FYP II: Final Report

Improvement of Cement Placement in Horizontal Wells by Liner Rotation Using CFD

by

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CERTIFICATION OF APPROVAL

Improvement of Cement Placement in Horizontal Wells by Liner Rotation Using CFD

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Approved by,

____

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ALI MAHMOUDI

ABSTRACT

Nowadays, efficient cementing job is a vital operation in the life of a well. Appropriate cement displacement can extend the life of the wellbore by providing long-term zonal isolation.
However, cement displacement is challenging issue in horizontal wells, but achieving maximum isolation is possible by using different techniques like proper mud properties, velocity and displacement rate, centralization of casing.

There are several studies has done in this filed for improving cement displacement. Practices and laboratory experiments has revealed that the casing movement can bring improvement in cement displacement; either reciprocation or rotation motion.

In this research focused mainly on seven inch (7″) liner rotation by using ANSYS CFX14 software. The software implement computational Fluid Dynamic (CFD) model for simulating and ensure the improvements in horizontal wells. Moreover, affect of pressure drop (ΔP) and Equivalent Circulation Density (ECD) on pipe rotation were investigated.
According to simulation result, pressure drop will increase by raising rotation speed. Further, equivalent circulation density will increase as well. Increase in this two factor leads to high efficiency in cement placement

ACKNOWLEDGEMENTS

First and foremost, I thank and praise God that blesses to finish my task for this project successfully.

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NOMENCLATURE

Di	Borehole diameter
Do	Casing outer diameter
ECD	Equivalent Circulation Denity
ρs	Density of spacer
ρpf	Density of pre-flush
ρm	Density of mud
ρc	Density of cement
MW	Mud Weight
Re	Reynolds Number
TVD	True Vertical Depth
τ	Time for one annular sweep
μc	Viscosity of cement
μp	Plastic viscosity
τy	Yield stress
W*	Peak to average velocity ratio
e	Eccentricity
NR	Reynolds number
V	Velocity of flow (m/s)
D	Diameter of pipe (m)
ρ	Density of water (kg/m3)
ή	Dynamic viscosity (kg/m.s)
ν	Kinematic viscosity (m2/s)
f	Friction factor

CHAPTER 1

INTRODUCTION

1.1 Background

Cement displacement is important factor for achieving proper cementing job in oil & gas wells. The quality of the cement bond has a direct impact on the economic life of the well; From the time the well is first produced until the well is abandoned, appropriate cement placement techniques will affect well productivity, both physically and economically [1].

Successful cement displacement will provide effective zonal isolation [2]. To achieve effective isolation, cement needs to fill the area around the pipe, nevertheless probably channels exist for short intervals in several cemented column. Research in cements placement issues has started since 1930s. Some key factors influencing primary cement job failures were identified by Jones and Berdine in 1940. They showed that poor zonal isolation could be attributed to channeling of the cement slurry through the mud. The presence of residual mud cake at the cement/formation interface was also identified as a cause of poor mud displacement [3]. In addition, various researchers have found failure of isolation may lead to fluid migration between permeable zones, water production, unsuccessful stimulation or even blowout like Macondo incident that happen in marine oil spill in 2010 [4].

In other hand, horizontal well drilling has developed widely that able to produce more amounts of hydrocarbons via gas recovery and EOR method. Especially in these types of the wells cement displacement become main concern; since eccentric or narrow annulus can reduce the efficiency of cement displacement. This improper cement bonds often result in remedial cement work that is time consuming and costly. About 15% of primary cement jobs fail, costing the oil and gas industry an estimated USD 450 million annually in remedial cementing work [5].

There are several researches have done to aid cement placement concern; that the mainly based on following practices:

1. Conditioning the drilling fluid (before initiating cement job in order to break the gel strength of drilling fluid).
2. Using proper spacer/flushes
3. Managed rheology and displacement rate
4. Pipe movement and centralization [6].

1.2 Problem Statement

Cement Placement is essential in horizontal drilling and multistage fracturing technologies. Poor cement job can result in gas or water channeling, migration, stimulation failure or even blowout. Casing Rotation is one of the techniques for improving the cement placement that involve simulation by using computational fluid dynamics (CFD) to shows its effects.

1.3 Objectives and Scope of Study

The research will entail cement placement that aims are as follow:

1. Improvement effects of liner rotation in cementing horizontal wells
2. Investigation effect of pressure drop (ΔP) and Equivalent Circulation Density (ECD) on liner rotation

1.3.1 Relevancy of the Study

This project will focus mainly on cement placement in horizontal well. Currently most wells were drilled horizontal to boost the production oil and gas fields. However cement displacement of this type of well is more risky to get whole zonal isolation in compare the vertical well. Furthermore, Casing rotation has play a crucial role for good cement job in horizontal wells.

1.3.2 Feasibility of the project within the scope and time frame

The Starting point of this project is literature reviews that entail reading books and technical papers related to Cement Placement in order to comprehend concept of topic. At early weeks self-learning involve the topic’s fundamental and real work problem. In order to develop computer skills for simulation, I have attempt the tutorial of ANSYS software from internet.

CHAPTER 2

LITERATURE REVIEW

2.1. Cement Displacement Techniques

Efficient mud displacement is essential in order to achieve a good cement bond and zonal isolation. Incomplete mud removal can lead to cement channelling, allowing hydrocarbon invasion and communication between permeable zones.

2.1.1. Effect of Mud Rheology

Mud Rheology is important factor in cement displacement, because it determines the force (shear stress) required to initiate movement in a mud which has been left before cement placement. Proper rheological characterization is essential to:

- Evaluate the slurry's mixability and pumpability
- Optimize mud removal and slurry placement
- Determine the friction pressure when the slurry flows in pipes and annuli
- Evaluate the slurry's ability to transport large particles
- Predict how the wellbore-temperature profile affects slurry placement
- Predict the annular pressure after slurry placement. [1]

Rheological models

These models are used to describe the fluid behavior under dynamic conditions. The time independed fluid model are divided to following categories [7]:

- ***Newtonian fluids*** comply with the Newtonian model, in which the shear stress(τ), is directly proportional to the shear rate (γ) and viscosity remain constant;

  $\tau = \mu\gamma$

  Unfortunately, this model cannot be usually be used for drilling field, because it is dealing with single viscosity term
- ***Non-Newtonian fluids*** cover any fluid whose behaviour deviates from the classic Newtonian model (i.e., the shear-stress/shear-rate relationship differs from a straight line that goes through the origin). *Bingham Plastic* and *Power Law are*

two classification of non-Newtonian fluid model that widely used in drilling industry [9].

Bingham Plastic model do not have constant viscosity and some amount of stress would be required to overcome the mud's gel structure before it would initiate movement. The equation for the Bingham Plastic model is:

$$\tau = \mu p \, \gamma + \tau y \qquad (1)$$

Shear rates are normally taken at 300 and 600 rpm rates on the viscometer. Based on readings, The Plastic Viscosity (μp) and the Yield Point (τy) are calculated as follows:

$$\mu p = \theta\, 600 - \theta\, 300 \qquad (2)$$

$$\tau y = \theta\, 300 - \mu p \qquad (3)$$

As mud solids increase, the plastic viscosity increases that tends to increase hole cleaning.

Gel strengths, 10-second and 10-minute indicate strength of attractive forces (gelation) in a drilling fluid under static conditions. However, the ***yield point*** is a measurement of the attractive forces in a fluid while under flowing conditions; A decrease in one usually results in a decrease in the other.

Excessive gelation is caused by high solids concentration leading to flocculation. Gelled mud can only be removed by applying sufficient shear stress to overcome the gelled strength of the mud. This shear stress can come from pipe movement or from the mobile mud (or other displacing fluids). In another word, the required shear stress is generated by frictional pressure drop.

Thus, the shear stresses generated can be increased by increasing the mud flow rate, or varying the properties of the mobile fluid. Ideally, the problem should be minimised by reducing the mud's low shear-rate viscosity and gel-strength during circulation before the casing is run. Once the hole has been circulated clean of cuttings, additional circulation can be used to condition the mud and to remove the gelled and dehydrated mud that becomes far more difficult to remove after a prolonged static period.

Power Law model is a used to describe a non-linear curve. The equation for drilling fluids is; $\tau = K\,(\gamma)^{n}$ (4)

K is consistency index and ***n*** is flow behavior index. The flow behavior index is descriptive of the degree to which the fluid is non-Newtonian.and determined as the slope of a plot of τ vs γ on logarithmic coordinates.

Drilling mud with a higher "k" value and a lower "n" value has more flat annular velocity profile. That means the cement has more chances to expose to high annular velocity at the near edge of wellbore.

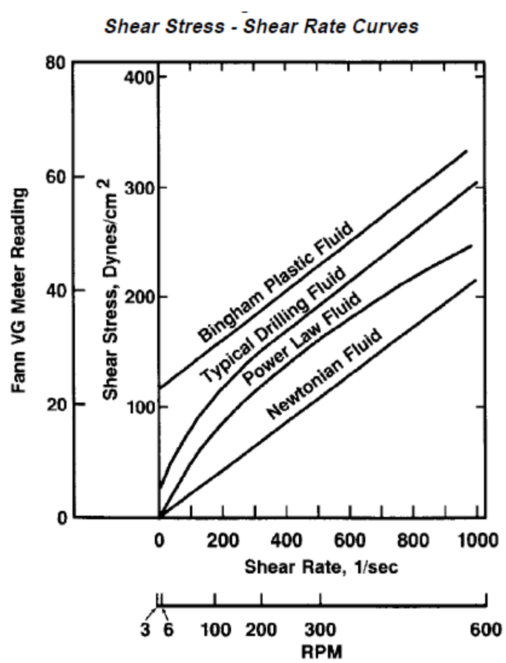


Figure 1: Shear Stress – Shear Rate Curves

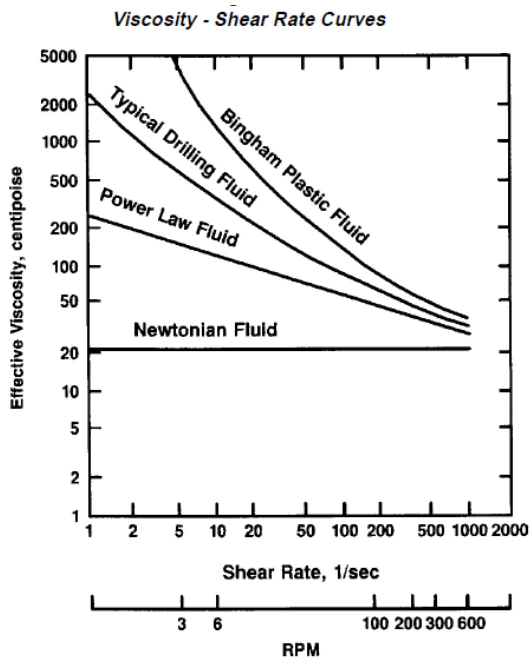


Figure 2: Viscosity –Shear Rate Curves

2.1.2. Effect of Annular Velocity and Displacement Rate

Based on fluid velocity in annulus, flow of the fluid can be Laminar or Turbulent. Typically at lower velocities (flow rates), flow regime will be laminar and as the flow rate increases and the flow starts to become turbulent.

Type of the flow can be determined from dimensionless Reynolds Number. The Reynolds number in annulus can be calculated from following equations:

$$\mathrm{Re} = \frac{\rho \mathbf{v} D_H}{\mu} = \frac{\mathbf{v} D_H}{\nu} = \frac{\mathbf{Q} D_H}{\nu A} \tag{5}$$

$$Re_a = \frac{928 V_a (D_h - D_o) W}{\mu_{ea} (\frac{2n_a + 1}{3n_a})^{n_a}} \tag{6}$$

Laminar flow occurs when Reynolds Numer smaller than 2300 and turbulent flow occurs when Reynolds Numer larger than 4000. Hence, between these rang flow considered as transition regime.

Based on defined formula, viscosity is indirectly proportional with the Reynolds number. Thus, by increasing viscosity of fluid, Reynolds number value will be reduce and the flow will begin to laminar regime.

Moreover, In both of flow regime usually center layers of fluid has higher moving rate in compare the layer near the wellbore or pipe and that is the reason the cement displacement near the wellbore wall will be complex [8].

Several studies have shown that if the fluid is in turbulent flow, the cement displacement will be more effective. However, in an eccentric annulus ensuring turbulence occurs at all points across the annulus is difficult. In most cases, the turbulent flow will result in gelled mud remaining in the narrow section of the annulus. Where turbulence for the spacer/wash can be achieved, the displacement rate should be as high as possible to achieve the best results. Moreover, if turbulent flow cannot be achieved; well designed laminar flow can aid to achieve effective cement displacement.

2.1.3. Effect of Casing Eccentricity (Stand-Off)

In horizontal and highly deviated wells usually annulus becomes eccentric that will affect on cement flow around the casing or liner in annulus. However using centralizer can reduce this issue [3], still the velocity distribution lead to low-velocity fluid flow on the narrow side and Flow will favor the wide side of the annulus [10]. In some cases, turbulent and laminar flow may establish in different areas across the annulus. Based on simulation has done by Moroni et ai. (2009) only 21.5% of total spacer and 25% of total cement flow into the narrow side of wellbore. [14]

Eccentricity effect will increase probability of incomplete zonal isolation and channeling contamination especially in horizontal wells.

Research and field experience have shown that minimum stand-off should be at least 70%.; and if it falls below about 60%, no practical combination of flow rate and fluid viscosity will remove the stagnant mud.

Generally cement simulation and centralizer programme will use to ensure the effective eccentricity (greater than 70% at all points along the string) and consideration of buoyancy and density differential terms.

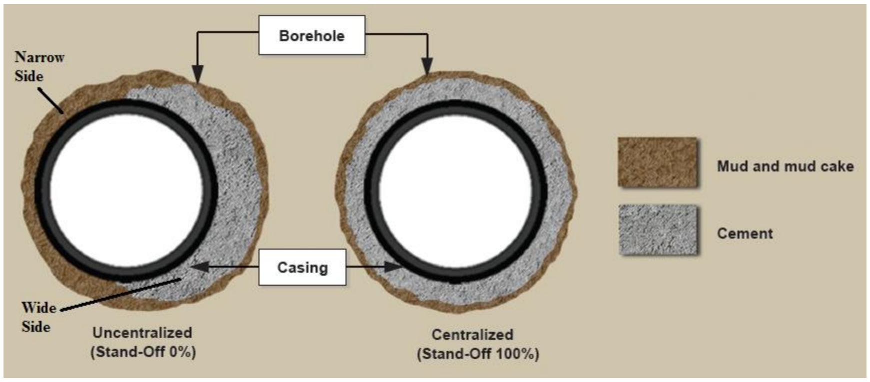


Figure 3: Casing Stand-Off

Based on Hele-Shaw displacement model that derived by Bittleston, Ferguson, and Frigaard (2001); Dimensionless spatial coordinates are $(\varphi, \xi) \in (0, 1) \times (0, Z)$, where φ is the azimuthal coordinate; $\varphi = 0$ denotes the *wide side* of the narrow eccentric annular space and $\varphi = 1$ denotes the *narrow side*.

The annular gap half-width is $H(\varphi, \xi)$ that defined as bellow:

$$H(\varphi; \xi) = H(\xi)(1 + e(\xi) \cos \pi\varphi) \quad (7)$$

Where $e(\xi) \in [0; 1)$ is the eccentricity; $e(\xi) = 0$, is concentric and $e(\xi) = 1$, implies that the casing contacts the wellbore wall on the narrow side, which we disallow.

2.1.4. Effect of Casing movement (Rotating and Reciprocating)

Casing movement can be either rotating or reciprocation that effect on cement placement. Although the physics of mud removal and cement placement through casing rotation is complex to analyse, the beneficial impression of casing movement have been shown in laboratory and field tests [14].

These methods are helpful; because, the cement placement efficiency will become greater in both laminar and turbulent flow regimes by casing motion. This Technique can break up the gel structure of the mud and enhancing mud displacement.

Based on McLean *et ai.* Research rotation may be more effective than reciprocation in cementing [6].

The advantages of pipe rotation to reciprocation are is follow: [12]

- Minimize the risk of getting stuck off-bottom
- Eliminate swab or surge pressures that lead to failure primary well control

Typically casing is reciprocated between 20 - 40 ft for one to five minutes.[11] However, the movement downhole can be reduced due to pipe stretch and buckling; the rotation undertaken for liners from 10 to 22 rpm will be adequate.[15]

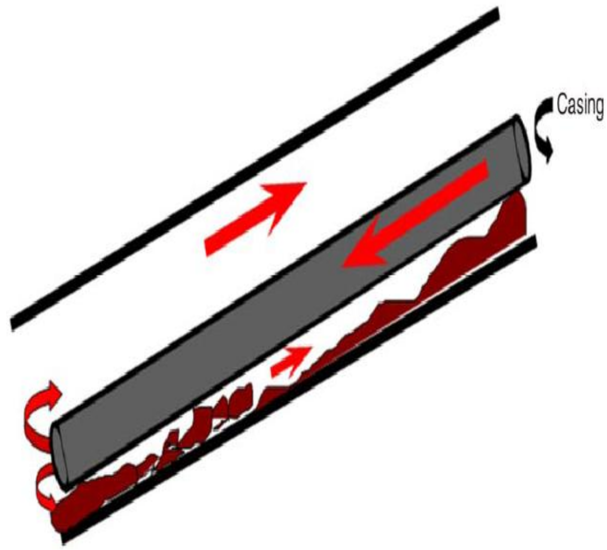


Figure 4: Pipe Movement in Eccentric Annulus

2.2. Investigated Parameters

2.2.1. Pressure Drop (ΔP)

Pressure drop is one of the factor has curial effect in cement placement. Based on most experimental result shows pipe rotation has positive effect in pressure drop. [16]
It means by increasing speed of rotation, pressure loss will boost. [17]
However there are a few studies that fail this theory and they believe pipe rotation has not effect or even can lead to reduce pressure drop. There are also some studies has reveled low rotational speed (below 60 RPM) pressure loss slightly increased and above 60 RPM, pressure loss increase linearly with rotation. [18]
Ozbayoglu et al (2009) did experiment for Non-Newtonian fluid and illustrate pipe rotation in realistic annulus will lead to turbulence flow and increase in pressure loss. [22]

2.2.2. Equivalent Circulation Density (ECD)

Circulation density is one of parameters that can push the fluid. Managed ECD can help for cleaning the hole or improve efficiency of cementing job, However if it will increase dramatically can lead to formation fracture. Moreover control ECD is more challenging in horizontal well at narrow annular clearance.

Most of published works have looked at hydraulic efforts in terms of changes in annular pressure drop. Based on ECD definition, it has direct relation with pressure drop (ΔP):

$$ECD = MW + \frac{\Delta P}{0.052 \times TVD} \tag{8}$$

Hence, ECD can predict by changes in pressure loss. In other hand pipe rotation affects to increase ΔP that lead to raise Equivalent Circulation Density.

The research has reveled increasing rotation speed at constant annular velocity produced a near-linear increase in ECD and also it has validated by filed practice. [23] [24]

2.3. Application Computational Fluid Dynamic (CFD)

Computational fluid dynamics is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Simulation is mainly based on Navier-Stokes equations are that rely on continuity equation, momentum equation and energy equation. The continuity equation is used for the calculation the mass transfer of the solid-liquid flow and the momentum equation is to observe the motion of the solid particles in the liquid.

The continuity equation defines as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$

The momentum equation defines as:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right) - \frac{\partial p}{\partial x_i}$$

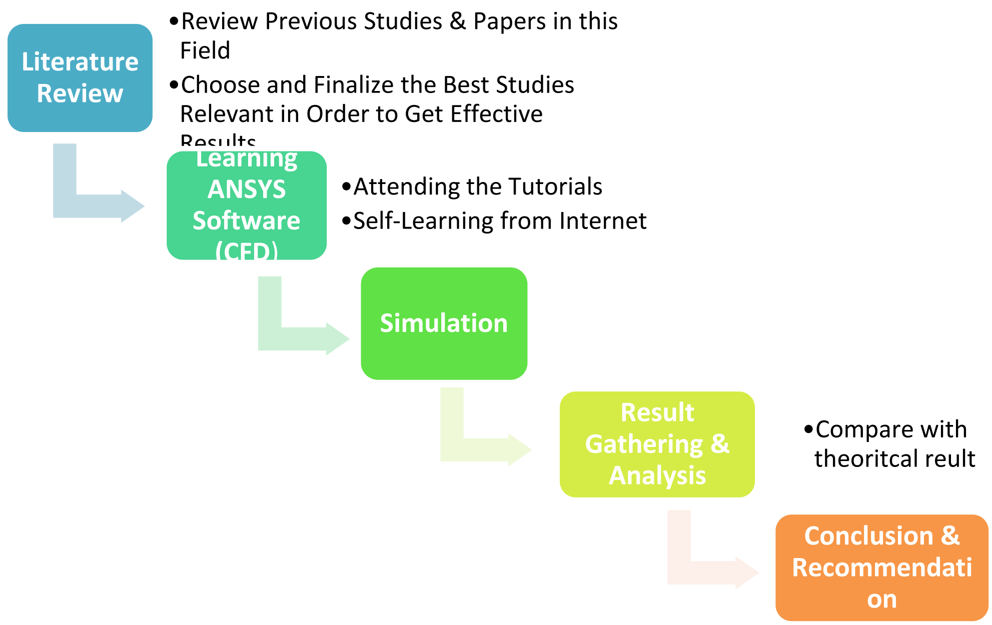
Numerous studies have done in oil well field by using CFD recently. This model can demonstrate flow profile of different parameters in well bore.

Yao and Robello (2008) were used computational fluid dynamic (CFD) software for the standoff devices analysis and Navier-Stoke equations for calculating pressure drop.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology



3.2 Input Parameters

For simulate cementing horizontal well following parameter has extract form "Successful Field Experience of Cementing with Liner Rotation". [20]

Table 1: Input Parameter

Parameters	Field Practice	Software Input	Remark
Hole Size	**8.5** in	**0.216** m	
Liner Size	**7** in	**0.178** m	
Model Length	**10** ft	**3.048** m	
Cement Density	**15.8** ppg	**1900** kg/m3	
Consistency (K)	**0.0014** lb sen^n/ft2	**0.067034** pa sec^n	
Power Law Factor (n)	**0.86**	**0.86**	
Flow Rate (q)	**6.22** bbl/min	**0.0164833** m3/sec	Mass flow rate=**31.3182** kg/sec
Rotation	**20 – 80** rev/min	**2.0943-8.3775** rad/sec	

3.3 Simulation Steps

The following figure shows procedure of working with ANSYS to generate Result

Figure 5: Simulation Steps in ANSYS Software

3.4. Designing Model

The model for this project has designed in CFX. First, geometry of model has started by Assuming two pipe that one is hole and other consider as liner. Second, the pipes have meshed(8.34×10^6). In additional, boundary conditions have defined as mass flow rate for input and standard pressure for output. In next stage cement has defined as fluid for displacement with its specific properties.

For this simulation only one phase is defined that is cement and concentric pipe was considered. Nevertheless by this model can save time for each run and avoid complex analysis.

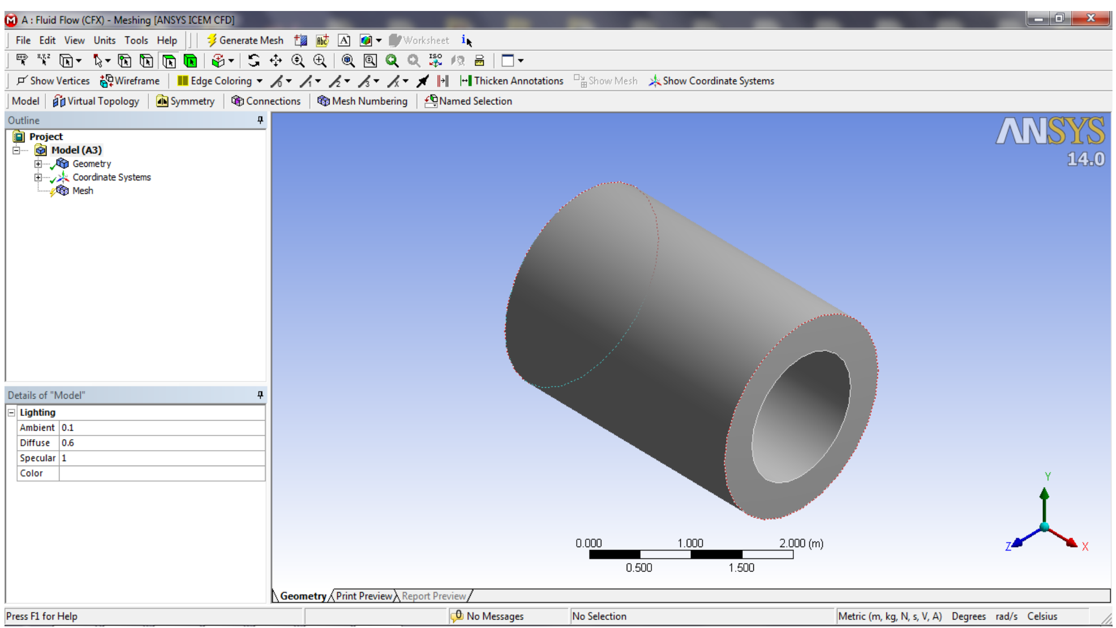


Figure 6: Designed Geometry

3.5 Gantt Chart

FYP I Activities/Timeline	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14	W 15	W 16	W 17
	21/5	28/5	4/6	11/6	18/6	25/6	2/7	9/7	16/7	23/7	30/7	6/8	13/8	20/8	27/8	3/9	10/9
Selection of Project Topic														Hari Raya	Study week	Final Examination Week	Final Examination Week
Preliminary Research Work																	
Literature Review/Project Background																	
Submission of Extended Proposal																	
Proposal Defense																	
Project Work Continues																	
Submission of Interim Draft Report																	
Submission of Interim Report																	

FYP II Activities/Timeline	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14	W 15	W 16
	21/9	28/9	5/10	12/10	19/10	26/10	2/11	9/11	16/11	23/11	30/11	7/12	14/12	21/12	28/12	4/1
Project work Continues															Study week	Final Examination Week
Submission of Progress Report																
Project Work Continues																
Pre-SEDEX																
Submission of Draft Report																
Submission of Technical Paper																
Oral Presentation																
Submission of Project dissertation (Hard Bound)																

Table 3: Gantt Chart FYP I & II

3.6 Key Milestone

Key Milestone for this study based on guideline of Final Year Project (FYP) is showing in Table 2:

Table 2: Final Year Project Key Milestone

Date	Activity
2 July 2012	Submission of extended Proposal
25 July 2012	Proposal Defenses
7 August 2012	Submission of interim Draft Report
15 August 2012	Submission of Interim Report
7 November 2012	Submission of Progress Report
26 November 2012	Submission of Poster
3 December 2012	Submission of Technical Paper
5 December 2012	Submission of Draft Final Report
19 December 2012	Oral Presentation
2 January 2013	Submission of Project dissertation

3.7 Tools

In this project computer system with medium performance has used to simulate using Computational Fluid Dynamic in ANSYS 14.

CHAPTER 4

RESULT & DISCUSSION

4.1 Flow pattern

The follow pattern is graphical output can generate from software that showed how cement is moving for inlet to reach outlet. It illustrates velocity distribution in annulus that can conclude to cement placement in boundaries. As the figure shows cement velocity is reducing from 4.7 ft/s at inlet (casing shoe) till become zero at out of annuli. By increase rotation motion, velocity profile has increase and lead to turbulent flow, however the velocity difference is not significant for difference rotation speed.

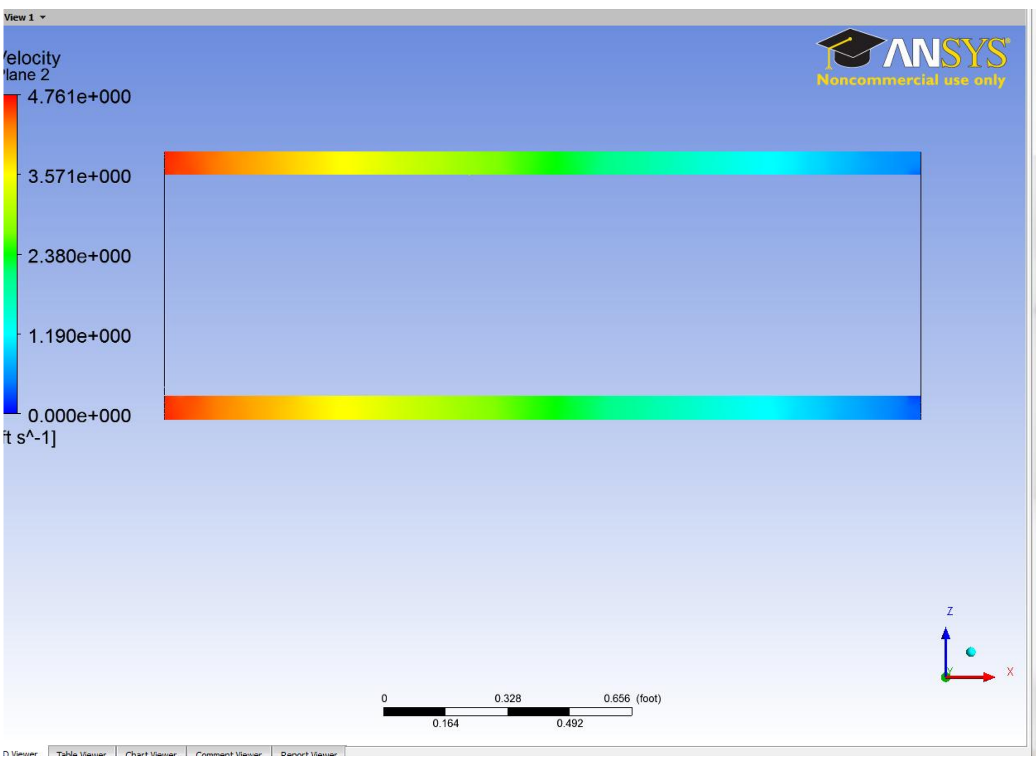


Figure 8: velocity Profile for 60 RPM

Moreover, ANSYS CFD can produce pressure profile as well. It can be seen inlet with red color (Warm) has highest pressure that will be reduce to 14.7 that assumed as standard pressure at surface.

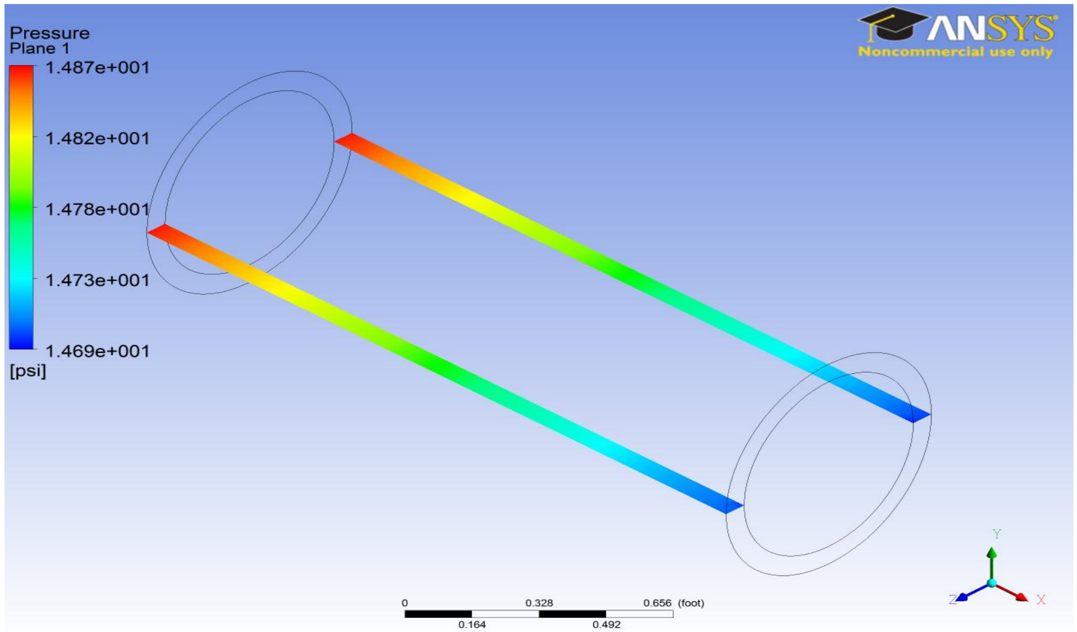


Figure 7: Pressure Profile for 60 RPM

4.2 Pressure Drop Effect

ANYSYS after each run can produce pressure verse length of hole (psi Vs. ft). These pressure figures can be found in appendixes.

For verify the simulation result, it has compared with theoretical formula based experiments. However flow regime for not rotation case (0 RPM) considered as laminar and liner rotation with different RPM were behaved turbulent. Table 9 shows present discrepancy for result validation. Following equation are used to calculate theoretical pressure drop:

No Rotation

$$\Delta p = 4\left[\left(\frac{6v}{R-kR}\right)\left(\frac{2n+1}{3n}\right)\right]^n \frac{m}{2(R-kR)} L \qquad (9)$$

Rotation

$$\frac{\Delta P}{\Delta L} = \frac{f_f \rho v_a^2}{21.1(D_o - D_i)} \qquad (10)$$

$$f_f = 8.274 N_{Re_a}^{-0.9075} + 0.00003 N_{Re_r} \qquad (11)$$

Table 3: *ΔP/ΔL between Theoretical & Simulation (q=6.2 BPM)*

Rotation / ΔP/ΔL	No Rotation	20 RPM	40 RPM	60 RPM	80 RPM
Theoretical	0.0616	0.1029	0.1005	0.1183	0.1368
Simulation	0.0700	0.0800	0.0805	0.0900	0.1040
Percent Discrepancy	13.70	22.24	19.92	23.89	23.99

Figure 9 shows pressure drop result of simulation and theoretical for 6.22 bbl/min flow rate.

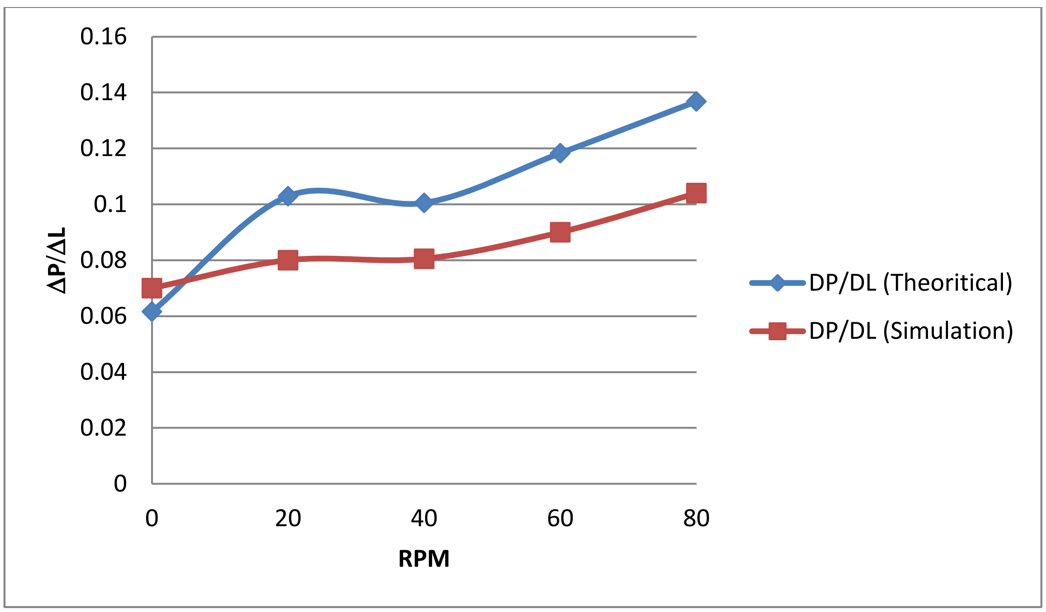


Figure 9: ΔP/ΔL for Different Rotation Speed (q=6.2 BPM)

As the graph shows simulation results are in good agreement with the theoretical results and present discrepancy for all is about 13% to 23%. For not rotation case simulated pressure drop has higher rate in compare theoretical, however for rotation mode, simulation got less pressure drop and by in higher rpm the gap between them is become huge. In overall pressure drop of simulation will increase by liner rotation in moderate proportion that leads to improve cement placement

Figure 10 compare pressure drop with 4.5 bbl/min flow rate

Table 4: Theoretical Vs. Simulation Calculations ***(q=4.5 BPM)***

Rotation / ΔP/ΔL	No Rotation	20 RPM	40 RPM	60 RPM	80 RPM
Theoretical	0.0466	0.0675	0.0569	0.0662	0.0759
Simulation	0.0585	0.0590	0.0585	0.0650	0.0745
Percent Discrepancy	25.53	12.56	2.72	1.84	1.90

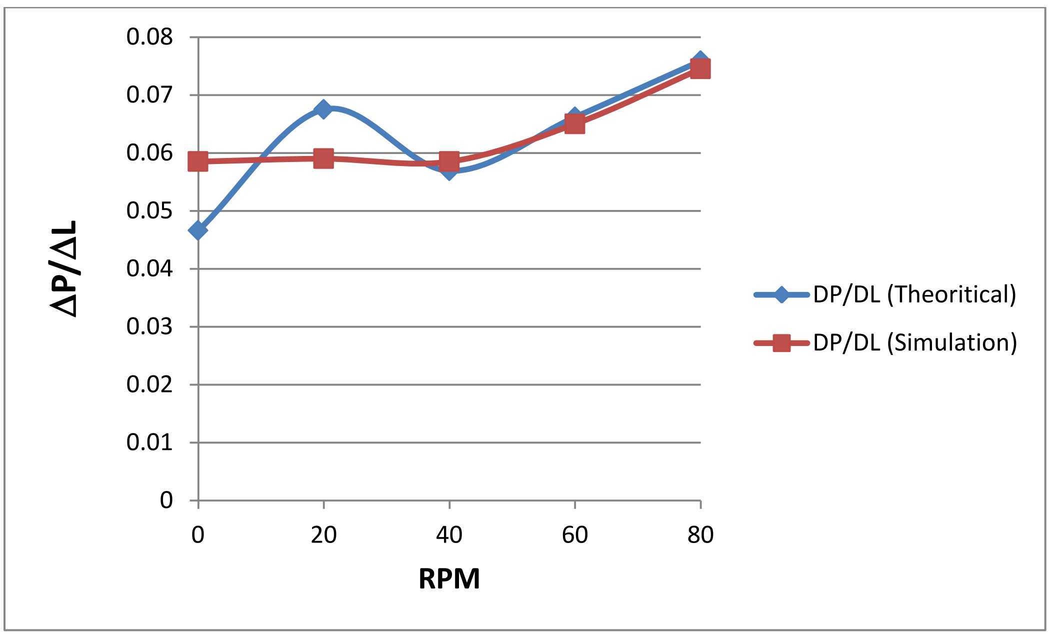


Figure 10: ΔP/ΔL for Different Rotation Speed (q=4.5 BPM)

It can be seen from figure 10 pressure drop 4.5 bpm with flow rate has closer agreement with theoretical result, however at 20 RPM shows peak in pressure drop. In overall it is observed that pressure drop has range is about 0.05 to 0.07 for 4.5 bpm cement flow rate.

In Additional, pressure drop were increase for higher flow rate that simulated and shows after 40 RPM pressure drop will increase dramatically that theoretical has shows same results.

4.3 Equivalent Circulation Density Effect

Equivalent circulation density (ECD) is another factor that investigated for this project, since research has reveled proportion pipe rotation speed has positive relation with pressure drop and ECD. Based on simulated pressure drop, ECD has calculated for 10000 ft well depth. Figure 11 shows ECD value for different flow rate and rotation speed. It is clearly illustrate higher ECD value as flow rate were increased to 6.2 bpm.

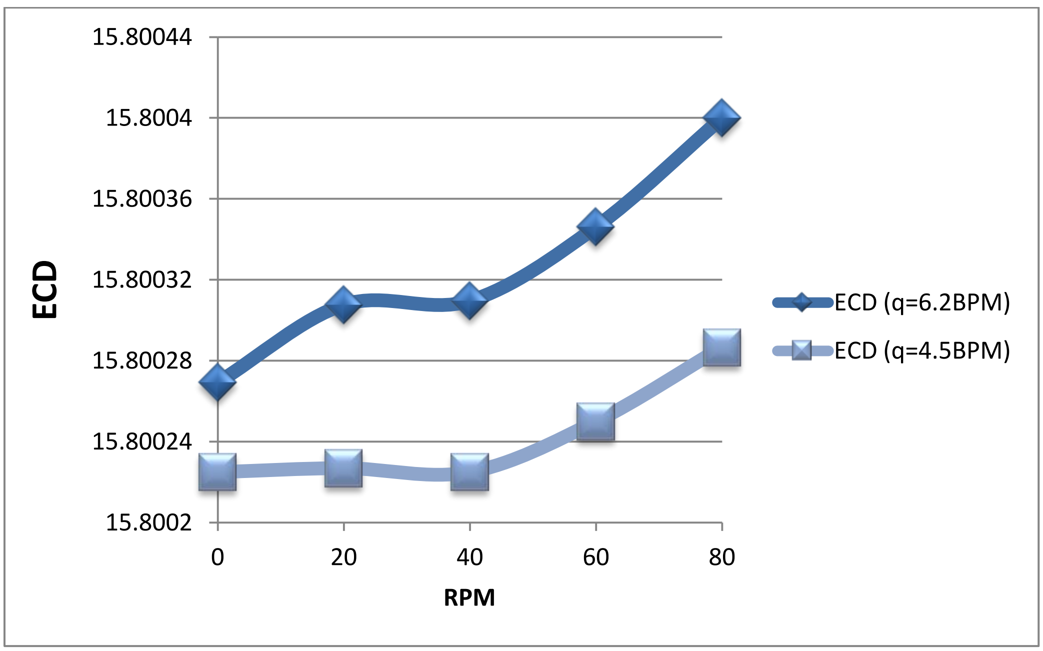


Figure 11: ECD vs. RPM

CHAPTER 5

CONCLUSION & RECOMENDATION

This project has aim to improve cement placement in horizontal well. The main objective is effect of pressure drop and equivalent circulation density that investigate by using ANSYS-CFX 14 software. In additional parameters like velocity profile of simulation has considered to ensure liner rotate in slurry. As a result of this simulation, the following points are summarized as conclusion:

ANSYS software can simulation and produce reasonable result for liner rotation cementing in the horizontal wells. Furthermore, simulation has an error difference of about 2% to 24% when compared with the theoretical formula results with exception of some few points due to limitations and assumptions considered in this study.

- ✓ Due to increase liner rotation, the pressure drop were increase causing the carrying capacity to increase

- ✓ The Equivalent Circulation Density (ECD) has a linear relationship with pressure drop (ΔP). Hence, as the pressure drop increase, the value of ECD will increase that shows cement placement can be improved.

- ✓ As the flow rate increase, pressure drop and ECD consequently were increases causing have proportional relation based on theoretical and field practice.

- ✓ Increase in RPM shows pressure drop will increase dramatically after 40 RPM, even though different flow rate has some effect on it.

For further studies in displacing cement through rotation of casing has following points will recommended:

- ➢ Simulation Actual case that consider as 3 Phase (Cement, Spacer & mud)
- ➢ Design geometry for eccentric hole and
- ➢ Assuming hole roughness that has important role in Friction Pressure
- ➢ Inclination section from vertical axis that has crucial effect in cement placement.

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APPENDIXES

Appendix 1- Pressure Drop Calculation (No Rotation)

$$\Delta p = 4\left[\left(\frac{6v}{R-kR}\right)\left(\frac{2n+1}{3n}\right)\right]^n \frac{m}{2(R-kR)} L$$

d_i: Inner pipe diameter (m)
d_o: Outer pipe diameter (m)
e: Eccentricity
k: Radius ratio
L: Length (m)
l_e: Entrance length (m)
M: Ratio of pressure drop in eccentric annulus to concentric annulus
m: Consistency index ($Pa.s^n$)
n: Power-law index
p: Pressure (Pa)
P: Modified pressure (Pa)
P_0: Modified pressure at z=0
P_l: Modified pressure at z=l
R: Outer pipe radius (m)
s: $1/n$
v: Velocity (m/s)
$\dot{\gamma}$: Shear rate (1/s)
δ: The distance between outer and inner pipe centers (m)
ε: r/R
η: Viscosity (Pa.s)
λ: Maximum velocity location/ R
ρ: Density (kg/m^3)
τ: Shear stress (Pa)

Appendix 2- Pressure Drop Calculation (Rotation)

$$\frac{\Delta P}{\Delta L} = \frac{f_f \, \rho v_a{}^2}{21.1(D_o - D_i)}$$

$$v_a = \frac{Q}{2.448\left(D_o{}^2 - D_i{}^2\right)}$$

$$N_{\mathrm{Re}_T} = N_{\mathrm{Re}_a} + N_{\mathrm{Re}_r}$$

$$N_{\mathrm{Re}_a} = \frac{757 \, \rho v_a (D_o - D_i)}{\mu_{e_a}}$$

$$N_{\mathrm{Re}_r} = \frac{2.025 \, \rho N (D_o - D_i) D_i}{\mu_{e_r}}$$

$$\mu_{e_a} = \left(\frac{K (D_o - D_i)^{1-n}}{144 v^{1-n}} \right) \left(\frac{2 + \frac{1}{n}}{0.0208} \right)^n$$

$$\mu_{eR} = K \left(\frac{1}{n} \right)^n (\xi) \left(\frac{1}{\omega} \right)^{1-n}$$

$$\xi = \left(\frac{D_o^2 - D_i^2}{D_o^2} \right) \left(\frac{15}{\pi} \right)^{1-n} \left(\frac{1}{\left(1 - \left(\frac{D_o}{D_i} \right)^{-\frac{2}{n}} \right)} \right)^n$$

If $N_{\mathrm{Re}_T} < 3000$

$$f_f = 8.274 \, N_{\mathrm{Re}_a}{}^{-0.9075} + 0.00003 \, N_{\mathrm{Re}_r} \; .....$$

If $3000 < N_{\mathrm{Re}_T} < 7000$

$$f_f = 0.0729 \, N_{\mathrm{Re}_a}{}^{-0.3017} + 0.000011 \, N_{\mathrm{Re}_r}$$

Appendix 3- Pressure Drop @ q=6.2 BPM

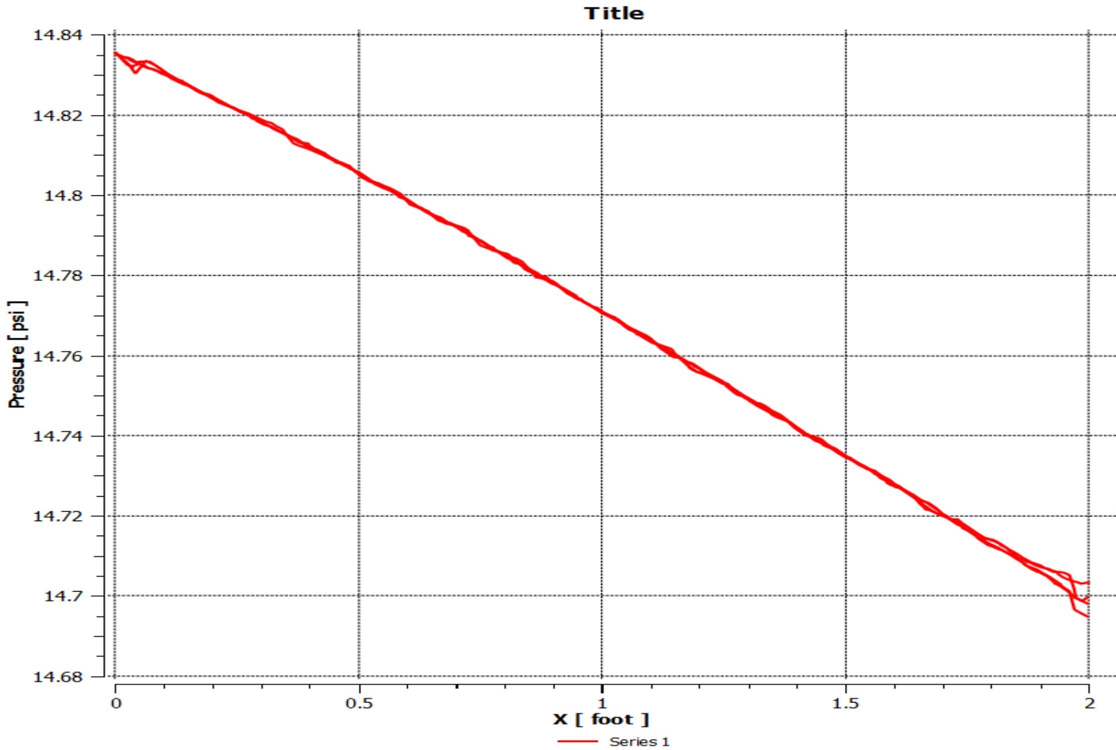

Figure 12: Pressure Profile @ 0 RPM (No Rotation)

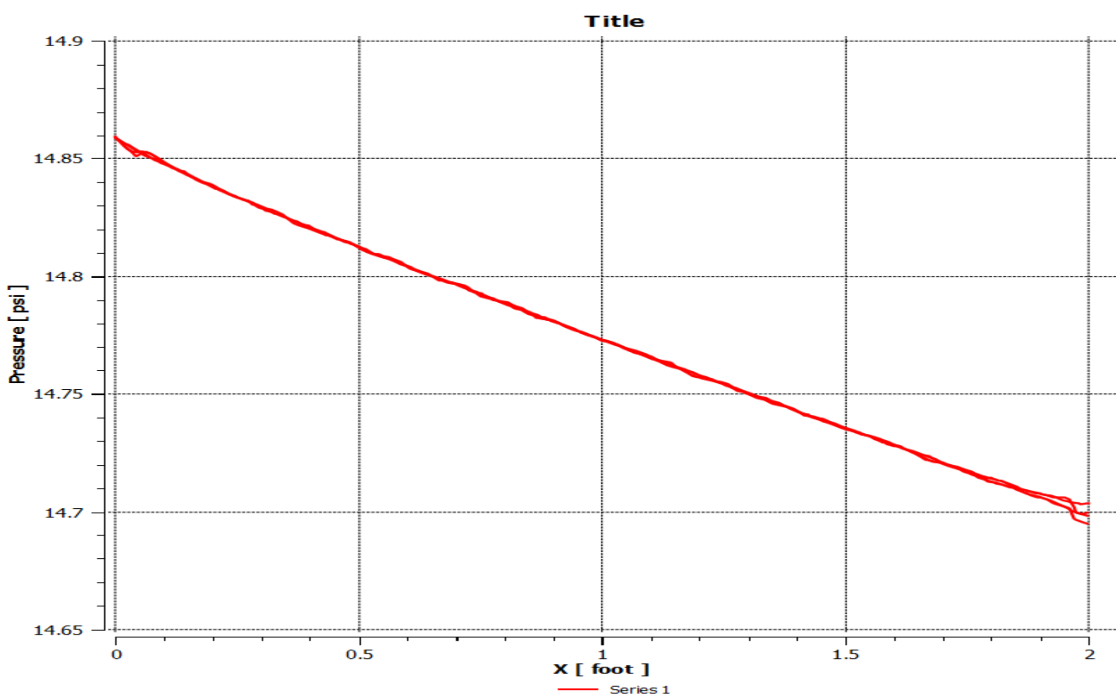

Figure 13: Pressure Profile @ 20 RPM

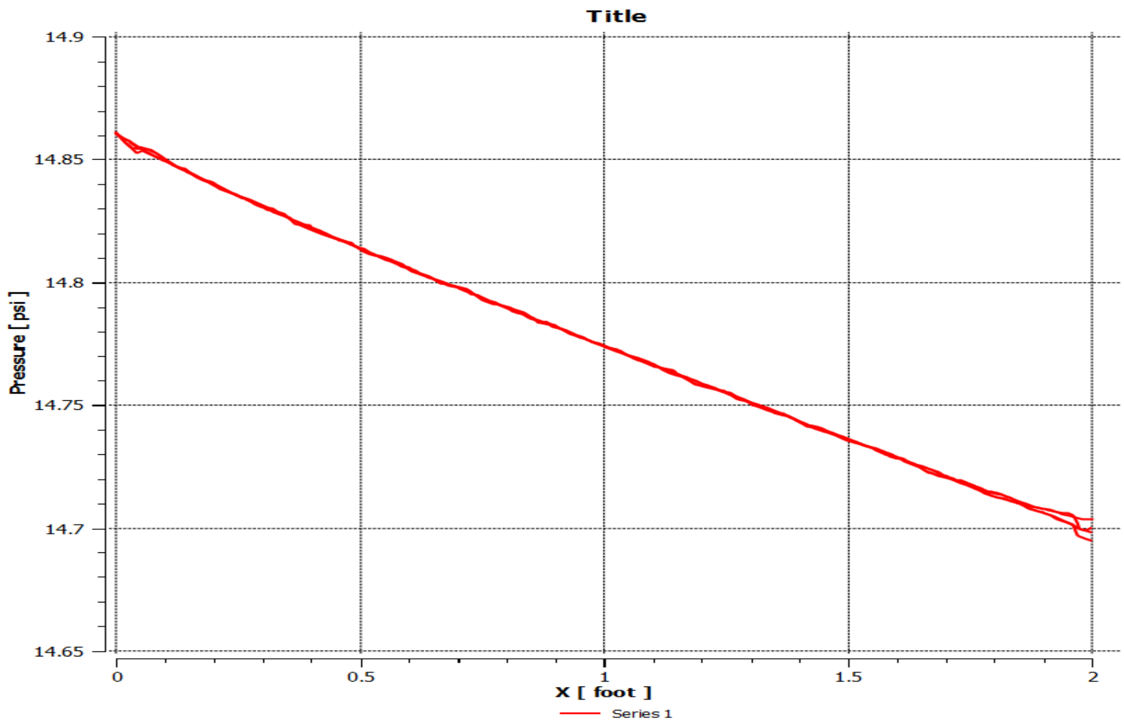

Figure 14: Pressure Profile @ 40 RPM

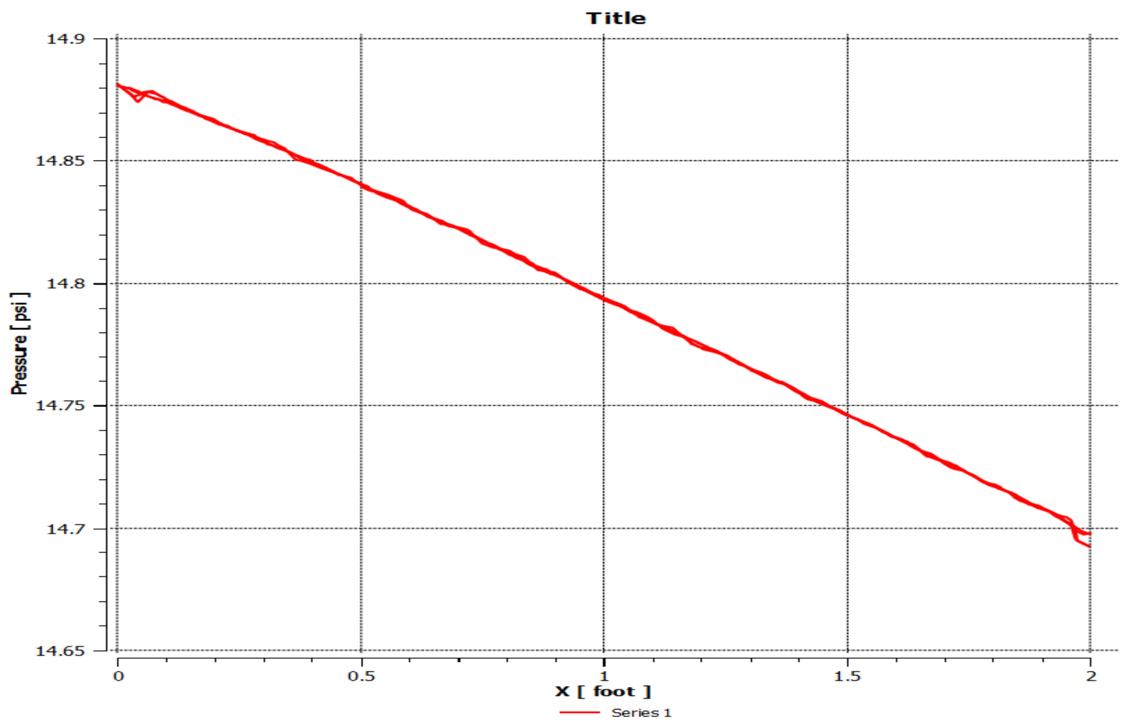

Figure 15: Pressure Profile @ 60 RPM

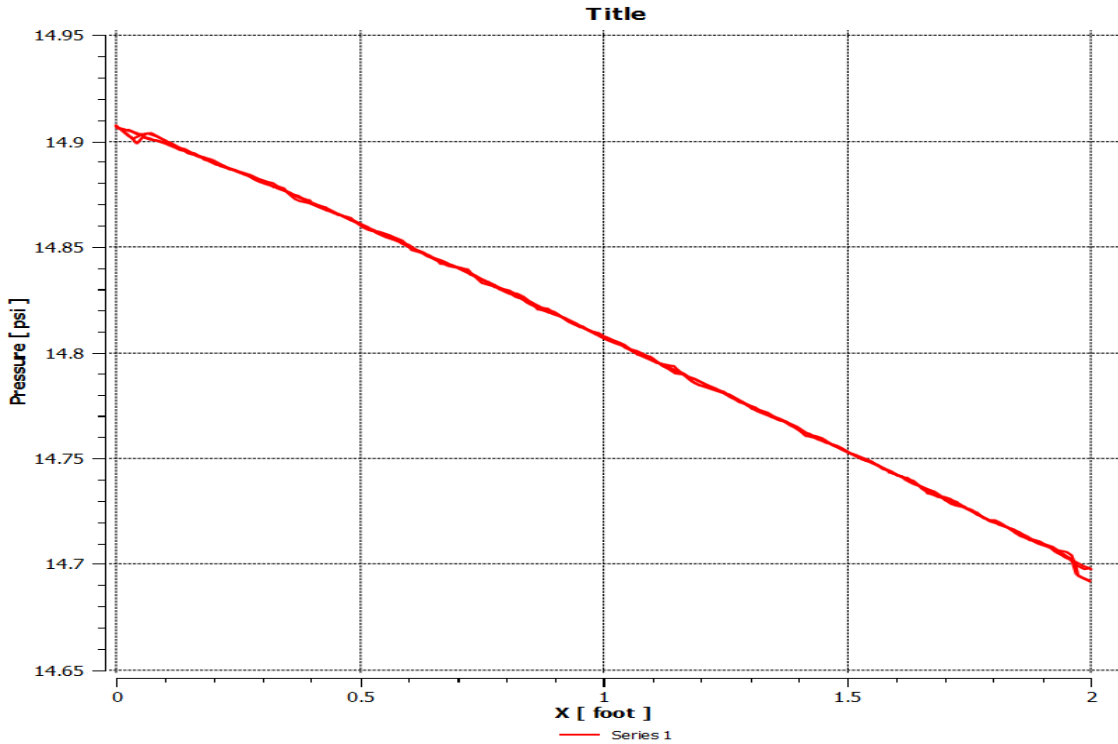

Figure 16: Pressure Profile @ 80 RPM

Table 5: Calculation for 0 RPM

D i	=	0.178			
D o	=	0.216	V	=	1.4018
ρ	=	15.8567	K	=	0.8241
q	=	0.016483	R	=	0.1080
n	=	0.86	R-KR	=	0.0190
m	=	0.067034			
l	=	0.6096	ΔP (Pa)	=	849.1312
			ΔP (Psi)	=	0.1231
		Theoretical	ΔP/ΔL	=	0.0616
		Simulation	ΔP/ΔL	=	0.0700
		Percent Discrepancy		=	13.7065

Table 6: Calculation for 20 RPM

D i	=	7				
D o	=	8.5		V	=	4.5904
ρ	=	15.8567		ξ	=	1.1469
q	=	261.266		μe a	=	29.7897
n	=	0.86		NR a	=	2774.4861
k	=	66.6666		μe r	=	57.2308
				NP r	=	117.8222
ω	=	20		NP T	=	2892.3083
				f	=	0.0097
			Theoretical	ΔP/ΔL	=	0.1029
			Simulation	ΔP/ΔL	=	0.0800
			Percent Discrepancy		=	-22.227172

Table 7: Calculation for 40 RPM

D i	=	7				
D o	=	8.5		V	=	4.5904
ρ	=	15.8567		ξ	=	1.1469
q	=	261.266		μe a	=	29.7897
n	=	0.86		NR a	=	2774.4861
k	=	66.6666		μe r	=	51.9381
				NP r	=	259.6577
ω	=	40		NP T	=	3034.1438
				F	=	0.0095
			Theoretical	ΔP/ΔL	=	0.1005
			Simulation	ΔP/ΔL	=	0.0700
			Percent Discrepancy		=	-30.371795

Table 8: Calculation for 60 RPM

D i	=	7				
D o	=	8.5		V	=	4.5904
ρ	=	15.8567		ξ	=	1.1469
q	=	261.266		μe a	=	29.7897
n	=	0.86		NR a	=	2774.4861
k	=	66.6666		μe r	=	49.0719
				NP r	=	412.2353
ω	=	60		NP T	=	3186.7214
				f	=	0.0112
			Theoretical	ΔP/ΔL	=	0.1183
			Simulation	ΔP/ΔL	=	0.0900
			Percent Discrepancy		=	-23.891464

Table 9: Calculation for 80 RPM

D i	=	7				
D o	=	8.5		V	=	4.5904
ρ	=	15.8567		ξ	=	1.1469
q	=	261.266		μe a	=	29.7897
n	=	0.86		NR a	=	2774.4861
k	=	66.6666		μe r	=	47.1348
				NP r	=	572.2362
ω	=	80		NP T	=	3346.7223
				f	=	0.0130
			Theoretical	ΔP/ΔL	=	0.1368
			Simulation	ΔP/ΔL	=	0.1040
			Percent Discrepancy		=	-23.994618

Appendix4- Pressure Drop @ q=4.5 BPM

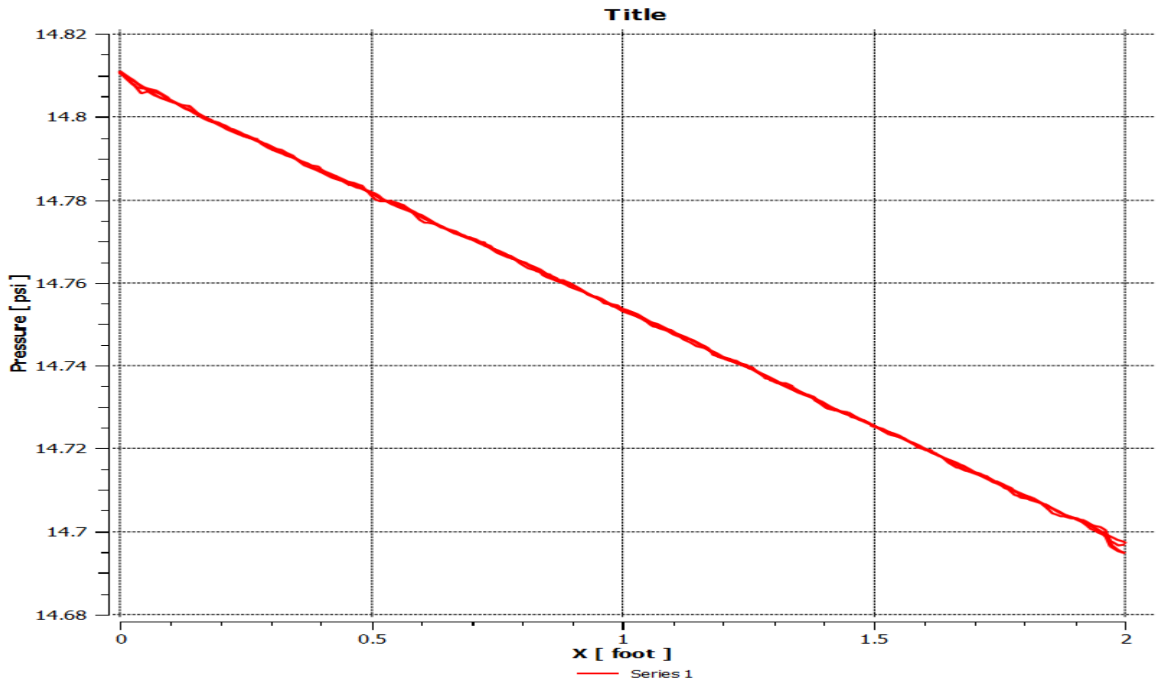

Figure 17: Pressure Profile @ 0 RPM

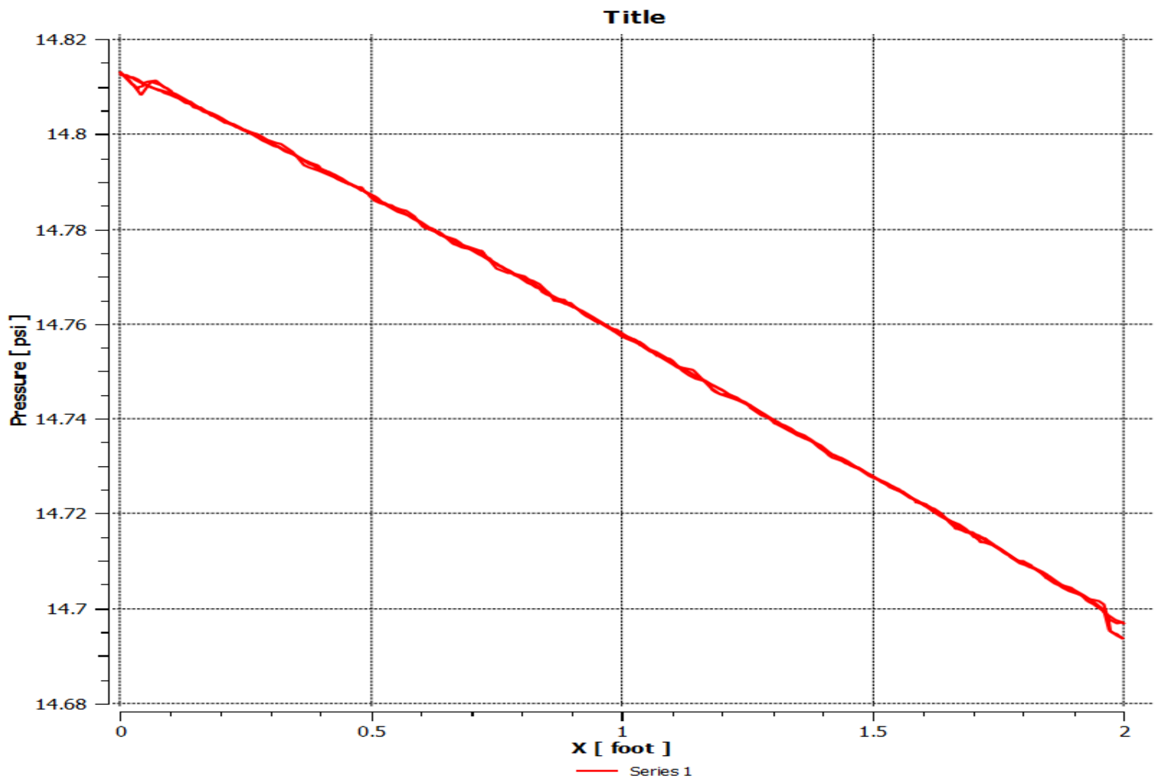

Figure 18: Pressure Profile @ 20 RPM

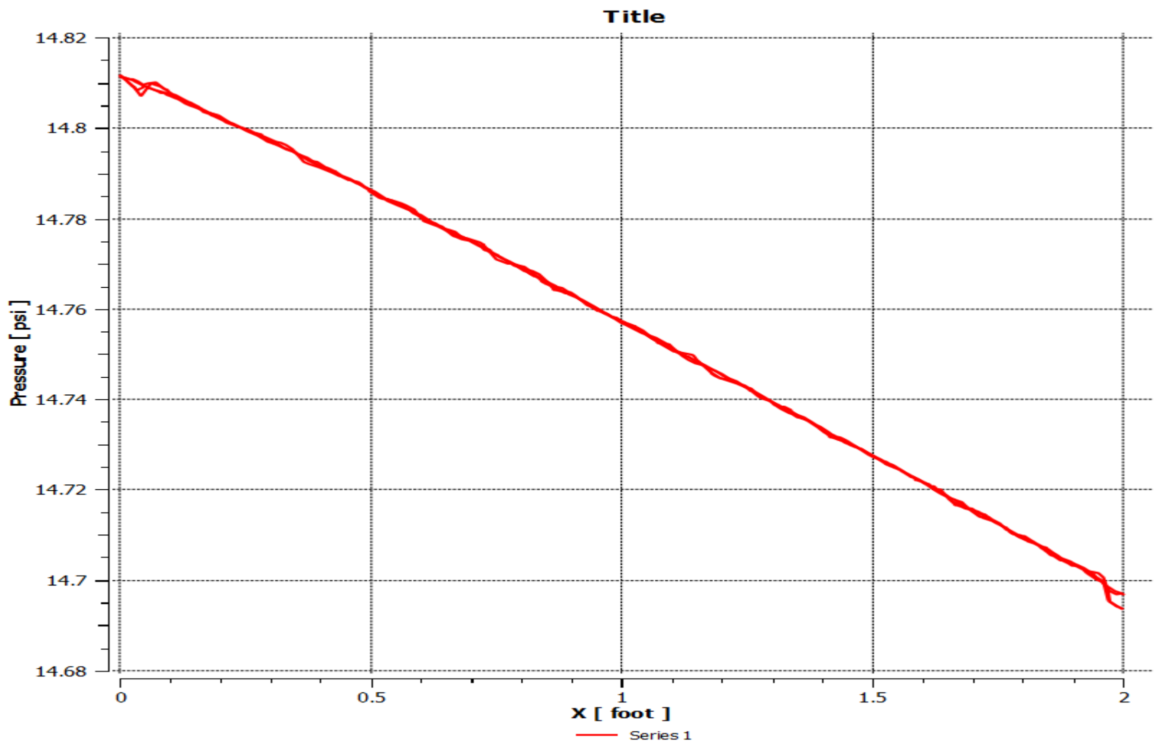

Figure 19: Pressure Profile @ 40 RPM

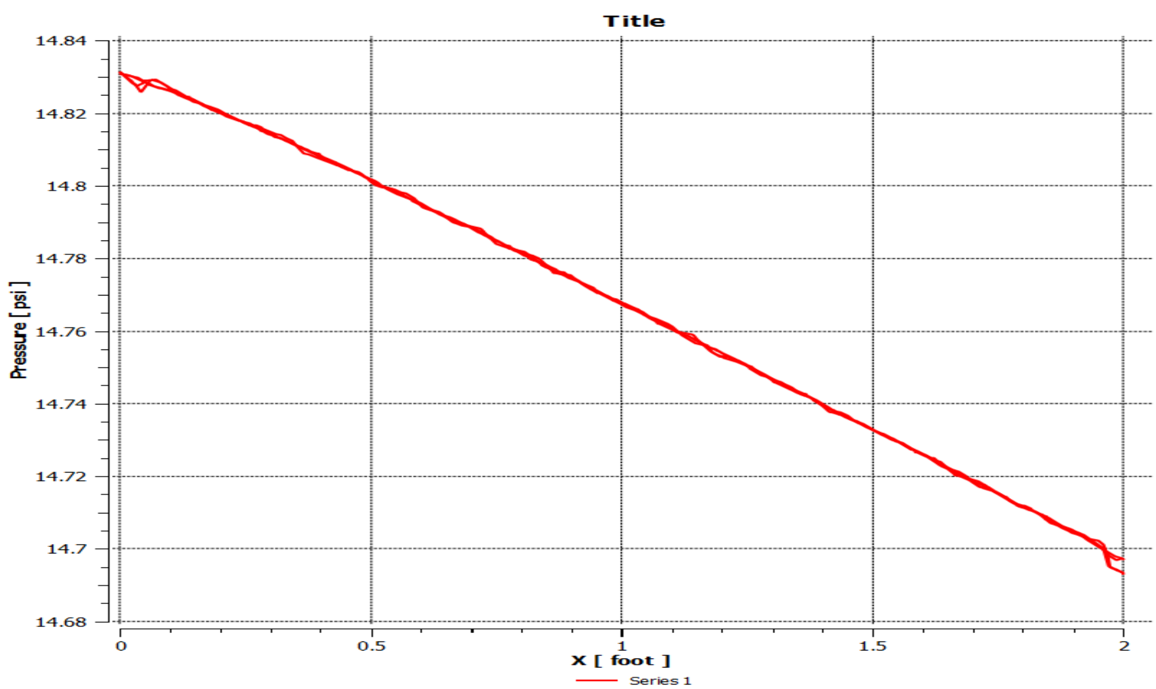

Figure 20: Pressure Profile @ 60 RPM

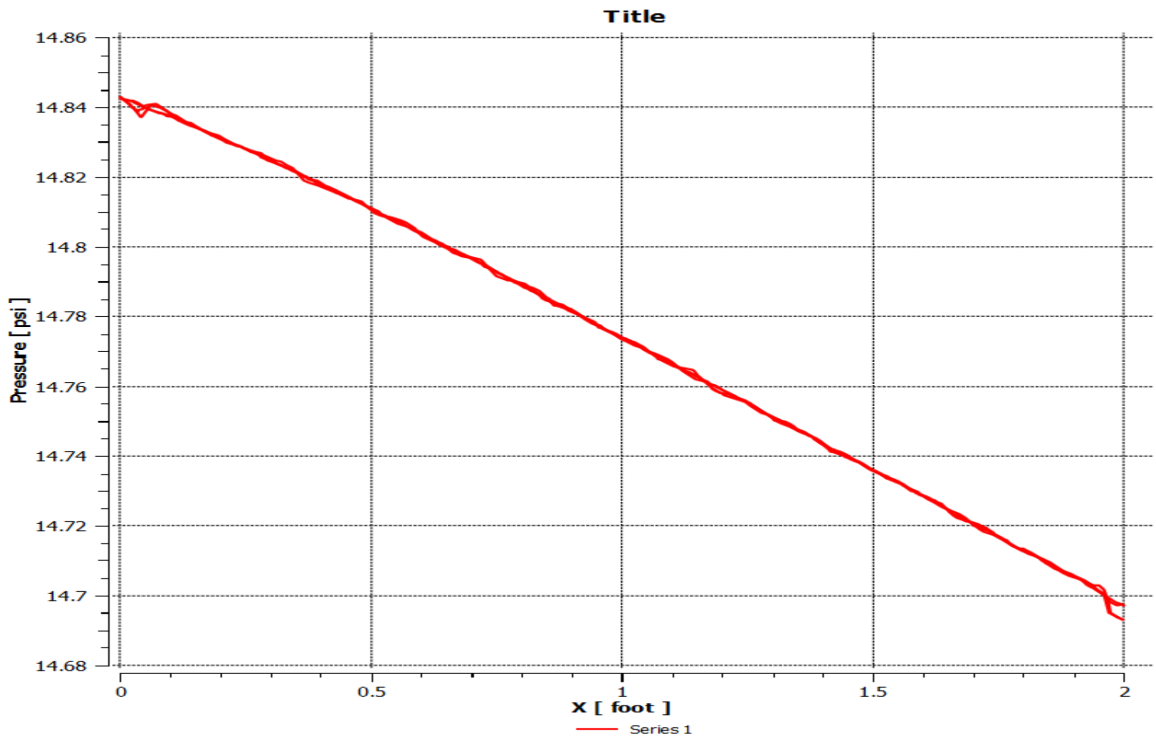

Figure 21: Pressure Profile @ 80 RPM

Table 10: Calculation 0 RPM -q=4.5 BPM

D i	0.178			
D o	0.216		V	1.0140
ρ	15.8567		K	0.8241
q	0.011924		R	0.1080
n	0.86		R-KR	0.0190
m	0.067034			
l	0.6096		ΔP (Pa)	642.7465
□			ΔP (Psi)	0.0932
		Theoretical	ΔP/ΔL	0.0466
		Simulation	ΔP/ΔL	0.0585
		Percent Discrepancy		25.5388

Table 11: Calculation 20 RPM -q=4.5 BPM

D i	7			
D o	8.5		V	3.3207
ρ	15.8567		ξ	1.1469
q	189		μe a	31.1712
n	0.86		NR a	1918.1144
k	66.6666		μe r	57.2308
			NP r	117.8222
ω	20		NP T	2035.9366
			f	0.0122
		Theoretical	ΔP/ΔL	0.0675
		Simulation	ΔP/ΔL	0.0590
		Percent Discrepancy		-12.564938

Table 12: Calculation 40 RPM -q=4.5 BPM

D i	7			
D o	8.5		V	3.3207
ρ	15.8567		ξ	1.1469
q	189		μe a	31.1712
n	0.86		NR a	1918.1144
k	66.6666		μe r	51.9381
			NP r	259.6577
ω	40		NP T	2177.7721
			f	0.0103
		Theoretical	ΔP/ΔL	0.0569
		Simulation	ΔP/ΔL	0.0585
		Percent Discrepancy		2.723392

Table 13: Calculation 60 RPM -q=4.5 BPM

D i	7			
D o	8.5		V	3.3207
ρ	15.8567		ξ	1.1469
q	189		μe a	31.1712
n	0.86		NR a	1918.1144
k	66.6666		μe r	49.0719
			NP r	412.2353
ω	60		NP T	2330.3497
			f	0.0120
		Theoretical	ΔP/ΔL	0.0662
		Simulation	ΔP/ΔL	0.0650
		Percent Discrepancy		-1.8440361

Table 14: Calculation 80 RPM -q=4.5 BPM

D i	7			
D o	8.5		V	3.3207
ρ	15.8567		ξ	1.1469
q	189		μe a	31.1712
n	0.86		NR a	1918.1144
k	66.6666		μe r	47.1348
			NP r	572.2362
ω	80		NP T	2490.3506
			f	0.0137
		Theoretical	ΔP/ΔL	0.0759
		Simulation	ΔP/ΔL	0.0745
		Percent Discrepancy		-1.9018392