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Computational Fluid Dynamics Analysis on Pipeline Erosion due to the Presence of Solid Particles

CHUKWUGOZIE JEKWU EJEH

CHUKWUGOZIE JEKWU EJEH holds a Master's of Science degree in Advanced Mechanical Engineering from the University of Leeds, United Kingdom. He is an Assistant Lecturer, Simulation Laboratory Technician in the Department of Oil and Gas Engineering at All Nations University College and Founder of the Engineering Computation Laboratory, Nigeria. His area of expertise is Computational Fluid Dynamics, Solid Mechanics, Petroleum Reservoir Static and Dynamics modeling and Flow Assurance Analysis.

GBEMISOLA PRECIOUS AKHABUE

GBEMISOLA PRECIOUS AKHABUE holds a Bachelor of Science degree in Environmental and Natural Resource Management from Presbyterian University College, Akuapem, Ghana. She is the Co-founder of Engineering Computation Laboratory, Nigeria. Her area of expertise is Environmental Impact Analysis, Natural Resource Management and Climate Change.

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ABSTRACT

It is evident that when reservoir fluids (oil and gas) are extracted, contaminant particle in the solid phase such as sand, scale, and insoluble materials are also transported through the wellbore to the surface facilities. These solid particles can impinge on the pipe walls, deforming or stripping away the surface material in a process known as erosion and may further cause damage of pipeline fitting, subsurface, surface handling equipment and erosion-corrosion leading to pipeline leakage, which plays a vital role in ensuring adequate gas flow. Computational Fluid Dynamics Analysis has been used to predict the rate of pipeline erosion in recent years by top research institution such as Multiphase Flow Assurance Innovation Centre (FACE), research cooperation between Instituto Federal Electoral (IFE), Norwegian Trent National University (NTNU), and Stiftelsen for industriell og teknisk forskning (SINTEF). This work was focused on using COMSOL Multiphysics CFD to estimate the maximum rate of pipeline erosion at the 90-degree elbow junction using methane gas as the transport fluid. The two equation k-ω turbulent model was used to model turbulent gas flow through a pipe geometry governed by the Reynold's Averaging Navier-Stokes (RANS) equation. A static and time-dependent simulation was performed to study fluid dynamic behavior in terms of velocity magnitude, pressure, erosion rate, and turbulence, and particle trajectories respectively. Erosion rate prediction was done using the Finnie, DNV and E/CRC model and studies showed that the rate of erosion was intense at the pipe elbow area where the transported solid particles collide in-elastically with the pipe wall. The maximum rate of erosion was estimated to be (10E-07 kg/s-m^2) and this estimate was concluded to be high when compared to published work in this area. Hence, occurrences of erosion-corrosion will be detrimental to the pipeline structural integrity and may cause flow assurance problems.

Introduction

Pipelines used to transport fluids such as oil and /or gas often contain solid contaminant particles, for example, sand, insoluble scales and other solids that are carried along with the moving fluid. These solid particles can impinge on the pipe walls, deforming or stripping away the surface material in a process known as erosion (Khanna et al., 2004). In addition to physical depletion of material from the pipe walls, erosion by solid particles may be detrimental to the condition of the pipelines in other, more indirect ways. For example, solid particles may damage corrosion-resistant layers inside the pipes or remove chemical inhibitors from the interior surfaces, exposing material in the pipe walls that may be more susceptible to corrosion (Tilly, 1973). Such synergistic effects, often indicated by the term erosion-corrosion, can be extremely costly as they may cause oil and gas pipelines to degrade at an accelerated rate. Computational Fluid Dynamics (CFD) analysis of pipeline erosion is a powerful and cost-effective tool for design, optimization, and diagnostics of Oil and Gas production equipment. It has been applied exhaustively in the Oil and Gas industry to tackle related problems of flow assurance (Zhang et al., 2009).

Understanding of the wearing in pipe materials and production control equipment caused by sand impingement is very important in protecting the pipeline, surface, and subsurface production equipment against unforeseen hazards such as pipeline leakages (Oka et al., 1997). Estimating sand erosion is complicated, most especially in multiphase flow systems due to factors such as impact velocity, impact angle, shape, size, properties of solid particles and target materials (Tilly, 1973). Investigations on the matter are being carried out recently by FACE (Multiphase Flow Assurance Innovation Centre), research cooperation between IFE, NTNU, and SINTEF and in co-cooperation with Blekinge Institute of Technology in Sweden.

Statement of Problem

In the oil and gas industry, the extraction of oil and gas from reservoirs are polluted with solid particles such as sand, scale, minerals and other solid particles causing several flow assurance problems (Oka et al., 1997). An example is the damage of pipeline fitting, subsurface, surface handling equipment and erosion-corrosion leading to pipeline leakage, which plays a vital role in ensuring adequate gas flow (Chen et al., 2004). Occurrences of erosion if not properly predicted, monitored and prevented, may cause pipeline leakages, negative influence on the entire production process and may lead to production shut down for an extended period of time, hence affects the economics of the oil and gas project (Khanna et al., 2004).

Aim

This paper is aimed at estimating the rate of erosion in a gas transmission pipeline along a 90° elbow section due to the presence of solid particles. The fluid (methane gas) dynamic behavior will be studied using the Computational Fluid Dynamics (CFD) module in COMSOL Multiphysics software. **Significance of Study** Application of Computational Fluid Dynamics analysis to study erosion rate in Oil and Gas pipelines using COMSOL Multiphysics will provide better predictions of corrosion hotspots, plan proactive measures to mitigate erosion occurrences, maintenance schedule and save money from reduced downtime (Chen et al., 2004).

Also, determining erosion tolerance of some equipment will help mechanical engineers optimize equipment placement in a facility because it is not wise to position crucial production equipment prone to erosion where it is hard to get service (Matsumura et al., 1991).

Review of Turbulence Modelling with Computational Fluid Dynamics

Turbulence is a state of irregular or unsteady motion where transported flow quantities such as momentum, mass and scalar species agitation with time and space in a specified media (Online Dictionary). Here, fluid and velocity properties such as air density, experience random variation as it is observed to take identifiable swirling pattern, enhanced mixing, containing a wide range of eddies sizes (ANSYS, 2006).

A flow is said to be turbulent if Reynolds Number, Re_N is above 500,000 along the surface and 2,300 for external and internal flows respectively. Factors such as free-stream air, wall boundary conditions and disturbances may lead to transition to turbulence effect at lower Reynolds number (ANSYS, 2006). The Reynolds number and turbulent intensity can be calculated from equations below. The figure below shows formation of small and large turbulent structures.

$$Re_L = \frac{\rho UL}{\mu} \quad (1)$$

$$I = 0.16 * Re_D{}^{-1/8} \quad (2)$$

where, ρ is density of fluid, kg/m^3
U is the free stream air velocity, m/s
μ is the is fluid resistance to motion in cemtipoise.
I is the turbulent intensity from hydraulic diameter for internal flows measured in percentage.

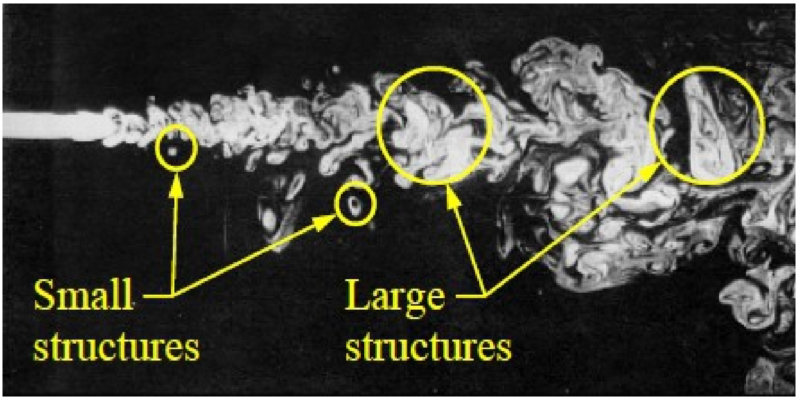

Figure 1; turbulent airflow showing development of large and small structures

Source: (Richardson, 1922)

Reynolds-Averaged Navier-Stokes (RANS) Models

Turbulence models are mean flow equations used to resolve details of flow fluctuations in Engineering applications. These models enable calculation of mean flow, before calculating full time-dependent flow path (Bakker, 2006). The common turbulence models used are those in the family of Reynolds Averaging of Navier-Stokes equations such as Zero equation model (mixing length model), One equation model (Spallart-Almaras) and Two equation models (K-ε and K-ω models) (Bakker, 2006). With large eddies, time-dependent calculations are performed explicitly compared to the small eddies influence on the flow pattern can be analysed using subgrid model (Fluent, 2002).

RANS models are widely used in industrial application where all turbulent length scales can easily be modelled. The time-averaging equation shown in Figure 2.2 below

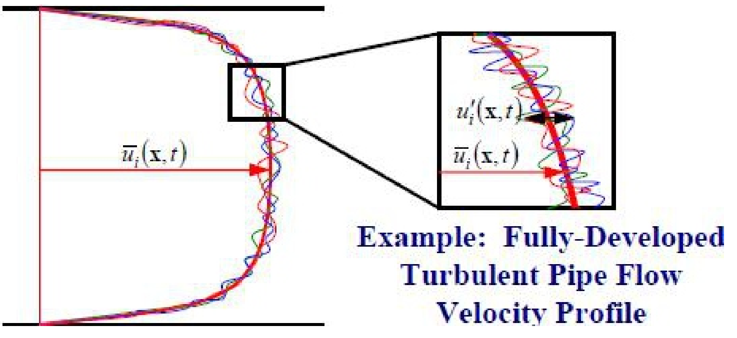

Figure 2; fully developed turbulent pipe flow using RANS model
Source: (ANSYS, 2006)

The equation below shows the Reynolds-average momentum equation. The Reynolds stress tensor (R_{ij}) is an additional unknown introduced by the averaging procedure and needs to be modelled (ANSYS, 2006).

$$P\left(\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_k \frac{\partial \overline{U}_i}{\partial x_k}\right) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu \frac{\partial \overline{U}_i}{\partial x_i}\right) + \frac{\partial R_{ij}}{\partial x_j} \quad (3)$$

K- ε Turbulent Models

In industrial applications such as external building flow, fume hood design, industrial ventilation and engineering research, Standard K- ε is the most widely used as it provides reasonable accurate and robust solutions. It is made up of sub-models for compressibility, combustion and buoyancy, but the ε term cannot be computed at the wall boundaries, therefore requiring wall functions. From previous study, it was observed that this model performs better in flow regimes with large streamline curvature, strong flow separation yielding inaccurate pressure gradient predictions and actual flow features (Gilkison, 2017; ANSYS, 2006).

Compared to Standard K-ε model, Renormalization group (RNG) k-ε model performs better for complex shear flows, swirl, separation and flows containing high strain rate. RNG K-ε model contains a differential viscosity model to provide accountability for low Reynolds effects, a second model derived analytically for turbulent Prandtl number and swirl modification (Gilkison, 2017; ANSYS, 2016).

Another type of turbulent model is the Realizable k-ε (RKE) model that meets critical mathematical constraints on the Reynolds stress. This model is more realizable, accurately predicts spreading flow rate of round and planar jets, higher performance to flow with strong adverse pressure gradients, recirculation, separation and flow rotation at boundary layers.

K - ω Turbulent Models

The K- ω turbulent models are now widely used than the K- ε family of turbulent models because its model equation has no term which are undefined at the surface wall boundaries and hence can be integrated not requiring wall functions. The Standard K- ω model is most widely used in aerospace industry as it contains sub models of K- ω to compute shear flow corrections, transitional flow and compressibility effects. They are suitable for transitional flows. The SST (Shear Stress Transport) K- ω model uses a combination function to gradually simulate transition from Standard K- ω at wall boundary to higher Reynolds number version of K - ε model towards outer region of boundary layer (ANSYS, 2006).

The Langtry-Menter 4-equation Transitional SST model makes use of gamma and Retheta in addition to k and omega equations, to describe gradual to turbulent transition flow process. It can be used for internal flow simulations and equation (2.4) below describes the Langtry-Menter 4-equation Transitional SST model to resolve smooth transition flow where μ_t is the turbulent viscosity, ρ is the fluid density, x_j is the position of transported particles, t is the flow time, p is the flow pressure and is the velocity at each transport position u_j, γ is the intermittency factor which triggers transition from laminar to turbulent and accurately predicts transition onset characteristics at boundary layer (ANSYS, 2006).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \hat{p}_k - \hat{D}_k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right]$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = p_\omega - D_\omega + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\frac{\partial(k)}{\partial x_j}\frac{\partial(\omega)}{\partial x_j} \quad (4)$$

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_j \gamma)}{\partial x_j} = p_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_f})\frac{\partial \gamma}{\partial x_j}\right]$$

$$\frac{\partial(\rho \hat{R}_{e\theta t})}{\partial t} + \frac{\partial(\rho u_j \hat{R}_{e\theta t})}{\partial x_j} = p_{\theta t} + \frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu + \mu_t)\frac{\partial \hat{R}_{e\theta t}}{\partial x_j}\right]$$

Factors Affecting Erosion in Pipeline

Effect of Velocity on Erosion

Figure 3a and Figure 3b below, the maximum erosion rate increases as the velocity increases and shows an exponential relationship (Abdullah, 2011). Erosion rate for the pipe bends at different angle is demonstrated in Figure 3b. When the velocity is relatively small, the maximum erosion location often takes place in a small angle around 20°. As the velocity increases, the maximum erosion location occurs at an angle between 45°-50°.This is mainly attributed to the fact that particle stays longer in the straight section when the velocity is small.

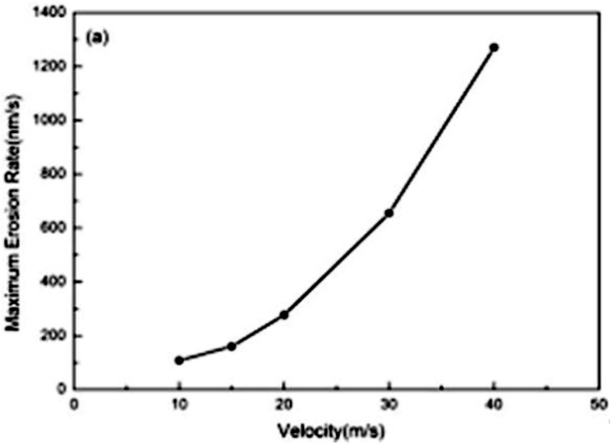

Figure 3a; effect of velocity on corrosion rate
Source: (Abdullah, 2011)

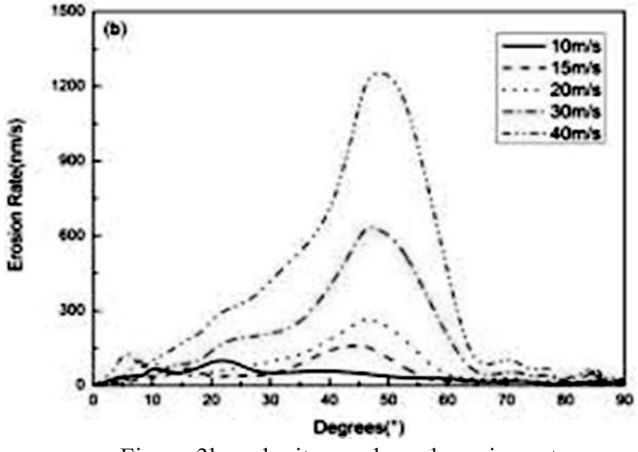

Figure 3b; velocity, angle and erosion rate
Source: (Abdullah, 2011)

Effect of Particle Diameter on Erosion

Erosion rate for the pipe bends with different particle diameter is illustrated in Figure 4. Figure 4a shows that as the particle diameter increases, the erosion rate increases, and when the particle diameter exceeds 150µm, the erosion rate tends to keep steady as particle diameter increases. This is may be because the larger particles transfer more momentum to the gas phase. Thus, the coupling effect between the solid particles and gas phase make the erosion rate increase slowly (Zhang et al., 2009). Although the increase tendency of the erosion caused by the particles from the diameter of 100µm to150µm is less remarkable than those from 50µm to 100µm, it is still more remarkable than the particles which diameter is larger than 150µm. Thus, the critical diameter of the particle erosion is 150µm. In Figure 4b, the maximum erosion location of the pipe bends under different particle diameter occurs at the angle about 45° (Abdullah, 2011). This angle will change slightly with the particle diameter increasing. This is because the drag force makes the impact angle of smaller particles increase slightly. Particle diameter does not play an important role in changing the maximum erosion angle.

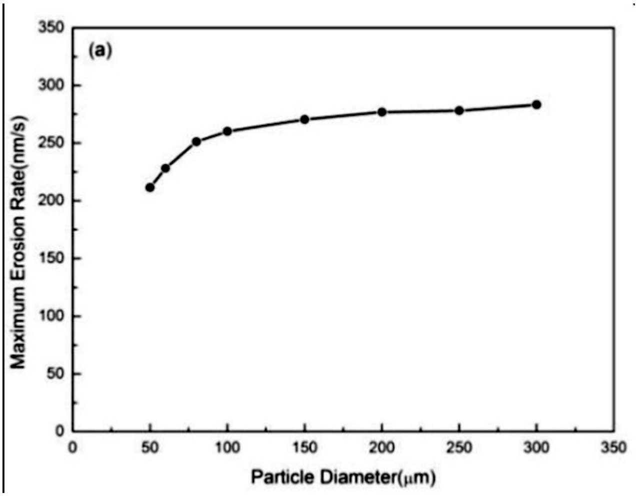

Figure 4a; particle diameter on erosion rate
Source: (Abdullah, 2011)

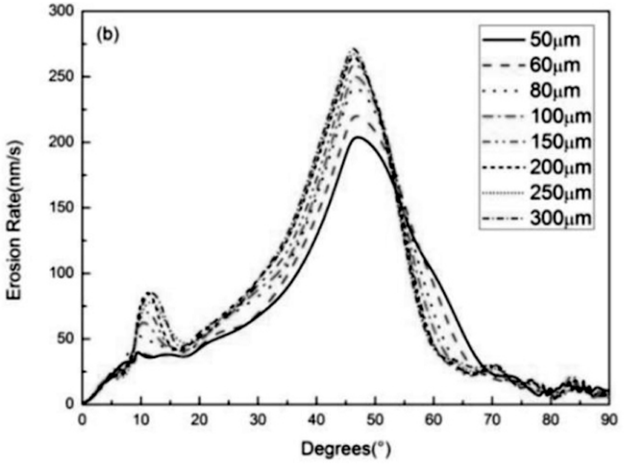

Figure 4b; particle size and erosion rate
Source: (Abdullah, 2011)

Effect of Particle Mass Flow Rate on Erosion

Erosion rate of the pipe bends under different particle mass flow rate is illustrated in Figure 5. In Figure 5a, the erosion rate increases linearly as the particle mass flow rate increases., causing inelastic collisions between particles and inner wall surface. The maximum erosion location occurs at the angle between 45° and 50°, as shown in Figure 5b. This angle keeps the same no matter how the particle mass flow rate changes.

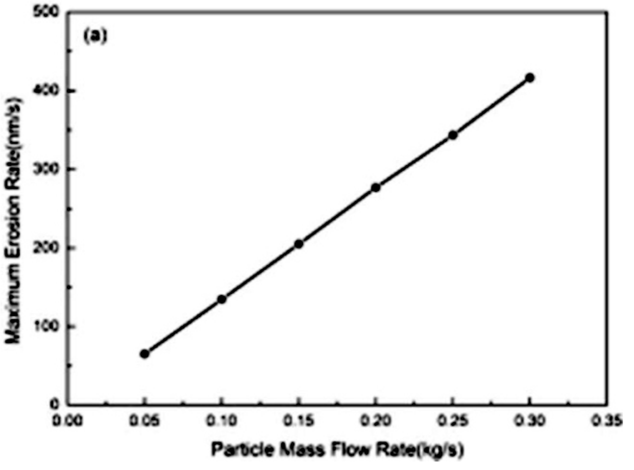

Figure 5a; particle mass rate to erosion rate
Source: (Abdullah, 2011)

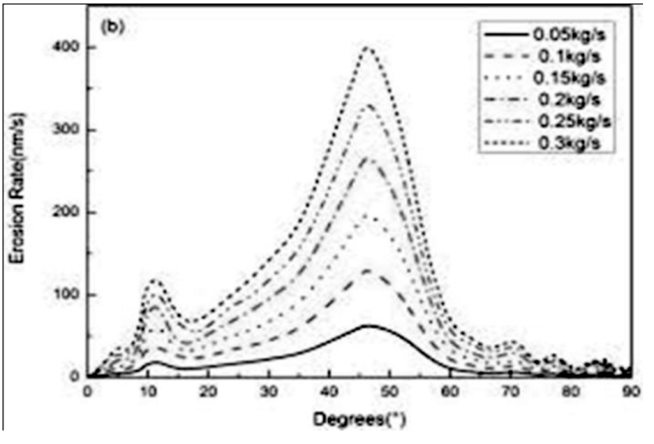

Figure 5b; particle angle to erosion rate
Source: (Abdullah, 2011)

Effect of Pipe Diameter on Erosion

Erosion rate for the pipe bend with different pipe diameter is illustrated in Figure 6a. Figure 6a shows that as pipe diameter increases, the erosion rate decreases quickly. As the pipe diameter increases to 400mm, the erosion rate arrives at a lower level. The erosion rate of the pipe bend with the diameter of 40mm is two orders of magnitude higher than that with the diameter of 400mm. This presents the remarkable influence of diameter (Abdullah, 2011). When the pipe diameter exceeds 400mm, the erosion rate will decrease slightly. This is mainly due to the fact that the pipe with large diameter has a relatively larger impact surface. Pipe with small diameter suffers from more particle collisions per unit area than those with large diameter, and ultimately are eroded more severely (Chen et al., 2004). As is shown in Figure 6b, there are two peaks in maximum erosion rate of the outermost of the elbow. The first one occurs at the angle between 15°and 20°, and the second occurs at the angle between 45° and 50°.The peak position changes as the pipe diameter increases. When the pipe diameter is rather small, such as 40mm or 100mm, the maximum erosion location occurs at the angle between 45° and 50°. When the pipe diameter is rather large, the maximum erosion location occurs at the angle between 15° and 20° (Abdullah, 2011). This is mainly because as the pipe diameter increases, the solid particles have more time to adapt to the changes around, and the gravity makes solid particles easier to move at the bottom of the pipe, thus the maximum erosion angle of pipe bends with larger diameter are smaller.

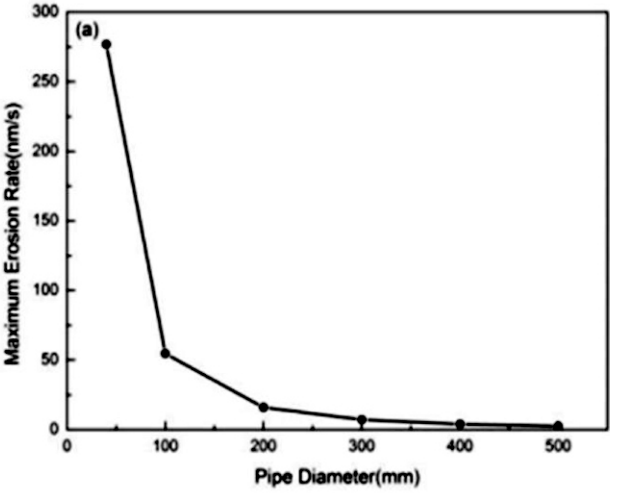

Figure 6a; pipe diameter on erosion rate
Source: (Abdullah, 2011)

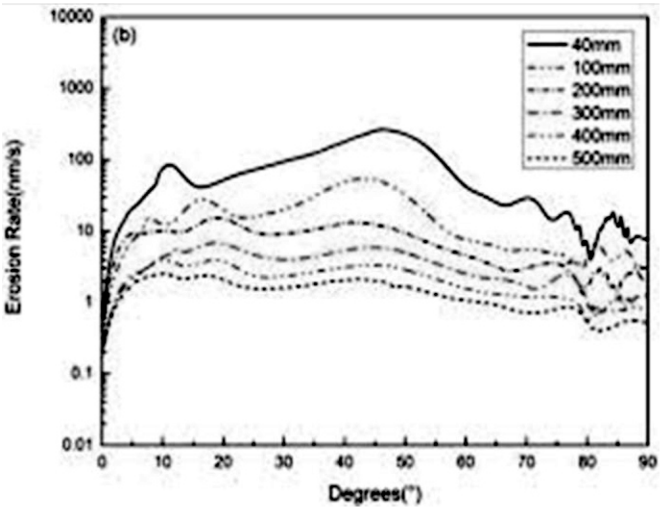

Figure 6b; pipe diameter and erosion rate
Source: (Abdullah, 2011)

Effect of Bend Orientation on Erosion

Erosion rate for the pipe bend with different bend orientation is illustrated in Figure 7. In Figure 7a, the maximum erosion rate occurs in the direction of H-V upward pipe bend. In this direction, the gravity has a significant influence on the particle movement, the particles tend to impact the elbow at a lower location than the other orientations, and as a result, the impact area that the solid particles collide with pipe wall is the smallest among these four directions (Chen et al., 2004). The number of particles impacting the pipe wall in unit area is the largest, thus it leads to a larger erosion rate. In Figure 7b, the erosion tendency in the direction of V-H at different angles is similar. However, the erosion tendency for the pipe bend in the H-V direction is quite different from each other (Abdullah, 2011). The flow direction of particles changes due to the gravity, particles deviate from the streamline and moves downward, thus the impact angle increases. Hence, for the pipe bend in H-V downward direction, the maximum erosion angle increases.

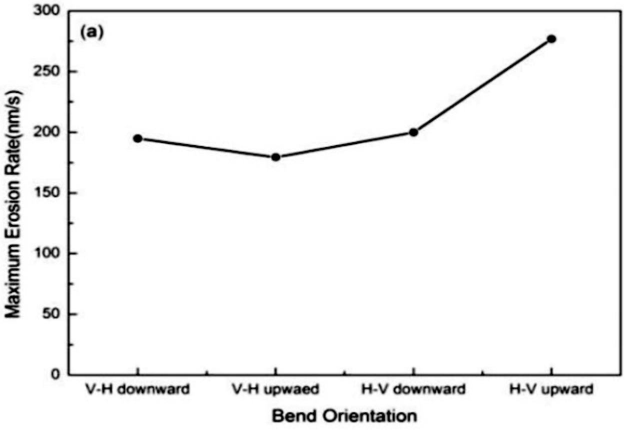

Figure 7a; bend orientation with erosion rate
Source: (Abdullah, 2011)

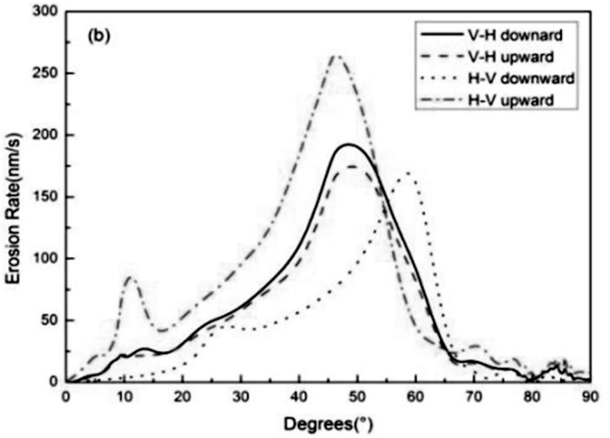

Figure 7b; bend orientation and erosion rate
Source: (Abdullah, 2011)

Application of CFD in estimating erosion rate in pipeline Elbow

Computational Fluid Dynamics (CFD) has been extensively used in Oil and Gas industries to study behaviour in fluids through pipes to solve flow assurance problems (Zhang et al., 2009). Simulation studies on the erosion rate estimation in Oil and Gas pipeline due to sand presence, has been done by Abdullah, (2011) using STAR-CCM+. In this study, a 90-

degree elbow with diameter of 0.0508 m and curvature r/D equal 1.5 was used to perform the investigation. Four cases were investigated upon to estimate the average erosion rate in a 90-degree elbow using air, Methane, gas mixture and, gas and oil respectively (Abdullah, 2011).

In all cases, sand particles were used as dispersed phase. Studies showed that, maximum pipe erosion is experienced at the pipe elbow than the other sections of the pipe. This concludes that, the pipe wall design thickness at the elbow section should allow for internal surface depletion (Chen et al., 2004).

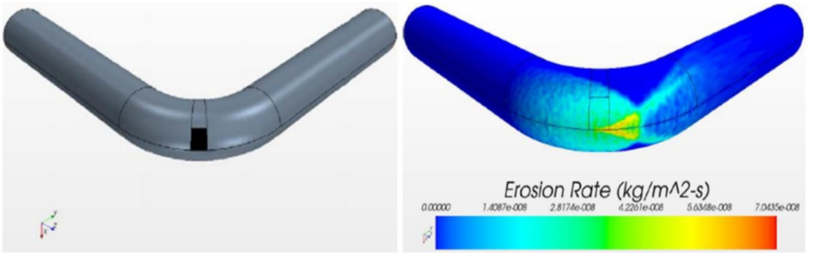

Figure 8; CFD investigation on erosion on a pipeline elbow
Source: (Abdullah, 2011)

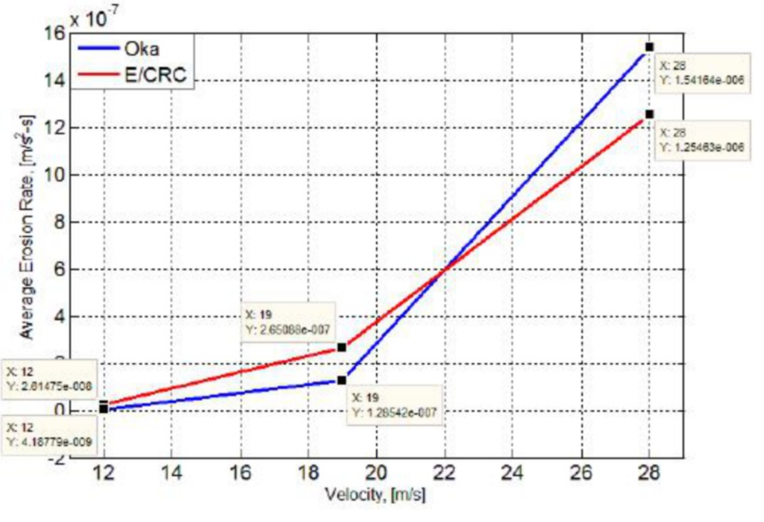

Figure 9; average corrosion rate with varying velocity
for oil-gas-sand on whole elbow
Source: (Abdullah, 2011)

Erosion-Corrosion in Pipelines

The transportation of petroleum products is often accompanied by sand particles and water which adversely affect the pipeline (Khanna et al., 2004). Erosion-corrosion in oil and gas pipeline has been an increasing problem in petroleum industry especially in the hydrogen sulphide environment. The control of erosion-corrosion problems can be expensive and time consuming due to the unplanned nature of stoppages and high maintenance costs. Integrity of the pipeline and the environment are of interest to the pipeline industry and the broader petroleum community (Islam et al., 2014). During erosion-corrosion process, the corrosive products formed on the pipeline surface in the form of oxide film are affected by mechanical action of the solid erosion process (Matsumura et al., 1991). Removal of the oxide film particles by the mechanical action subjects the exposed area to more stresses and degradation.

One of the common form of failure that occurs in the oil and gas industry results from CO_2/H_2S corrosion of the steel materials. This process is complex and influenced by many parameters and conditions (Matsumura et al., 1991). The general understanding of erosion-corrosion process is that there are electrochemical and mechanical processes involved which can affect the other.

Different tests and models have been proposed to understand the erosion-corrosion process and variation in results have been found in some cases. This could be as a result of the test conditions, environment, materials and equipment used in the tests (Tilly, 1973; Finnie, 1960 and Bitter, 1963).

METHODOLOGY

Simulation of pipeline erosion can be a powerful and cost-effective tool for design, optimization, and diagnostics. Some common industrial applications involve the use of Computational Fluid Dynamics with COMSOL Multiphysics to investigate transport of fluids and wear. In this project, the rate of erosive wear at the 90° pipe elbow is estimated and compared for three different erosion models which include Finnie, DNV and E/CRC.

CFD COMSOL Multiphysics is an advanced fluid flow modelling and simulation tool which has been extensively used for various industrial applications. Amongst other CFD modules in the COMSOL Multiphysics module library, the fluid flow analysis module was used in this work to model methane gas transport using the Navier-Stokes equation.

Model Geometry and Boundary Definition

The model geometry consists of two straight cylindrical pipe sections, each 140 cm and 80 cm in length respectively with 20 cm in diameter. The straight sections are connected by a 90° pipe bend with a 50 cm radius of curvature. The pipe is used to transport natural gas at room temperature at 273.15 kelvin, with a maximum inlet velocity of 40 m/s. The gas stream is treated as an incompressible fluid.

The pipe also transports solid particles at a rate of 0.6 kg/h. Although such particles would typically be assigned a size distribution, in this work, it was assumed that all particles have equal diameters of 0.17 mm.

Figure 10 below is a 3-Dimensional view of the pipeline geometry which was used as the model geometry to investigate on the degree of erosion rate with time experienced in a typical natural gas transport application.

Table 1: Pipe model creation input parameter

Parameter	Input	Value	Description
L1	1.8[m]	1.8 m	Length tube 1
L2	0.7[m]	0.7 m	Length tube 2
r1	0.06[m]	0.06m	Radius tube 1
r2	r1	0.06m	Radius tube 2
R3	0.5[m]	0.5m	Major radius elbow
r3	r1	0.06m	Minor radius elbow
fc	0.1	0.1	Proportion of particles with idealized cutting behaviour

kappa	2	2	Ratio of vertical/ horizontal forces
Hs	1.96[GPa]	1.96E9 Pa	Hardness, iron
rho	7860[kg/m^3]	7860 kg/m³	Density, iron
sigma	2850[kg/m^3]	2850 kg/m³	Density, SiC
Vi	16.5[m/s]	16.5 m/s	Inlet velocity

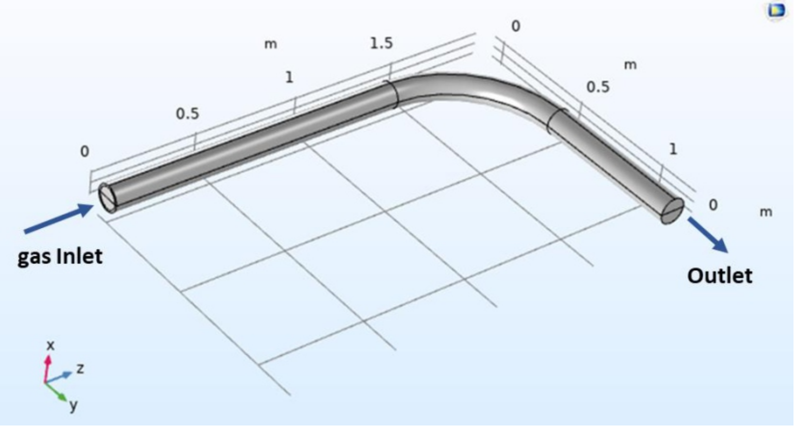

Figure 10: Pipeline model geometry showing a 90° pipe elbow

Physics and Turbulent Flow Model Selection

The high Reynolds number, ReD = 3.96 × 106 based on the pipe diameter, calls for a turbulence model with wall functions. Here the k-ω model is selected over the k-ε model because it is more accurate than the k-ε model for flows involving strong streamline curvature.

The Fluid Flow interfaces are used to simulate flow and pressure fields of liquids and gases. The physics interfaces cover single-phase flow, multiphase flow, thin-film flow, porous media flow and flow in pipes. The Single-Phase Flow branch contains physics interfaces for modelling low Mach-number (<0.3) flows of single-phase fluids.

The Turbulent Flow, k-ω interface is used for simulating single-phase flows at high Reynolds numbers. The physics interface is suitable for incompressible flows, and compressible flows at low Mach number (typically less than 0.3).

The equations solved by the turbulent Flow, k-ω interface are the Navier-Stokes equations for conservation of momentum and the continuity equation for conservation of mass. Turbulence effects are modelled using the Wilcox revised two-equation k-ω model with realizability constraints. The k-ω model is so-called low-Reynolds number model, which means that it can resolve the flow all the way down to the wall.

The Turbulent Flow, k-ω interface was used for stationary and time-dependent analysis.

The Particle Tracing for Fluid Flow interface was used to compute the motion of particles in a background fluid. Particle motion can be driven by drag, gravity, and electric, magnetic, and acoustophoretic forces. User-defined forces can be added. It is also possible to compute the particle mass and temperature as well as particle-fluid interactions.

Materials Properties

Methane gas obtained from the materials component library in COMSOL was used as the transmission fluid to model methane gas production of Coalbed methane reservoir from a hypothetical well in Nigeria. The standard properties used for this simulation is shown in Table 2 below, showing material property, variable, value, units of measurements and the property group.

Table 3: table showing material properties and description

	Property	Variable	Value	Unit	Property group
☑	Dynamic viscosity	mu	eta_gas_2(T[1/K])[Pa*s]	Pa·s	Basic
☑	Density	rho	1.93	kg/m³	Basic
	Thermal conductivity	k_iso ; kii = k_iso, kij = 0	k_gas_2(T[1/K])[W/(m*K)]	W/(m·K)	Basic
	Heat capacity at constant pressure	Cp	C_gas_2(T[1/K])[J/(kg*K)]	J/(kg·K)	Basic
	HC	HC	HC_gas_2(T[1/K])[J/(mol*K)]	J/(mol·K)	Basic
	VP	VP	VP(T[1/K])[Pa]	Pa	Basic

Solid materials or particles was used as the dispersed phase, modelled using the Particle tracer module/option in COMSOL. The particle diameter was assumed in this case to be the same with value 1.7E-4 m, mass flow rate of 0.6[kg/h] with a number of 50000 particles per release.

Mesh Creation

Mesh generation is the practice of generating a polygonal or polyhedral mesh that approximates a geometric domain. The term "grid generation" is often used interchangeably.

In computational solutions of partial different equations, meshing is a discrete representation of the geometry that is involved in the problem. Essentially, it partitions space into elements (or cells or zones) over which the equations can be approximated. Zone boundaries can be free to create computationally best shaped zones, or they can be fixed to represent internal or external boundaries within a model.

In this work, an unstructured mesh was created with boundary layers to properly resolve fluid flow profiles during simulation using partial differential equations. The mesh was made dense along the pipe walls where erosion rate will be investigated. A less dense mesh at the boundaries will yield an inaccurate prediction of erosion or wear rate at the longitudinal pipe section.

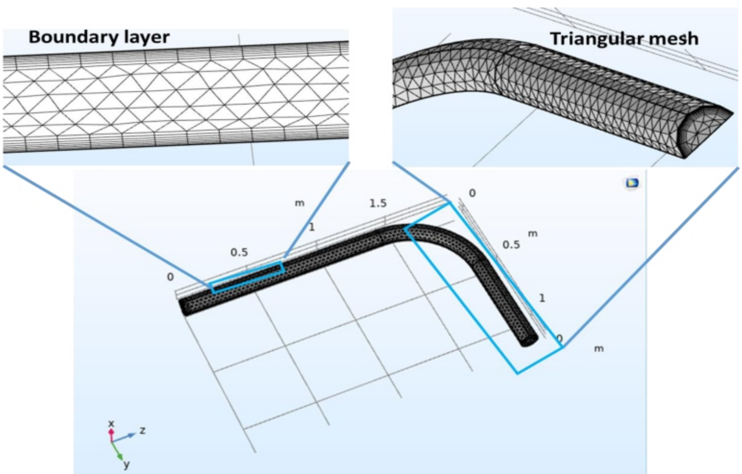

Figure 11; model meshing to create flow domain

Simulation Study

Two studies were conducted, which includes a static and transient simulation. The static simulation was run to obtain computational fluid dynamics parameters such as the fluid flow velocity, pressure and turbulence intensity distribution throughout the flow domain. Whiles the transient study was aimed at analysing the effect of particle transport to pipe wall erosion rate. It should be noted that, Computational Fluid Dynamics and Particle tracing module was used as the physics for this study.

RESULTS AND CONCLUSION

Segregated Solver Convergence Analysis

COMSOL Multiphysics makes use of the CFD module algorithm to study the dynamics behaviour and transport of fluid through a confined media using the Reynold's Averaging Navier-Stokes equation. Estimation error in the prediction flow profiles such as velocity, pressure, turbulence, viscous drag, and erosion rate prediction is measured using the segregated solver in COMSOL. From figure 12 below, the error of estimation is within the acceptable limits as the solution is seen to converge to the 10^{-4} after 45 iterations.

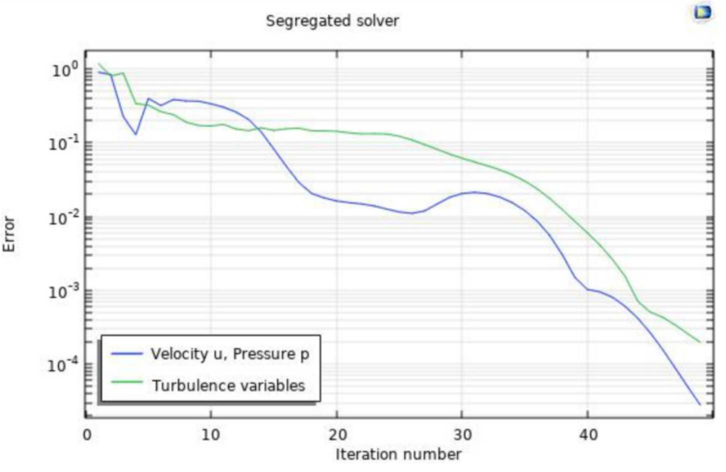

Figure 12: gas flow velocity, turbulence and pressure convergence plot

Analysing Fluid Flow Velocity Magnitude

Fluid flow velocity profile is a key parameter when studying the dynamic behaviour fluid. Using the two equation k-ω turbulent model as the physics, determination of turbulent gas flow and velocity predictions was made possible. It was observed in Figure 13 below that, the transport fluid undergoes turbulent flow regime as each molecules flows with approximately different velocities. The turbulent flow is seen be intense at the elbow section sequential random collision of transported particles with the pipe elbow internal wall surface. This implies that, the fluid flow Reynolds number is higher within this region.

Increased gas flow velocity is seen to occur above the standard set value of 40 m/s.

Critical information such as mass flow rate and pressure can be derived from the velocity magnitude predictions shown in Figure 13 below. This is very important to the production engineer to quantify flow regime and efficiency.

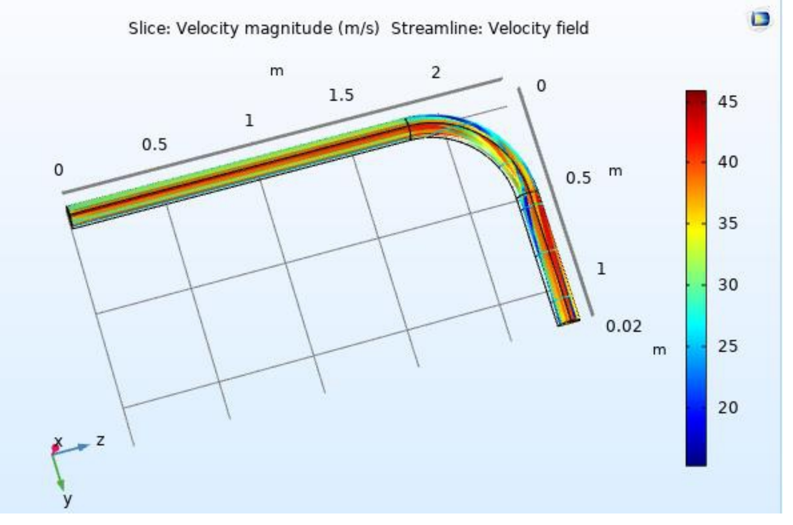

Figure 13: flow velocity magnitude predictions

Critical production information can be deduced from Figure 13 above. The plot shows that there is a time-dependent transition in flow regime from steady state to turbulent gas flow, mass flow rate and an idea of expected pressure distribution. This information is important to the production engineer to evaluate the tubing performance of the well.

Wall Resolution for Viscous Drag

Viscous drag is critical during fluid flow as it offers resistance to fluid flow, due to friction force. It is most experienced at the pipe walls as the fluid comes in contact with the solid surfaces. At each stage of the gas flow, the magnitude of the viscous drag changes due to turbulence and extends to 10 units. This is less experienced at the elbow region whose magnitude ranges from 80 – 110 units.

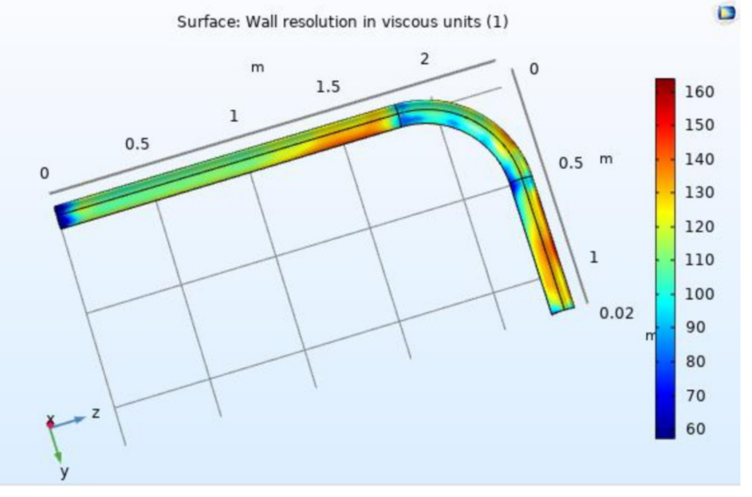

Figure 14: drag force predictions along pipeline section due to viscous drag

Theoretically, intermolecular forces exist between like and unlike molecules. These forces contribute to viscous drag when two molecules (like or unlike) due to relative motion. In this case, it could be observed that viscous drag is occurring at the wall surface where dipole-dipole attractive forces between the unlike molecules (metal and gas molecule).

Time-dependent Particle Tracing

Figure 15 below shows how solid particles in the fluid media are being transported from the inlet, through the pipe elbow and towards the outlet section. The pipeline longitudinal section was re-sized to ease visualisation of particle transport. The length modification was implemented in this case only. Visualisation of particles transport was made possible with the implementation of COMSOL particle tracing physics. In the study section, a time-dependent simulation was performed and results stored in solution for a 0.12 seconds flow period.

It can be observed that after 0.05 seconds, the particles disintegrate into smaller pieces due to multiple wall-particle collisions at the pipe elbow.

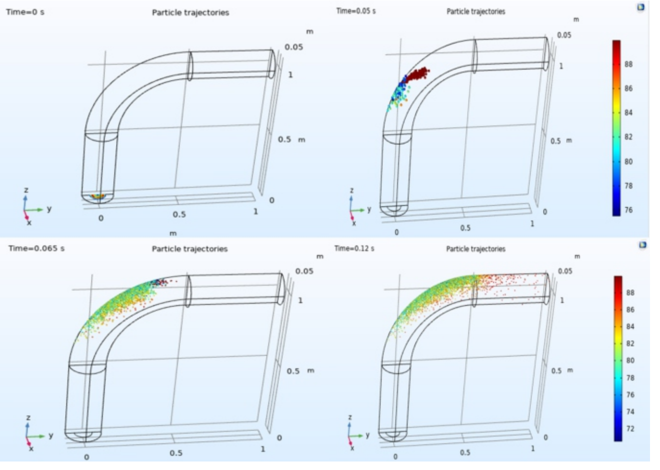

Figure 15: Time dependent evaluation of solid particles transport

Erosion Rate Analysis at Pipe Elbow for Different Erosion Model

Erosion of pipe surfaces is a crucial factor in flow assurance and is still an existing problem till date. Renowned research institutions have studied this problem and have concluded on its dangers to pipeline integrity and lifespan. Problems arising from pipe surface erosion rate, most especially at the elbow junction is the cause of pipeline leakages after a certain period of time and may further cause increased abnormal flow pressures due to the heat energy created as a result of friction.

Different models have been developed and embedded in to COMSOL particle tracing module to accurately predict erosion rate during fluid flow, in a confined media. Finnie, DNV and E/CRC models were implemented in the COMSOL flow modelling environment to provide predictions of erosion rate. Results obtained from these models shown in Figure 16, show similar erosion rate predictions.

In general, high erosion rate is experienced at the 90-degree pipe elbow section which confirms results obtained by Abdullah, (2011). Compared to Abdullah, (2011) work where STAR C++ CFD software used with water as the transport fluid, higher predictions were obtained in this work. The density of the transport fluid played an important role and informs that, fluid density influences the rate of erosion in pipelines.

The Finnie model predicted higher erosion rate compared to the DNV and E/CRC model. The Plot in Figure 16 below was obtained after 0.22 seconds when performing time-dependent studies.

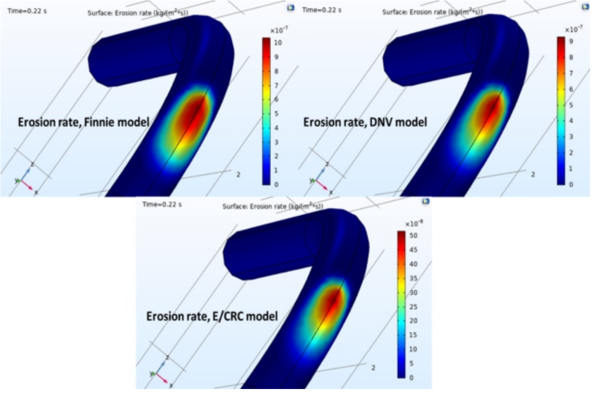

Figure 16: erosion rate predictions at pipeline elbow section using Finnie, DNV and E/CRC erosion model

Observation and Conclusion

Studies showed that, maximum pipe erosion rate is experienced at the pipe elbow than the other sections of the pipe. It is critical to ensure that, the pipe thickness at the elbow section should be design to minimise the rate of erosion.

From literature, the Finnie model provides a better prediction of maximum erosion rate at the pipe elbow. In this project, the maximum predicted erosion rate was about 10^{-7}kg/m2s which was higher than those results predicted by Abdullah, (2011) in page 18 of this work.

Also, comparing Abdullah, (2011) research where STAR C++ CFD software and water as the transport fluid was applied, to this project, lower predictions of erosion rate was obtained. This was as a result of the difference in density of the transport fluid, which played an important role and informs that, fluid density may influence erosion rate estimation in pipelines.

The momentum energy posed by solid particles is a function of the fluid flow rate, enabling constant in-elastic collisions throughout its transport. Frequent wall-particle collision experienced at the pipe elbow causes particles disintegration with time with constant reduction in diameter.

High prediction of erosion rate is detrimental to the lifespan and structural integrity of the fluid transmission pipeline, which was observed to be most intense at the pipe elbow.

Recommendation

It can be recommended that, pipeline design materials should be corrosion resistant (noble metals) and cost effective. An example is re-enforced carbon fibre which has shown to be promising in engineering applications such as aircraft design.

Achievement of the above statement, will enable better design of natural gas transport pipeline for the case gas field and extend the life span of the pipeline.

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