A Computational Approach to Assessing Pipeline Integrity under Gas Flow Erosion

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Abstract- ***This research presents a computational investigation of pipeline erosion under dry gas flow using Computational Fluid Dynamics (CFD). The pipeline geometry, developed in SolidWorks and simulated in ANSYS Fluent, incorporated ASTM A106 Grade B steel with bends and elbows to reflect field conditions. Gas was modelled with a density of 0.75 kg/m³, viscosity of 1.12 × 10⁻⁵ kg/m·s, and molecular weight of 19.71 kg/kmol. Sand particles (50–300 µm, 2650 kg/m³) were introduced at concentrations of 0.01–0.10%. Three flow scenarios were tested: 7.18 m/s (minimum), 14.35 m/s (baseline), and 21.52 m/s (maximum). Results showed the highest erosion at outer elbow bends, with peak rates increasing from 2.2 × 10⁻⁵ to 1.25 × 10⁻⁴ kg/m². Sensitivity analysis identified bends as critical erosion zones, while straight sections remained stable. Mitigation measures such as thicker bend walls, optimized flow conditions, and sand monitoring are recommended. A safer operating velocity of 12.0 m/s is proposed.***

Index Terms- ***Erosion, Pipeline, Simulation, Gas-flow***

I. INTRODUCTION

Crude oil in long-distance transmission pipelines may entrain globs of water droplet, sand or dirt, which can coalesce and fall out of the oil flow in stretches of pipeline that run at lower pressure and temperature. Those deposited particles will cause erosion problems, which is attributed to the collisions between particles and the inner wall of the pipeline (K. Wang *et al.,* 2017).

Pipelines are the safest and most cost-effective method for transporting petroleum products. As a crucial element of modern energy infrastructure, pipelines extend millions of kilometers globally to meet the demands of the expanding energy market (Khan *et al.,* 2021). The word erosion is derived from the Latin verb ‘‘erodere’’ meaning to gnaw but nowadays the world has acquired a broader definition such as wearing a way of rocks by glaciers and also material removal by caveating liquids occurring in the numerous industrial installations where solid particles are entrained in a fluid stream (Majid *et al.,* 2012). Pipeline integrity is greatly reduced by erosions. Pipeline erosions is a significant concern in the oil and gas industry, and it can be influenced by variety of factors, including fatigue stress, human activities and natural phenomenon. Fatigue can be described as a structural damage of materials due to stress (Algadi, A. 2017).

A leak of high-pressure water pipe in a mixture of soil and sand can create an erosive slurry impact on nearby pipes. Slurry erosion will form by the interaction of solid particles suspended in liquid and a surface which experience losses of mass by repeated impacts of particles. This type of erosion has been reported as the major source of failure of many engineering equipment such as slurry equipment and hydraulic components (Majid, *et.al,* 2010). Slurry erosion is one of the types of wear that leads to the gradual removal of material from the target surface due to impingement of the solid particles suspended in the liquid phase. In the present scenario, the components of most of the machines as well as equipment are deteriorated by slurry erosion (Singh *et al.,* 2021).

“Pipeline integrity” includes failure prevention, inspection and repair, and it also includes products, practices and services that help operators maximize their assets. Reliable pipeline and its integrity should be ensured from the composition of its tubular

structure to the high-tech ways of building, modelling, managing, monitoring and repairing. It begins at the project conception stage and allows for risk mitigation and long-term optimized performance to be built into the final design. This concept started during mid-1990s (Gabbar & Kishawy, 2011).

Despite the rare and decreasing frequency of containment loss and improving emergency response, major accidents' environmental, societal, and economic consequences remain drastic. Following the relatively high accident rate of pipelines during the 1970s, the introduction and inefficacy of early prescriptive pipeline safety guidelines in the 1980s, many countries have included performance- based risk and integrity management in their legislation in the past three decades (Viera & Shirazi, 2021). Pipelines are crucial infrastructure components in modern energy-intensive economies, facilitating the safe and efficient transport of essential resources. The structural integrity of pipelines is paramount, as failures can lead to significant environmental, societal, and economic repercussions (Sun *et al.,* 2022). The integrity of these systems has been a focal point for regulators, practitioners, and academics, evolving from simple visual inspections to advanced, risk-based integrity management strategies utilizing real-time data. This evolution reflects the critical need for reliable infrastructure to support societal development and economic stability (Khan *et al.,* 2021).

One of the primary concerns in pipeline management is the phenomenon of erosion-corrosion, which can significantly compromise structural integrity (Beccati, *et al.,* 2019). Erosion-corrosion is a complex process that involves the combined effects of mechanical erosion due to particle impingement and chemical corrosion. Studies have demonstrated that variables such as particle size, shape, and concentration critically influence the rate and extent of material degradation in pipelines. For instance, experiments with sand-water suspensions revealed that the physical characteristics of sand particles, along with their concentration, play a pivotal role in the erosion wear of pipelines, leading to wall thickness reduction and surface damage. The erosion-corrosion process can result in pits, craters, and cutting wear mechanisms, with the severity of damage often varying along the pipeline's surface (Chalgham *et al.,* 2020). Thanks to the advantages of safety, efficiency and low cost, pipelines are widely used in transporting large quantities of oil and gas products over long distances. Pipelines may suffer from different types of defects such as erosion, corrosion, fatigue cracks, stress corrosion cracking (SCC), dent, etc. These defects, if not properly managed, may result in pipeline failures including leak or rupture, which could lead to very expensive downtime and environment hazards (Xie & Tian, 2018). The severity of erosion is directly linked to droplet velocity, with higher velocities causing significantly more damage. Erosion and corrosion interact, with corrosion dominating at lower production rates and erosion becoming more prevalent at higher rates. Numerical simulations identified specific pipeline areas, such as joints and bends, as particularly vulnerable to erosion due to droplet accumulation. The research emphasizes the importance of managing production conditions to mitigate erosion and protect pipeline integrity (J. Zhang, 2020).

According to Zhang and Liu, (2015), gas-flow erosion is primarily induced by the impact of solid particles carried within the gas stream on the internal pipe surfaces. This intricate process is influenced by particle velocity, impact angle, and pipe material properties. The authors employed numerical simulations to track particle trajectories and predict erosion rates, highlighting the significance of flow dynamics, including turbulence and secondary flows, in determining erosion patterns.

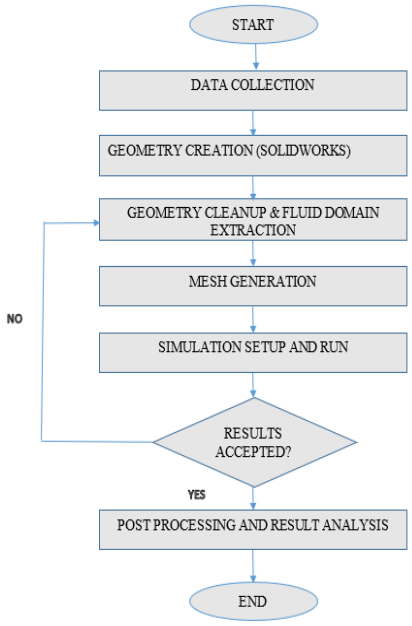
This research aims to investigate the impact of gas flow erosion on the integrity of pipelines using computer simulation. By simulating various erosion scenarios, this study seeks to identify critical factors contributing to pipeline degradation and to develop strategies for mitigating these effects. The findings will contribute to the broader understanding of pipeline integrity management and offer insights into improving the resilience and safety of these vital infrastructure systems.

II. MATERIALS

SolidWorks Software was used to design the 3D pipeline system with joints, valves, reducers among other components. SpaceClaim Software (ANSYS) was used for sorting the geometry designed on SolidWorks prior to running the simulations. ANSYS Fluent Software was used for running the simulations and monitoring the flow behavior, pressure drop, erosion rate, etc. The software were installed and all the computational activities were carried out on a personal computer (laptop). Maximum Efficiency Ratio (MER), Gas Essay and Well Hook up Path data were used throughout the study.

Methods

The methods employed in this research for the achievement of the outlined objectives can be summarized in the flow chart below:



3.1 Data Collection

Data used during the study was sourced from NNPC Exploration and Production Limited (NEPL);

I. Maximum Efficiency Ratio (MER) test data: which is a detailed evaluation of individual wells performance, carried out at a certain time intervals to obtain the properties and production data of a particular well.
II. Well hook up path: An AutoCAD drawing of a well geometry, providing the materials used and geometrical dimensions (path).
III. Gas Essay: The detailed gas compositional analysis report for the produced gas and some other properties of gas used are obtained from this data.

3.2 Geometry Creation

As the first step in the simulation process, the pipeline geometry was created using SolidWorks, a 3D computer-aided design (CAD) software. SolidWorks was used due to its accuracy and flexibility in mechanical design, which allowed for precise dimensioning, proper alignment of joints, and seamless connections between components.

Table 1: Major Components Used in Geometry Creation

S/N	Materials & Description
1	BARE PIPE, SMLS, SCH 160, ASTM A106 GR B, 12M
2	TEE RED, BW, ASME B16.9, ASTM A234 Gr, SCH160
3	BEND, SCH 160, 90 DEGREES LONG RADIUS
4	ELBOW, SCH 160, 90 DEGREE
5	FLANGE, WN,2500 LB RTJ, ASME, B16.5, ASTM A105
6	R 33 X 230mm RTJ GASKET
7	GLOBE VALVE, RTJ, 2500#

Note: Additional components present in the pipeline system are not included in the table as they are considered to have insignificant impact on the objectives of this study.

This is to ensure that the geometry closely resemble actual field layouts and would perform reliably in fluid flow simulations. Special attention was given to modelling the internal surfaces where erosion would occur, as these surfaces form the basis of interaction between the fluid flow, solid particles and the pipe walls.

3.3 Geometry Clean up and Fluid Domain Extraction

Following the geometry design, the model was imported into ANSYS Space Claim for cleanup and preparation. This step involved inspecting the geometry for gaps, overlapping faces, or unstitched faces that could prevent successful meshing or volume extraction. Tools within repair tab, such as stitch, missing faces, and gaps were used to identify and fix these issues, ensuring the geometry was water tight and fully enclosed. Once the geometry was verified as a single solid body, the internal fluid domain was extracted. This created a separate solid body that defines the flow region, which was essential for meshing and simulation in Fluent.

3.4 Mesh Generation

After creating the geometry and extracting the fluid domain, the next step was to generate a mesh for numerical simulation. Fine meshing is essential for capturing flow details and predicting erosion accurately, especially in areas with complex geometry like bends. The study focused on a representative elbow section where erosion effects are often most severe. Figure (1) below illustrates the meshed elbow section of the piupeline:

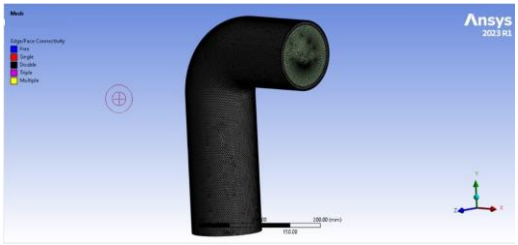


Figure 1: Meshed Elbow Section of the pipeline.

A tetrahedral mesh was selected for the curved elbow. The mesh consisted of 454,192 elements and 176656 nodes, with a global element size of 22.772 mm. A local refinement of 1.8 mm was applied around the outer bend to capture high gradients. Twelve inflation layers were added along the inner wall for near-wall resolution, with a layer growth rate of 1.20.

3.5 Setup Fluid Properties, Flow Conditions and Boundary Conditions in ANSYS Fluent

3.5.1FluidProperties

Following the meshing stage, the simulation setup began with defining the properties of the working fluid. In this study, the fluid was a mixture of natural gas produced with solid particles (sand). The gas is modelled as a compressible gas with a molecular weight of 19.71 kg/kmol, density of 0.75 kg/m³ at standard inlet conditions, the dynamic viscosity of 1.12×10^{-5} kg/m·s. These values along with the molecular composition of the gas that can be seen in figure (2) are all obtained from the gas essay data used.

Molecular Composition		
No.	Component	[mol %]
1	N_2	4.01
2	CO_2	1.54
3	CH_4	81.32
4	C_2H_6	7.92
5	C_3H_8	3.96
6	i-C_4H_{10}	0.61
7	n-C_4H_{10}	0.55
8	i-C_5H_{12}	0.06
9	n-C_5H_{12}	0.03
10	C_6H_{14}	0.00
11	C_7H_{16}	0.00
12	C_8H_{18}	0.00
13	C_9H_{20}	0.00
14	C_{10+}	0.00
	Total	100.00
Sample Properties:		
Molecular Weight [g/mol]		19.71
Specific Gravity [air = 1]		0.680

Figure (2): Composition of the natural gas produced (Gas essay data)

3.5.2FlowConditions

The flow rate was based on the actual production data of the gas well, with a gas rate of 18.320 MMSCFD converted into an inlet velocity using the pipe's internal diameter (101.6 mm). This resulted in an inlet velocity of approximately 14.35 m/s. The inlet temperature used was 323 K (50°C), and the operating inlet pressure was 5.31 MPa. Reynolds number (based on D = 0.1016 m) is calculated to be $Re = 4.88 \times 10^6$ (highly turbulent).

3.5.3BoundaryConditions

The simulation domain was assigned appropriate boundary conditions to control how the fluid entered, moved through, and exited the pipe (elbow) section. The inlet was defined as a velocity inlet, applying the

calculated velocity, temperature, and turbulence intensity. The operating pressure of the domain was maintained at 5.31 MPa to match the actual pipeline pressure. The pipe walls were treated as no-slip walls, with the discrete phase (sand particles) allowed to rebound or stick upon impact to capture realistic erosion behavior.

3.6 Simulation Run and Monitoring

After meshing and defining the fluid–solid properties, the simulation was run in ANSYS Fluent using a pressure-based 3D steady solver with the energy equation enabled and the SST k–ω turbulence model for accurate near-wall predictions. The gas phase was modeled as a compressible ideal gas at 770 psi and 323 K, with an inlet velocity of 14.35 m/s. The Discrete Phase Model (DPM) simulated sand particle transport (density = 2650 kg/m³) with a specified size distribution injected at the inlet. Particle–wall interactions were set to rebound, and the Finnie erosion model predicted wall material loss along the elbow. Several iterations were performed, the instant flow rate served as the baseline, while lower and upper flow rates represented the minimum and maximum cases. Table (2) presents the simulation data for the baseline, minimum and maximum cases as can be seen as thus;

Table 2: Simulation Parameters for the three iteration cases

Iteration (Case)	Velocity (m/s)	Particle Size (µm)	Particle conc. (%)
Minimum case	7.18	50	0.01
Baseline Case	14.35	150	0.05
Maximum Case	21.525	300	0.10

IV. RESULTS AND DISCUSSIONS

4.1 Minimum Case

For the first iteration (minimum case) with velocity of 7.18 m/s, particle size of 50 µm, and particle concentration of 0.01%, the CFD simulation results indicate that erosion occurs primarily at the outer bend of the elbow section of the pipeline.

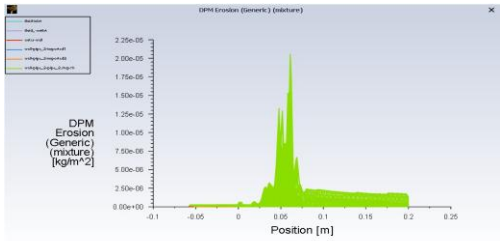


Figure 3: Minimum Case DPM Erosion distribution chart against position

At the lowest flow condition, the erosion distribution indicates generally low rates, with a sharp peak of about 2.2×10^{-5} kg/m² occurring around the bend region, approximately 0.05 m along the wall. This peak reflects the point where particle impacts are most intense due to centrifugal forces as the flow negotiates the curve. The negative values (on the position axis) shows the section of the wall before the bend, while the positive side represents the wall after the bend where erosion is most intense. Outside this localized zone, the pipeline shows negligible wear, suggesting that overall damage remains mild and poses little immediate threat to integrity. Nevertheless, this specific area represents a potential weak point, as its susceptibility to impact makes it more likely to deteriorate under higher flow conditions.

4.2 Baseline Case

For the baseline (second iteration), the velocity of 14.35 m/s, particle concentration of 0.05% and particle size of 150µm is used.

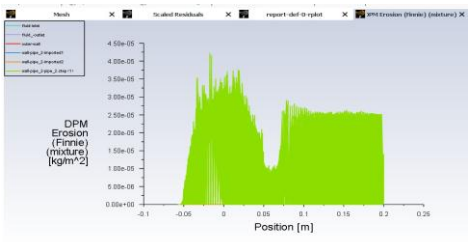


Figure 4: Baseline DPM Erosion Distribution against position

The second iteration showed a markedly higher erosional effect compared to the first, with a peak erosion rate of about 4.2×10^{-5} kg/m² occurring at the very start of the bend, followed by another slightly less intense peak further along the curve. This distribution indicates that the curved section of the elbow is highly susceptible to repeated particle impact, as the entrained solids possess sufficient momentum to deviate from the gas streamlines and strike the outer wall directly. The concentration of erosion along the bend, in contrast to the minimal effect observed in the straight pipe sections, confirms that elbows represent the most vulnerable regions for wear and material loss

4.3 Maximum case

For the maximum case (last iteration), the velocity of 21.525 m/s, particle concentration of 0.10% and particle size of 300µm is used.

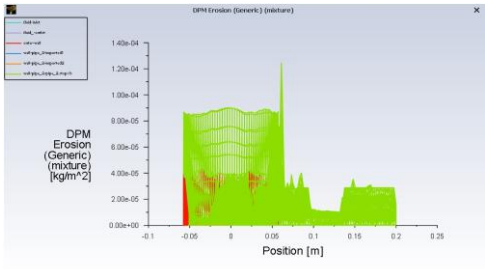


Figure 5: Maximum case DPM erosion distribution against position.

Under the maximum flow condition, the erosion distribution shows a sharp rise in rates compared to earlier cases, with peak values reaching 1.25×10^{-4} kg/m². Unlike the localized damage seen at lower velocities, the affected zone here spreads across a wider section of the elbow and into the downstream region, reflecting the compounded influence of higher velocity, larger particle size, and greater particle concentration. This results in erosion that is not only more severe but also more extensive, with the outer curvature of the elbow and adjacent downstream wall emerging as the most vulnerable sections of the pipeline. The pattern emphasizes that under such conditions, erosion becomes a serious integrity concern, requiring focused inspection and protective strategies in these critical areas.

4.4 Sensitivity Analysis

To evaluate the influence of varying flow conditions on pipe wall erosion, a sensitivity analysis was conducted using minimum, baseline, and maximum case iterations. The resulting erosion rate distributions are presented in Table 6 and Figure 19, providing a comparative view of how erosion intensity and location shift across the different scenarios.

Position (mm)	Min Case (kg/m²·s)	Baseline Case (kg/m²·s)	Max Case (kg/m²·s)
140			0
150		0.000001	
160			0.000085
200	0		
220	0.000005	0.000042	
250	0.000022		
260		0.00001	
265			0.000015
280	0.000008		
300	0		
320		0.000028	
350			0.000035
420		0	
450			0

Figure 8 illustrates the erosion rate trends along the pipe wall for the three iterations, highlighting differences in peak intensity and positional shifts.

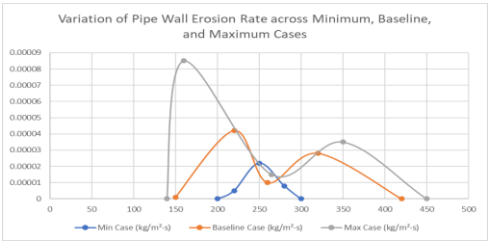


Figure 8*:* Erosion Rate vs. Position in Pipe Bend under Different Iteration Scenarios

The chart shows that erosion follows a similar trend across the three cases, with negligible rates at the pipe inlet, sharp peaks around the bend, and a decline downstream. The minimum case recorded the lowest peak erosion, while the maximum case showed the highest intensity with more sustained wear along the bend. The baseline case lies in between, capturing moderate peaks and a gradual decline, demonstrating how flow variations directly influence both the magnitude and distribution of erosion.\

CONCLUSIONS

ANSYS Fluent successfully captured the effects of particle size (50, 150 and 300µm), concentration (0.01, 0.05 and 0.10%), and velocity (7.18, 14.35 and 21.525 m/s) respectively, showing that erosion severity increases with larger, denser particles and higher gas velocities. The comparative analysis established that velocity, particle size, and concentration are the dominant factors influencing erosion. To mitigate these effects and enhance pipeline integrity, strategies such as increasing wall thickness at bends, optimizing flow to reduce erosive velocity, and integrating sand monitoring or separation systems are recommended. Based on the results, an inlet velocity of about 12.0 m/s is proposed as a safe operational threshold, as it reduces erosion risk while maintaining turbulent flow and acceptable throughput.

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