a vertical well is estimated to be between 3.161 g/ft^2 and 12.379 g/ft^2.
5) For an inclined well which has a 30 degree inclination is expected to have 6.757 g/ft^2 to 17.368 g/ft^2 epoxy loss.
6) For 45 degree inclination this number varies between 9.142 g/ft^2 and 19.055 g/ft^2.

7) For a 60 degree inclination however, most of the tests failed to give any recovery thus it is not recommended to use high viscosity epoxy mixtures in order to increase the success rate of the remedial job.

8) As far as the tests conducted in the static experiment setup suggest, the density of the mixture should be kept around 14 ppg or less to increase the recovery of the epoxy. After 14 ppg, barite tends to break free from the mixture as it falls through water.

9) Higher inclinations will cause higher adhesion thus decrease the amount of epoxy delivered to the target. The volume of epoxy prepared for the inclined sections should always be kept more than the vertical case in order to assure the success of the work.

10) Smaller annular size will usually lead to less epoxy loss due to smaller inner surface area.

11) As the epoxy flow stabilizes towards the bottom of the well, interaction with the walls will decrease and the adhesion concentration will also decrease.

12) Barite is a good candidate for weighting epoxy mixtures up to 14 ppg density. It will however, break free from the mixture significantly if the density exceeds this number.

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