CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY & PROBLEM STATEMENT

Sand is the primary cause of erosion in oil and gas transportation through pipeline (Barton, 2003). In oil and gas industry American Petroleum Institute Recommended Practice 14E (API RP 14 E) is the most commonly used tool to evaluate production rate to limit erosion in oil and gas transportation system.

This evaluation technique has received many criticisms describing the failing to be applied for solid particle erosion problems in pipeline (Salama, 1998). Apart from that, this technique gives the option to only reduce the flow velocity to control the severe effect of sand erosion, which is not applicable for large producing well which certainly has large flow rate. A part from that the result of it is so simple and requiring little input which is the mixture density (Craig, 1990).

The study of the factors that affect the severity of sand erosion is important to solve the issue of equipment damage, pipeline erosion and maintenance cost. Using the CFD analysis the sand erosion problem in pipeline is simulated with reference to paper available. From the simulation results, recommendation is proposed to provide solution to the sand erosion problems.

1.2 OBJECTIVE

The objectives of conducting this CFD simulation study are as below:

- To simulate the flow of crude above wax appearance temperature (WAT) in pipe with 90° bend
- To assess the erosion rate at the 90° bend with varying crude oil flow rate, viscosity, and sand particle size
- To assess the velocity distribution at the 90° bend for different pipe geometry

1.3 SCOPE OF STUDY

In this study the crude oil having the density of 924.13 kg/m^3 and viscosity of 0.1401cP which mimics the crude from one of the South China Sea oilfield (Zhu et al, 2010) is numerically simulated, using a commercial computational fluid dynamics (CFD) code, FLUENT version 6.2.16 together with Gambit version 2.2.30 for geometric modeling at different flow rate, density and sand particle size.

The crude flow is adiabatic at temperature higher than its wax appearance temperature (WAT) which is at 50° C. Above the wax appearance temperature (WAT) the crude behaves as a Newtonian fluid.

Below wax appearance temperature (WAT), which is unique for a given crude oil, wax crystal starts to appear and become suspended in the Newtonian base liquid. As the temperature is reduced further, wax crystal starts to grow in size and precipitate from the solution (Tiwary & Mehrotra, 2002).

In this study, a few assumptions have been made. They are:

- 3-Dimensional Flows
- Fully Developed Turbulent Flows
- Steady State Flows
- Adiabatic

CHAPTER 2

LITERATURE REVIEW

2.1 THE API 14E EROSION MODEL

API 14E provide the most simple erosion model for elbows in production system. From this equation, the flow velocity V is calculated in the function of empirical constant, C and gas/liquid mixture density, ρ_m. The value of C factor depends on the service required from the pipes. For example, API 14E suggest a C value of 100 is acceptable for corrosive service which dealing with corrosive chemical (CO2, H2S, etc.), but higher values may be appropriate for erosive service dealing with solid particle such as sand, although these values are not specified. There had been much debate about appropriate value for *C* and different oil companies use different values for different application (Salama, 1998).

$$V = \frac{C}{\sqrt{\rho_m}}$$

2.2 SAND AND PARTICULATE EROSION

Barton (2003) in his paper stated three important factors determining the rate of particle erosion.

- The flow rate of sand and the manner in which it is transported through the pipe
- The velocity, viscosity and the density of the fluid
- The size, shape and hardness of the particles

2.2.1 The Sand Transport

The transport mechanism plays an important role in controlling the erosion within oil production system. Gas systems usually run at high velocity (>10m/s) making them relatively more prone to erosion than liquid systems. Apart from that, if the flow is not steady, sand may accumulate in pipe when the flow is low, and is only flushed through when the flow rate is high.

2.2.2 The Velocity, Viscosity and the Density of the Fluid

The particle erosion rate is highly dependent on the particle impact velocity. It is accepted that the erosion rate is proportional to the particle impact velocity raised to a power *n* depending on the pipe material. For example *n* typically ranges between 2 and 3 for steel (Barton, 2003).

In cases of erosion, the particle impact velocity will be close to the velocity of the fluid carrying the particle. In dense viscous fluids particle tend to be carried around the obstructions by the flow rather than impacting them (Barton, 2003). For low density fluid, particle tend to travel in straight lines, impacting on the walls when the flow direction changes.

2.2.3 Sand Size and Hardness

Sand size seen on the production depends on the reservoir geology. Without prior sand exclusion measure before the wellhead, particle sizes typically range between 50 to 500 micron. A sand particle density of about 2600 kg/m^3 is generally accepted as being representative of solid particle carried together during crude flow via pipeline for erosion service (Barton, 2003).

Small particle of ~10microns rarely hit the wall during crude transportation, thus cause less erosion relatively for larger particle (Barton, 2003). The erosion damage also reduces for very large sand size (~1mm), since these particles tend to move slowly inside the crude and causing less damage (Barton, 2003). It is well established that the harder the material the more severe the erosion is in pipe.

2.3 RICHARDSON'S EXTRAPOLATION

In numerical analysis, Richardson extrapolation is a sequence acceleration method, used to improve the rate of convergence of a sequence (Wikipedia, 2010). This method is utilized to increase the rate of numerical integration, in numerical analysis.

As recommended by Ferziger & Peric (2002), Richardson's extrapolation-to-the-limit technique is used to assess the numerical accuracy in the grid dependency study. In this method, the computational grid is consistently being reduced to finer grid until it reaches the zero limit. The equation utilized by Ferziger & Peric is:

$$I = I(h_2) + \frac{1}{\left(h_1/h_2\right)^2 - 1}\left[I(h_2) - I(h_1)\right]$$

Where I is the velocity of interest for each mesh, h is the cell size and $I(h_n)$ is the velocity monitored for various grid size. When the grid size approaches a zero limit (grid size is very small approaching to 0 value), the velocity of interest, I is calculated. The relative error of the consistently refined grid size is calculated by:

$$e^r = \left(\equiv \frac{\left|X_{ext} - X_{MX}\right|}{X_{ext}} \% \right)$$

Where X_{ext} is the Richardson's extrapolation value, and X_{MX} is the value observed for gradually refined mesh size. The chosen mesh should maintain the relative error value of below 0.05%.

2.4 FLOW VELOCITY PROFILE

In fluid dynamics, velocity profile is crucial in categorizing the type of flow of a fluid. The velocity profile is observed at the 2D cross-section of a circular pipe. For a Newtonian laminar flow the velocity distribution at a cross section will be parabolic in shape with the maximum velocity at the center being about twice the average velocity in the pipe. Meanwhile, for Newtonian turbulence flow the velocity profile across the pipe are fairly flat with a maximum velocity of about 1.2 times the average velocity.

The velocity of the fluid in contact with the pipe wall is essentially zero and increases the further away from the wall for both laminar and turbulent flows. The Figure 2-1 illustrates this phenomenon.

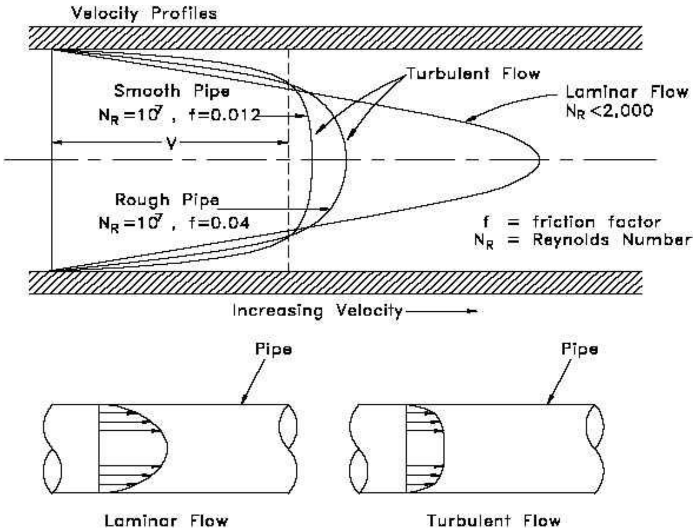

Figure 2-1: Velocity Profile for Laminar and Turbulent Flow (Source: http://www.tpub.com)

2.5 VISCOSITY

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress (Wikipedia, 2010). If a fluid has low viscosity the shear force on the wall is small results in small little friction thus easy to flow in a particular distance (http://www.princeton.edu, 2010). Formally, viscosity (represented by the symbol η "eta") is the ratio of the shearing stress (*F*/*A*) to the velocity gradient ($\Delta v_x/\Delta z$ or dv_x/dz) in a fluid.

$$\eta = \frac{(F/A)}{\Delta vx/\Delta z}$$

From the equation, the viscosity is high when the shearing stress is high and when the velocity gradient is small; i.e. the fluid requiring higher shear stress to move the fluid in a particular distance.

2.6 THE COMPUTATIONAL FLUID DYNAMICS (CFD)

2.6.1 Fluid Flow Modeling

Computational fluid dynamics (CFD) involves the solution of the Navier-Stokes and continuity equation (Ferziger & Peric, 1997). The governing equations for the fluid flow are the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \underline{u}) = S_m$$

and the three momentum equations:

$$\frac{\partial \rho u_i}{\partial t} + \nabla.(\rho \underline{u} u_i) = -\frac{\partial p}{\partial x_i} + \nabla.\rho \nu \nabla u_i + S_i$$

ρ = density
$\underline{u}$ = velocity vector
u_i = i'th component of the velocity vector
v = kinematic viscosity
p = pressure
S_m and S_i = sources into the equations.

This is given as three equations because the i takes the values 1, 2, and 3 that correspond to velocity components in the X, Y, and Z directions respectively.

In the past, researchers used the Reynolds Averaged Navier-Stokes (RANS) to get the numerical solution which require large amount of computational time and memory, which nowadays is achieved using an isotropic eddy-viscosity assumption coupled with the standard two-equation $k - \epsilon$ model of turbulence (Anthony & Srdjan, 2000).

2.6.2 Turbulence Model

FLUENT standard $k - \varepsilon$ model is utilized for the transportation of crude inside pipeline flowing at high Reynolds number. For this model the turbulence is nearly homogeneous and the effect of molecular viscosity is neglected as reported by Rashmi et al (2009).

The standard $k - \epsilon$ model has been used to resolve the turbulence in the system (Launder & Spalding, 1974). The two equations in this model, constitute of the conservation of the turbulent kinetic energy,k, and the dissipation rate,ϵ, as expressed as:

$$\frac{\partial \rho k}{\partial t} + \nabla.(\rho \underline{u} k) = \nabla.\left[\mu_{lam} + \frac{\rho v_t}{\sigma_k}\right]\nabla k + \rho v_t G - \rho \varepsilon$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla.(\rho \underline{u} \varepsilon) = \nabla.\left[\mu_{lam} + \frac{\rho v_t}{\sigma_\varepsilon}\right]\nabla \varepsilon + C_{1\varepsilon} \rho v_t G \frac{\varepsilon}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}$$

In this equation the kinematic turbulent viscosity, v_t, is calculated using:

$$v_t = C_\mu \frac{k^2}{\varepsilon}$$

In the above equation, the C, and σ quantities are model parameters and G is the inner product of the rate of deformation tensor. Turbulence affects the solution of the motion of the flow through viscosity; the kinematic viscosity in the momentum equations is a sum of laminar and turbulent components, and the near wall assumptions.

2.6.3 Particle Erosion and Accretion Theory

Particle erosion and accretion rates can be monitored at wall boundaries (Fluent 6.3, 2010). The erosion rate is defined as:

$$R_{\text{erosion}} = \sum_{p=1}^{N_{\text{particles}}} \frac{\dot{m}_p C(d_p) f(\alpha) v^{b(v)}}{A_{\text{face}}}$$

where $C(d_p)$ is a function of particle diameter, α is the impact angle of the particle path with the wall face, $f(\alpha)$ is a function of impact angle, v is the relative particle velocity, A_{face} is the area of the cell face at the wall. Based on Edward et al (2000) works, the values of $C = 1.8 \times 10^{-9}$, $f = 1$ and $b = 0$ are acceptable for sand eroding both carbon steel and aluminum.

CHAPTER 3

METHODOLOGY

3.1 STUDY PROCESS FLOW

Regarding this study, the process flow as shown below has been established.

1. Analyze the characteristic of sand erosion in crude oil pipeline
2. Establish assumption to meet condition
3. Investigate suitable parameters to be introduce into numerical analysis
4. Development of pipe geometry (Gambit 2.2.30)
5. Grid dependency study
6. Simulation of crude Flow with sand erosion (Fluent 6.2.16)
7. Initial data results gathering & analysis
8. Model improvement to reduce the erosion effect
9. Propose Recommendation & Improvement

Figure 3-1: The CFD Study of Sand Erosion in Pipe with 90° Bend Process Flow

3.2 THE PIPE GEOMETRY

The geometry is developed in Gambit 2.2.30, a tool for drawing and generation of mesh. The base geometry is a straight pipe with 90° bend. The pipe has upstream straight pipe with length of $20D_i$ as recommended by Hilde (2007) for the turbulent flow to fully develop before reaches volume of interest, which in this study is 90° bend. The bend downstream straight pipe length is $10D_i$.

The next geometry developed with at the same grid before with addition of small pipe attached at the 90° bend. The small pipe diameter is $D_i/10$. The D_i used in this study is 0.5m. Figure 3-2 illustrates the pipe geometry.

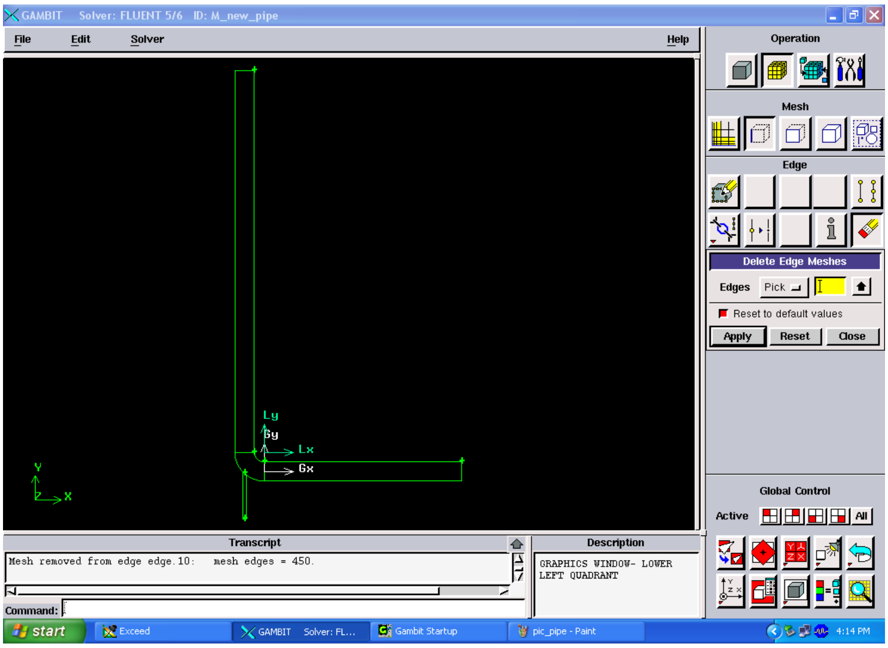

Figure 3-2: Geometry 2 90° Bend with small Pipe

3.3 GRID DEPENDENCY STUDY

The main purpose of this grid dependency study is to select the most suitable grid size for the entire CFD simulation work. The geometry is consistently reduced in their grid size by increasing the circular node value at the bend area. The bend volume is meshed using the T-Grid Scheme; meanwhile the upstream and downstream straight pipe is meshed using the Hex/Wedge Scheme.

The T-Grid Scheme is selected for the bend volume as recommended by Fluent user guide 6.2. The result of velocity U, observe at the bend is compared to the Richardson's extrapolation-to-the-limit technique. The result is shown in the Table 3-1.

Mesh	NC	Cell Size	U	Er
M1	5	0.314	1.038	33.235
M2	10	0.157	1.246	19.827
M3	25	0.063	1.437	7.540
M4	50	0.031	1.553	0.134
M5	100	0.016	1.554	0.047
M6	200	0.008	1.555	0.002
M5	400	0.004	1.555	0.006
Richardson's		0.000	1.555	

Table 3-1: Numerical Accuracy Error using Richardson's Technique

Based on Ferziger & Peric (2002), the chosen mesh should maintain the relative error value of below 0.05%. Thus for the usage of the simulation work, M5 is chosen.

3.4 SIMULATION OF SAND EROSION

The simulations are performed in Fluent 6.2.16. The mesh as describe Section 3.2 & 3.3 is the basis of all simulations. The main purpose for the simulation is to examine the effect of varying fluid viscosity, density, and particle size to the erosion at 90° bend in pipe. The simulation of the same pipe with small pipe attached 90° bend as also conducted to investigate the effect of different geometry to the erosion rate.

The base case is crude oil under the following conditions:

- Re = 5.94×10^3, where the flow is turbulent (Bulk Velocity = 1.8 m/s^2)
- Temperature 50°C (773 K)
- Sand particle Size of 50μm
- Adiabatic

All the properties of the data used in this study are data from the Zhu et al (2010) paper (Appendix A).

For the effect of fluid flow rate to the erosion rate, the values varied are 1.8, 5, 25, 85, 400, and 2000 m/s^2.

For the effect of sand particle size to the erosion rate, the values varied are 50, 100, 150, 300, 800, 1200 μm.

3.4.1 Models

- The standard $k-\epsilon$

  This model is recommended by Rashmi et al (2009) in his paper at high Reynolds number fluid in the pipe.
- Discrete Phase Model (DPM)

  Enabling the Erosion/Accretion and Interaction with Continous Phase options.

3.4.2 Boundary Condition

- Inlet

  The inlet is defined as velocity inlet, with 1.8m/s^2. This is bulk velocity of the turbulent crude flow in pipe. The hydraulic diameter and turbulence intensity value of 0.5 and 5% is used as recommended by Fluent 6.3 user guide.
- Outlet

  The outlet is defined as outflow.

- Wall

  Discrete Phase Model is enabled at the pipe wall. The Discrete Phase Reflection Coefficient and Erosion Model are defined as recommended by Fluent 6.3 user guide. Refer the appendix B.

3.4.3 Solution

As proposed by Fluent User Guide 6.3 for sand erosion in pipe, the solution parameters are modified. Enter value of 0.7 for Pressure and 0.3 for Momentum in the Under-Relaxation Factors options.

3.4.4 Post Processing

The erosion rate is Compute only selected range of 90° bend using the Iso-clip tool.

CHAPTER 4

RESULTS

The results are presented in this chapter. The objectives of this CFD simulation are to observe the effect of varying fluid flow rate, viscosity and sand particle size to the erosion rate at 90° bend. Table 4-1 gives an overview of the simulation cases.

Geometry	Case	Bulk Velocity (m/s)	Viscosity (cP)	Sand Particle Size (μm)
Normal 90 ° Bend	1	1.8, 5, 25, 85, 400, 2000	0.1401	50
	2	1.8	1.2870, 0.9340, 0.6450, 0.2960, 0.1401, 0.1040, 0.0824, 0.0507, 0.0010	
	3	1.8	0.1401	20, 50, 70, 100, 150, 300, 800, 1200
Small Pipe at 90 ° Bend	4	1.8, 5, 25, 85, 400,2000	0.1401	50

Table 4-1: Overview of Cases Simulated in Fluent

To evaluate the erosion rate, the Surface Integrals Report option is used. The Surface Iso-Clip tool is utilized to cut the pipe Wall into the bend segment desired to be observed. In the Iso-Clip, set the min value of -0.75 and max value of 0.25 for x-direction Grid. Next, set the min value of -0.25 and max value of 0.75 for y-direction Grid as reference to the previous Clip surface.

Select the Area-Weighted Average, then the DPM erosion in the Surface Integral windows to Compute for the selected elbow erosion rate.

To evaluate the erosion rate at Geometry 2, another Wall segment downstream of the bend is chosen, since it is not valid to evaluate erosion rata at the bend area with small pipe attached. In the Iso-Clip, set the min value of 0 and max value of 5 for x-direction Grid. Next, set the min value of -0.25 and max value of 0.25 for y-direction Grid as reference to the previous Clip surface.

4.1 Case 1: Bulk Velocity of 1.8, 5, 25, 85, 400, and 2000 m/s

Bulk Velocity(m/s)	Erosion Rate (kg/m2-s)
1.8	6.9785e-11
5	1.5177e-09
25	1.1270e-07
85	2.3856e-06
400	1.0461e-04
2000	5.8900e-03

Table 4-2: Different Bulk Velocity and Erosion Rate

4.2 Case 2: Crude Oil Viscosity of 1.2870, 0.9340, 0.6450, 0.2960, 0.1401, 0.1040, 0.0824, 0.0507, and 0.0010 cP

Viscosity (cP)	Erosion Rate (kg/m2-s)
1.2870	5.17e-10
0.9340	4.33e-10
0.6450	1.79e-10
0.2960	1.58e-11
0.1040	5.20e-11
0.0824	7.66e-11
0.0507	1.05e-10
0.0356	1.04e-10
0.0010	1.03e-10

Table 4-3: Different Crude Oil Viscosity and Erosion Rate

4.3 Case 3: Sand Particle Size of 20, 50, 70, 100, 150, 300, 800, and 1200 μm

Particle Size (μm)	Erosion Rate (kg/m2-s)
20	1.5938e-10
50	6.9785e-11
70	4.7914e-11
100	4.1266e-11
150	4.2034e-11
300	4.9613e-11
800	4.2333e-11
1200	5.2036e-11

Table 4-4: Different Sand Particle and Erosion Rate

4.4 Case 4: Geometry 2 with Bulk Velocity same as Case 1

Bulk Velocity (m/s)	Erosion Rate (kg/m2-s)
1.8	8.6806e-12
5	5.9984e-11
25	1.2025e-08
85	4.5458e-07
400	1.9575e-05
2000	5.6793e-04

Table 4-5: Geometry 2 with Bulk Velocity of 1.8, 5, 25, 85, 400, and 2000m/s

CHAPTER 5

DISCUSSION

5.1 CASE 1: VARY BULK VELOCITY

At constant particle size, as the bulk velocity increase, the erosion rates at 90° bend increases. This also means that the higher the flow rate, the more the erosion occurs at the bend. At high flow rate of fluid, more mass is transferred in pipe at a short duration of time compared to at low liquid flow rate. The amount of sand particles would then be higher at high flow rate and hence increasing the erosion.

5.2 CASE 2: VARY FLUID VISCOSITY

As the viscosity reduces, the erosion rate reduces at 90° bend area. Viscosity is the measure of the resistance of the fluid to move. When the fluid viscosity is high it means that the velocity gradient of the flow is small meanwhile, the fluid shear stress is high at wall. The carried sand in crude oil will also induce the same shear rate at wall, thus high erosion occur at high viscosity.

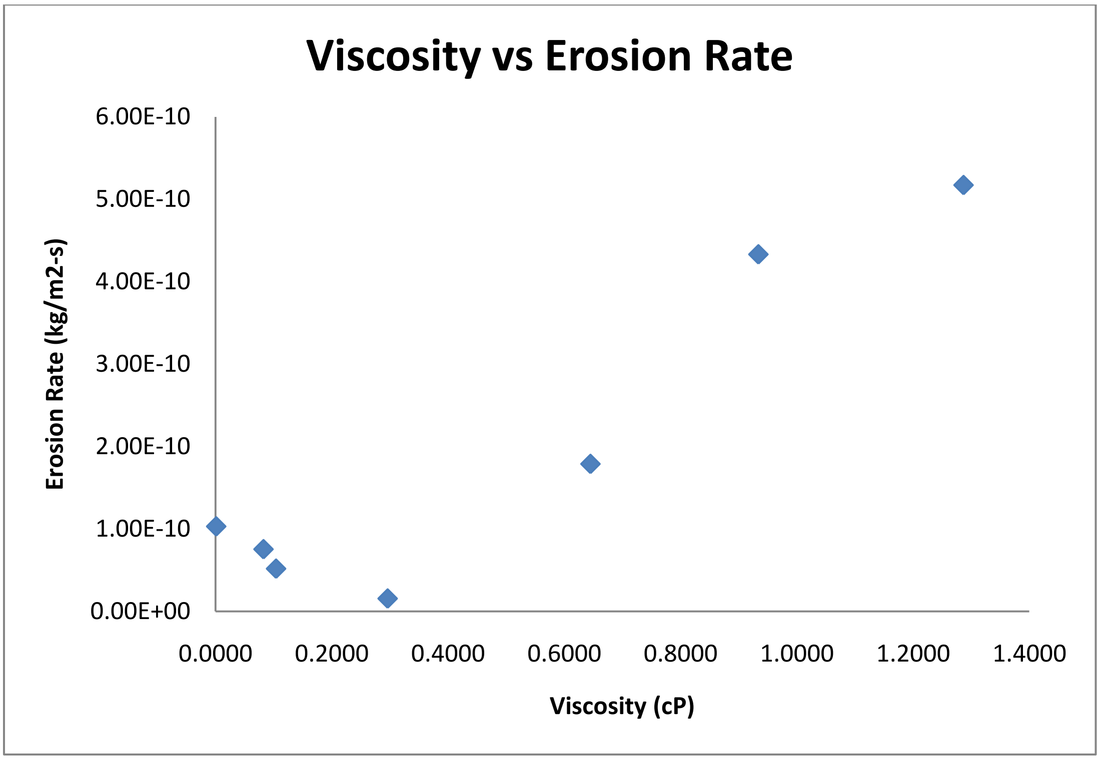

Figure 5-1: Graph of Erosion Rate versus Particle Size

5.3 CASE 3: VARY PARTICLE SIZE

The erosion rate at 90° bend is high when the particle size is small and reduces as the particle size is increased. Lighter particle is easy to be carried by the fluid flow thus causing high erosion rate compare to heavy particle. Beyond 150μm the erosion rate starts to plateau to a constant value of 4.1266e-11 kg/m^2-s as shown in Figure 5-1, in agreement with that observed by Barton, 2003 due to slower movement and transport of heavier particles.

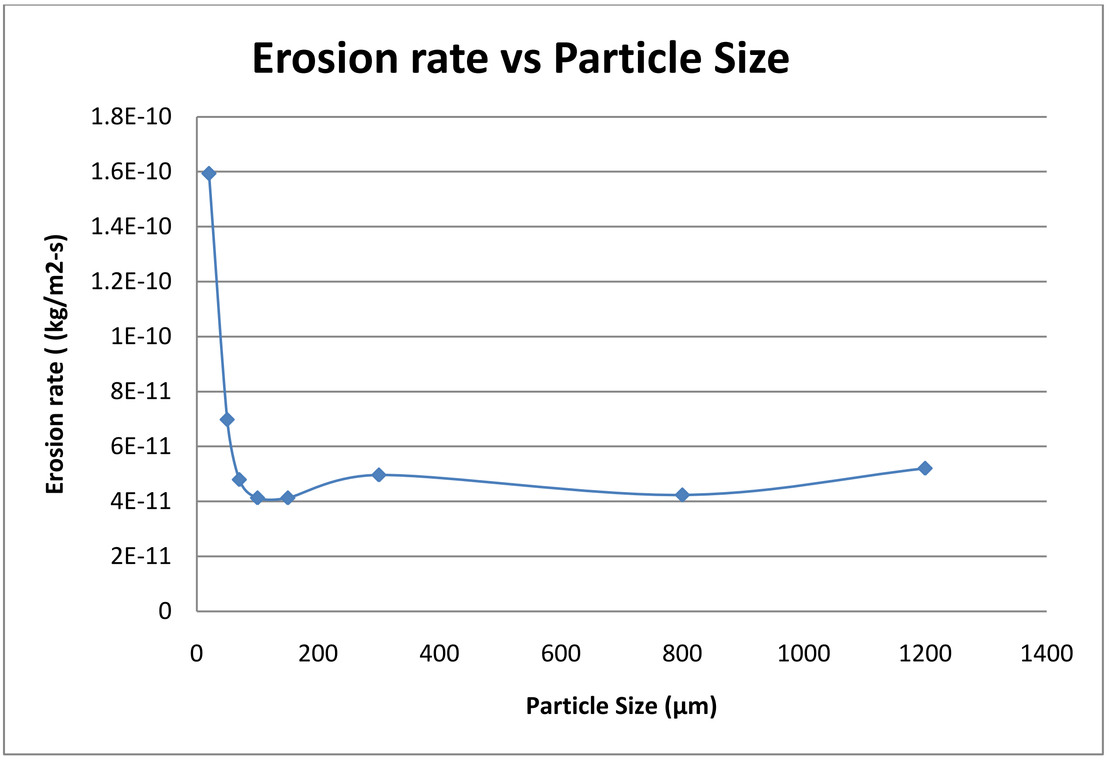

Figure 5-2: Graph of Erosion Rate versus Particle Size

5.4 CASE 4: SMALL PIPE AT 90° PIPE BEND

The introduction of the small pipe at 90° bend reduces the erosion rate at downstream pipe significantly. The crude carrying sand tends to flow through the small pipe causing the rate of erosion at the small pipe to be high and hence reducing the erosion in the main pipe. In this situation, the usage of small pipe would be beneficial if the maintenance cost of replacing the small pipe is much lower than replacing the whole mainstream pipe. Further study may be conducted to justify this statement.

Bulk Velocity (m/s)	Erosion Rate (kg/m2-s)		% of Reduction in Erosion (%)
	Geometry 2	Geometry 1	
1.8	8.6806e-12	6.9785e-11	87.56
5	5.9984e-11	1.5177e-09	96.05
25	1.2025e-08	1.1270e-07	89.33
85	4.5458e-07	2.3856e-06	80.94
400	7.5389e-06	1.0461e-04	92.79
2000	1.9575e-05	5.8900e-03	99.67

Table 5-1: Percent of Erosion Reduce in Geometry 2

The Figure 5-2 and Figure 5-3, showing the velocity contour in pipe for different geometry. The high velocity is concentrated at small pipe in Geometry 2.

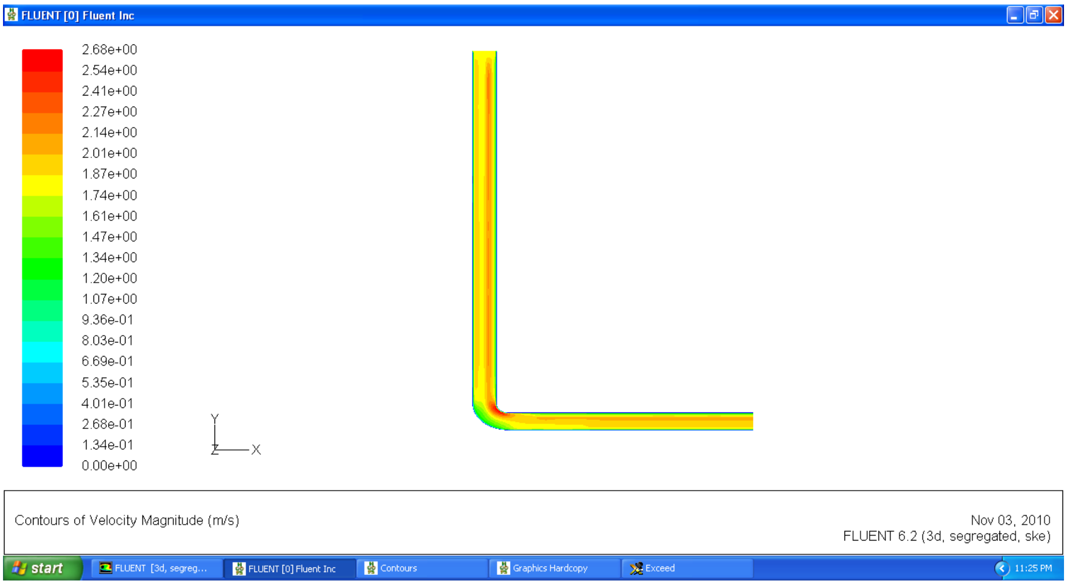

Figure 5-3: Geometry 1 Velocity Distribution

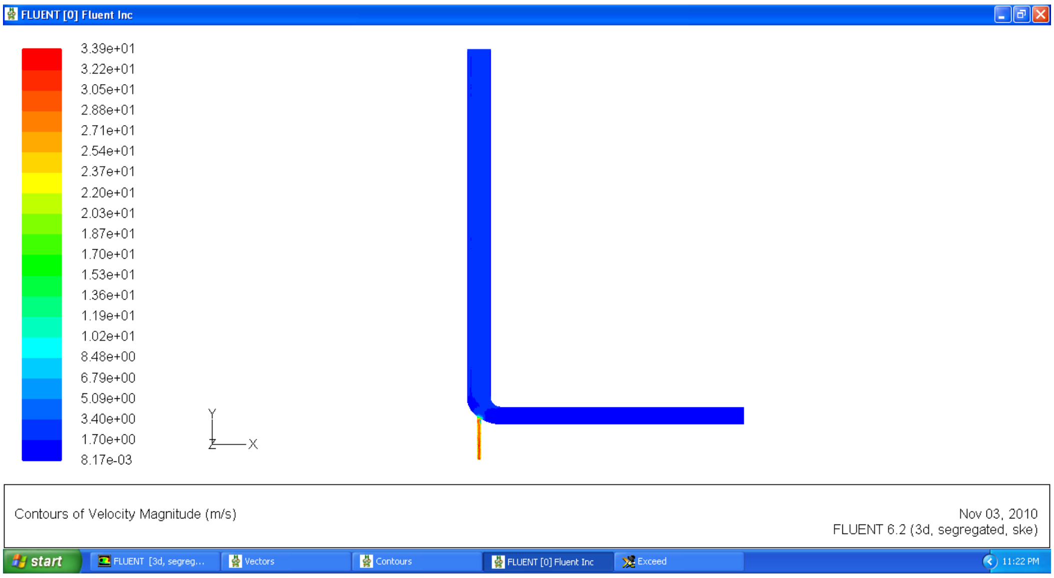

Figure 5-4: Geometry 2 Velocity Distribution

CHAPTER 6

CONCLUSION

The sand erosion in crude oil pipe with 90° bend simulation work is successfully conducted using the Fluent 6.2 together with Gambit version 2.2.30. The grid used is validated by the utilizing Richardson's extrapolation-to-the-limit technique; whereby the value extrapolated is compared with the value obtained by gradually reducing the grid size.

From the simulation results, the erosion rate increases as the flow rate increase, viscosity increase and the particle size decrease. Being able to control the fluid properties such as viscosity and flow rate is vital to reduce the erosion problem in pipe bends.

The presence of 90° bend severely increases the erosion rate in pipe. This area is highly affected by the sand particle due to the flow turbulence and sudden change in geometry. The inertia of the particle is considerably an issue in this situation.

A modified geometry of the pipe at the 90° bend with introduction of small pipe helps to reduce the erosion occurring at the downstream of the bend but high erosion rate could be observed within the small pipe with. The joint area of the small pipe with the main pipe showing highest erosion rate.

A part from that, the multiphase model in Fluent also is proposed to be utilized since the crude flow in pipe consist of oil, gas and water phase.

In conclusion, the single phase of crude oil in pipe with 90° bend simulation is done by procedure recommended by Fluent user guide 6.2. The use of CFD software has helped the user in dealing with cost issue in conducting experiment. Solution to this erosion problem will increase the profit margin of the oil production.

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LIST OF APPENDIX

Appendix A: Properties of Crude Oil by Zhu et al (2010)
Appendix B: Value of Discrete Particle Model by Fluent 6.2 User Guide
Appendix C: Tutorial FLUENT's Erosion Model

APPENDIX A:

Table 1 Planned output parameters of one oil field in South China Sea

Production year	Oil	Water	Gas
2012	3164.1 m^3/d	2818.7 m^3/d	28476.6 m^3/d
2026	328.1 m^3/d	11671.9 m^3/d	2953.4 m^3/d

Table 2 Experimental data of viscosity of crude oil

Temperature	Viscosity
10 □	2689 mPa·s
20 □	1051 mPa·s
30 □	485.5 mPa·s
40 □	247.4 mPa·s
50 □	140.1 mPa·s
60 □	82.91 mPa·s
70 □	52.07 mPa·s
80 □	35.56 mPa·s

APPENDIX B:

Coefficient	Value
1	0.993
2	-0.0307
3	4.75e-04
4	-2.61e-06

Table of Normal Discrete Phase Reflection Coefficient Value

Coefficient	Value
1	0.988
2	-0.029
3	6.43e-04
4	-3.56e-06

Table of Tangent Discrete Phase Reflection Coefficient Value

Point	Angle	Value
1	0	0
2	20	0.8
3	30	1
4	45	0.5
5	90	0.4

Table of Piecewise-linear Impact Angle Function for Erosion Model

**Set constant value of the Diameter Function and Velocity Exponent Function, 1.8e-9 and 2.6 respectively

APPENDIX C: